SCIENCE FOR SOLUTIONS

NOAA COASTAL OCEAN PROGRAM
Decision Analysis Series No. 23, Volume 2

SCIENCE-BASED RESTORATION MONITORING OF COASTAL HABITATS

Volume Two: Tools for Monitoring Coastal Habitats

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Science for Solutions

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Acknowledgments

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Note to Readers

Science-Based Restoration Monitoring of Coastal Habitats, Volume Two: Tools for Monitoring Coastal Habitats is a guidance manual that provides technical assistance and useful tools for the development and implementation of sound scientific monitoring of coastal restoration efforts. It also provides detailed information of the habitats, an inventory of coastal restoration monitoring program, a review of monitoring techniques manuals and quality control/quality assurance documents, an overview of governmental acts affiliated with monitoring, cost analysis of monitoring expenses, a glossary of terms, and a discussion of socioeconomic issues affiliated with coastal habit restoration.

The National Centers for Coastal Ocean Science (NCCOS) provide an essential point through which NOAA, together with other organizations with responsibilities for the coastal environment and its resources, can make significant strides toward finding solutions to critical problems. By working together toward these solutions, we can ensure the sustainability of these coastal resources and allow for compatible economic development that will enhance the well-being of the Nation now and in future generations.

A specific objective of the NCCOS is to provide the highest quality scientific information to coastal managers in time for critical decision making and in formats useful form these decisions. To this end, the Decision Analysis Series was developed by the Coastal Ocean Program to synthesize information on issues of high priority to coastal managers. As a contribution to the Decision Analysis Series, this report provides a critical synthesis of information need to successfully plan and conduct a coastal habitat restoration monitoring program. A list of available documents in the Decision Analysis Series can be found on the inside back cover.

As with all of its products, the NCCOS is very interested in ascertaining the utility of *Science-Based Restoration Monitoring of Coastal Habitats, Volume Two: Tools for Monitoring Coastal Habitats*, particularly in regard to its application to the monitoring and management decision process. Therefore, we encourage you to write, fax, call, or email us with your comments. Please be assured that we will appreciate these comments, either positive or negative, and that they will help us direct our future efforts. Our contact information is below.

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EXECUTIVE SUMMARY

Healthy coastal habitats are not only important ecologically; they also support healthy coastal communities and improve the quality of people's lives. Despite their many benefits and values, coastal habitats have been systematically modified, degraded, and destroyed throughout the United States and its protectorates beginning with European colonization in the 1600's (Dahl 1990). As a result, many coastal habitats around the United States are in desperate need of restoration. The monitoring of restoration projects, the focus of this document, is necessary to ensure that restoration efforts are successful, to further the science, and to increase the efficiency of future restoration efforts.

WHAT IS RESTORATION MONITORING?

The science of restoration requires two basic tools: the ability to manipulate ecosystems to recreate a desired community, and the ability to evaluate whether the manipulation has produced the desired change (Keddy 2000). The latter is often referred to as restoration monitoring.

For this manual, the definition of restoration monitoring is as follows:

> "*The systematic collection and analysis of data that provides information useful for measuring restoration project performance at a variety of scales (locally, regionally, and nationally), determining when modification of efforts are necessary, and building long-term public support for habitat protection and restoration*."

Restoration monitoring contributes to the understanding of complex ecological systems (Meeker et al. 1996) and is essential in documenting restoration performance and adapting project and program approaches. When the results of monitoring restored coastal areas are disseminated and shared amongst practitioners, they can provide tools to help plan management strategies and improve future restoration practices and projects (Washington et al. 2000). Restoration monitoring can be used to determine whether project goals are being met and if mid-course corrections are necessary. Monitoring provides information on whether selected project goals are good measures for future projects and on how to do routine maintenance in restored areas (NOAA et al. 2002). Restoration monitoring also provides the basis for a rigorous review of the pre-construction project planning and engineering.

Without effective monitoring, restoration projects are exposed to several risks including:

- The inability to obtain early warnings indicating that a restoration project is not developing as expected
- The inability to assess whether specific project goals and objectives (both ecological and human dimensions) are being met
- The inability to determine what measures might need to be taken to better achieve those goals
- Increased difficultly in gauging how well a restoration site is functioning both before and after implementation, and
- Decreased project coordination and efficiency

To address these and other issues associated with restoration monitoring, NOAA has provided guidance to the public in two volumes. The first volume, *Science-Based Restoration Monitoring of Coastal Habitats, Volume One: A Framework for Monitoring Plans under the Estuaries and Clean Waters Act of 2000 (Public Law 160-457)* was released in 2003. It outlines the steps necessary to develop a monitoring plan for any coastal habitat restoration project. Experienced restoration practitioners, biologists, and ecologists as well as those new to coastal habitat restoration and ecology can benefit from the step-by-step approach to designing a monitoring plan outlined in *Volume One*. *Volume Two*, *Tools for Monitoring Coastal Habitats* expands upon the information in *Volume One*. *Volume Two* is designed more for practitioners who do not have extensive experience in coastal ecology or social science than is *Volume One*. Professionals familiar with coastal habitats and their social and ecological aspects, however, may benefit from the annotated bibliographies, literature review, and other tools provided in *Volume Two*.

The first section of *Volume Two*, **Monitoring Progress Toward Goals** (Chapters 1-14) includes:

- An introduction to Volume Two
- Information on the structural and functional characteristics of coastal habitats that may be of use in restoration monitoring
- Annotated bibliographies of restoration-related literature and technical methods manuals for each habitat type, and
- A chapter concerning the human dimensions of coastal habitat restoration monitoring

The second section, **Context for Restoration** (Chapters 15-18) includes:

- A review of methods to select reference conditions
- A sample list of costs associated with restoration monitoring
- An overview of an online, searchable database of coastal monitoring projects from around the United States, and
- A review of federal legislation that supports restoration and restoration monitoring

Volume Two is intended to provide readers with information on and pertinent to monitoring of restoration activities and, in so doing, includes references to ecological and human dimensions characteristics and to restoration efforts. *Volume Two* is not intended, however, as a treatise on the ecology and social aspects of each of the habitats. Numerous texts and published documents that do this well are already available, particularly for the ecological characteristics. Likewise, detailed discussions of the restoration of the various habitats are also not presented; again, for many of the habitats, scientific publications on individual restoration methods and projects already exist.

Volume Two is also not intended as a 'how to' or methods manual; many of these are already available on a regional or habitat specific basis[1]. *Volume Two* does not provide detailed procedures that practitioners can directly use in the field to monitor habitat characteristics, although it does mention or list many that are commonly used. The tremendous diversity of coastal habitats across the United States, the types and levels of impact to them, the differing scales of restoration activities, and variety of techniques used in restoration and restoration monitoring prevent the development of universal protocols. Thus, the authors of this volume have taken the approach of explaining, based on information found in the scientific literature, *what can be measured* during restoration monitoring, *why it is important*, and *what information it provides* about the progress of a restoration effort. Based on this information, the individual practitioner can then develop monitoring protocols suited to the goals of his or her particular restoration project.

AN INTRODUCTION TO THE CHAPTERS

Chapter 1: Introduction - Provides context for the publication of this document and the associated *Volume One*. Chapter 1 also describes the selection and organization of information in each of the following chapters, who the intended audience is as well as how they should use *Volume Two*. It

[1] Many 'how to' and sampling/monitoring methods manuals for specific habitats are listed in the second appendices of chapters 2-14.

is recommended that all readers, regardless of the habitat or social characteristics they are interested in monitoring, should read Chapter 1.

Chapter 2: Water Column - A conceptual volume of water extending from the water surface down to, but not including the substrate. The water column is unique among the habitats covered in *Volume Two* as characteristics of the water column will be a part of virtually all monitoring efforts. Therefore, those interested in any type of coastal habitat restoration should also read Chapter 2.

Chapter 3: Coral Reefs - Highly diverse ecosystems, found in warm, clear, shallow waters of tropical oceans worldwide. They are composed of marine polyps that secrete a hard calcium carbonate skeleton that serves as a base or substrate for the colony. Restoration of coral reefs can be challenging as water temperatures that may be outside of the control of restoration practitioners can directly affect corals.

Chapter 4: Oyster Reefs - Dense, highly structured communities of individual oysters growing on the shells of dead oysters. Oyster reefs can filter massive amounts of water, removing large amounts of suspended and dissolved material. It is partially the removal of historic oyster beds that has contributed to the decline in water quality in some estuaries such as the Chesapeake Bay.

Chapter 5: Soft Bottom - Loose, unconsolidated substrate characterized by fine to coarse-grained sediment. At first glance, soft bottoms may appear to be devoid of life. The soft, often organic, sediments are, however, teaming with organisms that live below the sediment surface and provide an important link in estuarine food webs.

Chapter 6: Kelp and other Macroalgae - Relatively shallow (less than 50m deep) subtidal and intertidal algal communities dominated by very large brown algae. Kelp and other macroalgae grow on hard or consolidated substrates forming extensive three-dimensional structures that support numerous plant and animal communities.

Chapter 7: Rock Bottom and Rocky Shoreline - Includes all wetlands, deepwater, and shoreline habitats with substrates having an aerial cover of stones, boulders, or bedrock 75% or greater and vegetative cover of less than 30% (Cowardin et al. 1979). Water regimes are restricted to subtidal, permanently flooded, intermittently exposed, and semi-permanently flooded. The rock bottom habitats addressed include bedrock and rubble.

Chapter 8: Soft Shoreline - Includes all habitats having three characteristics: (1) unconsolidated substrates with less than 75% aerial cover of stones, boulders, or bedrock; (2) less than 30% aerial cover of vegetation other than pioneering plants; and (3) any of the following water regimes: irregularly exposed, regularly flooded, irregularly flooded, seasonally flooded, temporarily flooded, intermittently flooded, saturated, or artificially flooded (Cowardin et al. 1979). This definition includes cobble-gravel, sand, and mud. Most commonly, these areas include beaches and mudflats used by people for recreation and shorebirds as feeding areas.

Chapter 9: Submerged Aquatic Vegetation (SAV; includes marine/brackish and freshwater) - Seagrasses (marine SAV) and other rooted aquatic plants grow on soft sediments in sheltered, shallow waters of estuaries, bays, and lagoons. Freshwater species are found in estuaries, rivers, and lakes and are adapted to the short- and long-term water level fluctuations typical of freshwater ecosystems. SAV along with kelp habitats can be thought of as underwater forests as they provided extensive, diverse vertical structure for animals and other plants to colonize.

Chapter 10: Marshes (marine/brackish and freshwater) - Transitional habitats between terrestrial and aquatic systems where the water table is usually at or near the surface, or the land is covered by shallow water tidally or seasonally. Freshwater species are adapted to the short- and long-term water level fluctuations typical of freshwater ecosystems. Coastal marshes are the kidneys of estuaries, filtering out sediments, nutrients, and other pollutants carried in runoff before they can impact downstream water quality.

Chapter 11: Mangrove Swamps - Swamps dominated by shrubs or trees that live between the sea and the land in areas that are inundated by tides and are of the genera *Avicennia*, *Rhizophora*, and *Laguncularia*. Mangroves thrive along protected shores with fine-grained sediments where the mean temperature during the coldest month is greater than 20º C, which limits their northern distribution. They serve many of the same functions as coastal salt marshes, which they often replace, at lower latitudes.

Chapter 12: Deepwater Swamps - Forested wetlands that develop along edges of lakes, alluvial river swamps, in slow-flowing strands, and in large coastal-wetland complexes. They can be found along the Atlantic and Gulf Coasts and throughout the Mississippi River valley. They are distinguished from other forested habitats by the tolerance of the dominant vegetation to prolonged flooding.

Chapter 13: Riverine Forests - Forests found along sluggish streams, drainage depressions, and in large alluvial floodplains. Although associated with deepwater swamps in the southeastern United States, riverine forests are found throughout the country in areas that do not have prolonged flooding. "Riparian" or "floodplain" forests are other terms that can be used to describe riverine forest habitats.

Chapter 14: Human Dimensions - Provides stakeholders engaged in restoration efforts with a basic understanding of the human dimensions issues in coastal restoration. A human dimensions approach to coastal restoration monitoring focuses on identifying and describing how people value, utilize, and benefit from the restoration of coastal habitats. Restoration projects that address diverse social values associated with coastal habitats, and that attempt to answer the questions *who cares about coastal restoration?* and *why it is important to them?*, are more likely to succeed in the long run. By incorporating human dimensions measures into their monitoring efforts, practitioners can increase public awareness of and support for restoration projects. As with Chapters 1 and 2, practitioners are encouraged to read and use the material and resources presented in Chapter 14, regardless of the particular habitat they are attempting to restore.

Chapter 15: Reference Conditions - Reviews methods available for choosing areas or conditions to which a restoration site may be compared both for the purpose of setting goals during project planning and for monitoring the development of the restored site over time. Examples of different methods that have been used in the past and lessons learned from them are provided.

Chapter 16: Cost Estimates - A listing of generalized costs associated with personnel, labor, and equipment to assist in the development of planning preliminary cost estimates of restoration monitoring activities. Some of this information will also be pertinent to estimating costs of conducting a restoration project as well.

Chapter 17: Review of Monitoring Programs - Provides a brief description of the online review of monitoring programs in the United States. The database can be accessed through the NOAA Restoration Portal (http://restoration.noaa.gov/). This database will allow interested parties to search restoration program databases by parameters and methodologies used in monitoring, contact responsible persons, and provide examples that could serve as models for establishment or improvement of their own monitoring efforts.

Chapter 18: Review of Acts - A summary of the major United States Acts that support restoration monitoring. These resources may be used in documenting support for restoration and restoration monitoring activities.

Glossary - A listing and description of many of the technical terms found throughout *Volume Two* that may not be familiar to the reader.

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CHAPTER 1: INTRODUCTION TO VOLUME TWO

INTRODUCTION

Coastal habitats provide ecological, cultural, and economic value. They act as critical habitat for thousands of species, including numerous threatened and endangered species, by providing shelter, spawning grounds, and food (Mitsch and Gosselink 2000). They often act as natural buffers, providing ecological, social, and economic benefits by filtering sediment and pollution from upland drainage thereby improving water quality, reducing the effects of floodwaters and storm surges, and preventing erosion. In addition to these ecosystem services, healthy coastal habitats provide many human values including opportunities for:

- Outdoor recreation and tourism
- Education
- Traditional use and subsistence lifestyles
- Healthy fishing communities, and
- Obtaining other marketable goods

Therefore, healthy functioning coastal habitats are not only important ecologically, they also support healthy coastal communities and, more generally, improve the quality of human lives. Despite these benefits, coastal habitats have been modified, degraded, and removed throughout the United States and its protectorates beginning with European colonization (Dahl 1990). Thus, many coastal habitats around the United States are in desperate need of restoration and subsequent monitoring of restoration projects.

WHAT IS RESTORATION MONITORING?

The science of restoration requires two basic tools: the ability to manipulate ecosystems to recreate a desired community and the ability to evaluate whether the manipulation has produced the desired change (Keddy 2000). The latter is often referred to as restoration monitoring.

For this manual, restoration monitoring is defined as follows:

> "*The systematic collection and analysis of data that provides information useful for measuring project performance at a variety of scales (locally, regionally, and nationally), determining when modification of efforts are necessary, and building long-term public support for habitat protection and restoration*."

Restoration monitoring contributes to the understanding of complex ecological systems (Meeker et al. 1996) and is essential in documenting restoration performance and adapting project and program approaches when needs arise. If results of monitoring restored coastal areas are disseminated, they can provide tools for planning management strategies and help improve future restoration practices and projects (Washington et al. 2000). Restoration monitoring can be used to determine whether project goals are being met and if mid-course corrections are necessary. It provides information on whether selected project goals are good measures for future projects and how to perform routine maintenance in restored areas (NOAA et al. 2002). Monitoring also provides the basis for a rigorous review of the pre-construction project planning and engineering.

Restoration monitoring is closely tied to and directly derived from restoration project goals. The monitoring plan (i.e., what is measured, how often, when, and where) should be developed with project goals in mind. If, for example, the goal of a restoration project is to increase the amount of fish utilizing a coastal marsh, then measurements should be selected that can quantify progress toward that goal. A variety of questions about sampling techniques and protocols need to be answered before monitoring can begin. For the fish utilization example, these may include:

- Will active or passive capture techniques be used (e.g., beach seines vs. fyke nets)?
- Where and when will samples be taken?
- Who will conduct the sampling?
- What level of identification will be required?
- What structural characteristics such as water level fluctuation or water chemistry will also be monitored and how?
- Who is responsible for housing and analyzing the data?
- How will results of the monitoring be disseminated?

Each of these questions, as well as many others, will be answered with the goals of the restoration project in mind. These questions need to be addressed before any measurements are taken in the field. In addition, although restoration monitoring is typically thought of as a 'post-restoration' activity, practitioners will find it beneficial to collect some data before and during project implementation. Pre-implementation monitoring provides baseline information to compare with post-implementation data to see if the restoration is having the desired effect. It also allows practitioners to refine sampling procedures if necessary. Monitoring during implementation helps insure that the project is being implemented as planned or if modifications need to be made.

Monitoring is an essential component of all restoration efforts. Without effective monitoring, restoration projects are exposed to several risks. For example, it may not be possible to obtain early warnings indicating that a restoration project is not on track. Without sound scientific monitoring, it is difficult to gauge how well a restoration site is functioning ecologically both before and after implementation. Monitoring is necessary to assess whether specific project goals and objectives (both ecological and human dimensions) are being met, and to determine what measures might need to be taken to better achieve those goals. In addition, the lack of monitoring may lead to poor project coordination and decreased efficiency.

Sharing of data and protocols with others working in the same area is also encouraged. If multiple projects in the same watershed or ecosystem are not designed and evaluated using a complementary set of protocols, a disjointed effort may produce a patchwork of restoration sites with varying degrees of success (Galatowitsch et al. 1998-1999) and no way to assess system-wide progress. This would result in a decreased ability to compare results or approaches among projects.

CONTEXT AND ORGANIZATION OF INFORMATION

In 2000, Congress passed the *Estuary Restoration Act (ERA), Title I of the Estuaries and Clean Waters Act of 2000*. The ERA establishes a goal of one million acres of coastal habitats (including those of the Great Lakes) to be restored by 2010. The ERA also declares that anyone seeking funds for a restoration project needs to have a monitoring plan to show how the progress of the restoration will be tracked over time. The National Oceanic and Atmospheric Administration (NOAA) was tasked with developing monitoring guidance for coastal restoration practitioners whether they be academics, private consultants, members of state, Tribal or local government, non-governmental organizations (NGOs), or private citizens, regardless of their level of expertise.

To accomplish this task, NOAA has provided guidance to the public in two volumes. The first, *Science-Based Restoration Monitoring of Coastal Habitats, Volume One: A Framework* *for Monitoring Plans Under the Estuaries and Clean Waters Act of 2000 (Public Law 160-457)* was released in 2003. It outlines the steps necessary to develop a monitoring plan for any coastal habitat restoration project. *Volume One* briefly describes each of the habitats covered and provides three matrices to help practitioners choose which habitat characteristics may be most appropriate to monitor for their project. Experienced restoration practitioners, biologists, and ecologists as well as those new to coastal habitat restoration and ecology can benefit from the step-by-step approach to designing a monitoring plan outlined in *Volume One*.

Volume Two, *Tools for Monitoring Coastal Habitats* expands upon the information in *Volume One* and is divided into two sections **Monitoring Progress Toward Goals** (Chapters 2-14) and **Context for Restoration** (Chapters 15-18). The first section, Monitoring Progress Toward Goals includes:

- Detailed information on the structural and functional characteristics of each habitat that may be of use in restoration monitoring
- Annotated bibliographies, by habitat, of restoration-related literature and technical methods manuals, and
- A chapter discussing many of the human dimensions aspects of restoration monitoring

The second section, Context for Restoration includes:

- A review of methods to select reference conditions
- A sample list of costs associated with restoration and restoration monitoring
- An overview of an online, searchable database of coastal monitoring projects from around the United States, and
- A review of federal legislation that supports restoration and restoration monitoring

The Audience

Volumes One and *Two* of *Science-Based Restoration Monitoring of Coastal Habitats* are written for those involved in developing and implementing restoration monitoring plans, both scientists and non-scientists alike. The intended audience includes restoration professionals in academia and private industry, as well as those in Federal, state, local, and Tribal governments. Volunteer groups, non-governmental organizations, environmental advocates, and individuals participating in restoration monitoring planning will also find this information valuable. Whereas *Volume One* is designed to be usable by any restoration practitioner, regardless of their level of expertise, *Volume Two* is designed more for practitioners who do not have extensive experience in coastal ecology. Seasoned veterans in coastal habitat ecology, however, may also benefit from the annotated bibliographies, literature review, and other tools provided.

The information presented in *Volume Two* is not intended as a 'how to' or methods manual: many of these are already available on a regional or habitat-specific basis. *Volume Two* does not provide detailed procedures that practitioners can directly use in the field to monitor habitat characteristics. The tremendous diversity of coastal habitats across the United States, the types and levels of impact to them, the differing scales of restoration activities, and variety of techniques used in restoration and restoration monitoring prevent the development of universal protocols. Thus, the authors have taken the approach of explaining *what one can measure during restoration monitoring, why it is important*, and *what information it provides* about the progress of the restoration effort. The authors of each chapter also believe that monitoring plans must be derived from the goals of the restoration project itself. Thus, each monitoring effort has the potential to be unique. The authors suggest, however, that restoration practitioners seek out the advice of regional experts, share data, and use similar data collection techniques with others in their area to increase the knowledge and understanding of their local and regional habitats. The online database of monitoring projects described in Chapter 17 is intended to facilitate this exchange of information.

The authors do not expect that every characteristic and parameter described herein will be measured, in fact, very few of them will be as part of any particular monitoring effort. A comprehensive discussion of all potential characteristics is, however, necessary so that practitioners may choose those that are most appropriate for their monitoring program. In addition, although the language used in *Volume Two* is geared toward restoration monitoring, the characteristics and parameters discussed could also be used in ecological monitoring and in the selection of reference conditions as well.

MONITORING PROGRESS TOWARDS GOALS

The progress of a restoration project can be monitored through the use of traditional ecological characteristics (Chapters 2 - 13) and/or emerging techniques that incorporate human dimensions (Chapter 14).

THE HABITAT CHAPTERS

Thirteen coastal habitats are discussed in twelve chapters. Each chapter follows a format that allows users to move directly to the information needed, rather than reading the whole text as one would a novel. There is, however, substantial variation in the level of detail among the chapters. The depth of information presented reflects the extent of restoration, monitoring, and general ecological literature associated with that habitat. That is, some habitats such as marshes, SAV, and oyster reefs have been the subject of extensive restoration efforts, while others such as rocky intertidal and rock bottom habitats have not. Even within habitats there can be considerable differences in the amount of information available on various structural and functional characteristics and guidance on selecting parameters to measure them. The information presented for each habitat has been derived from extensive literature reviews of restoration and ecological monitoring studies. Each habitat chapter was then reviewed by experts for content to ensure that the information provided represented the most current scientific understanding of the ecology of these systems as it relates to restoration monitoring.

Habitat characteristics are divided into two types: structural and functional. Structural habitat characteristics define the physical composition of a habitat. Examples of structural characteristics include:

- Sediment grain size
- Water source and velocity
- Depth and timing of flooding, and
- Topography and bathymetry

Structural characteristics such as these are often manipulated during restoration efforts to bring about changes in function. Functional characteristics are the ecological services a habitat provides. Examples include:

- Primary productivity
- Providing spawning, nursery, and feeding grounds
- Nutrient cycling, and
- Floodwater storage

Structural characteristics determine whether or not a particular habitat is able to exist in a given area. They will often be the first ones monitored during a restoration project. Once the proper set of structural characteristics is in place and the biological components of the habitat begin to become established, functional characteristics may be added to the monitoring program. Although structural characteristics have historically been more commonly monitored during restoration efforts, measurements of functional characteristics provide a better estimate of whether or not a restored area is truly performing the economic and ecological services desired. Therefore, incorporating measurements of functional characteristics in restoration monitoring plans is strongly encouraged.

When developing a restoration monitoring plan, practitioners should follow the twelve-step process presented in *Volume One* and refer to the appropriate chapters in *Volume Two* (habitat and human dimensions) to assist them in selecting characteristics to monitor. The information presented in the habitat chapters is derived from and expands upon the *Volume One* matrices (*Volume One* Appendix II).

Organization of Information

Each of the habitat chapters is structured as follows:

1. Introduction
   a. Habitat description and distribution
   b. General ecology
   c. Human impacts to the habitat
2. Structural and functional characteristics
   a. Each structural and functional characteristic identified for the habitat in the *Volume One* matrices is explained in detail. Structural and functional characteristics have generally been discussed in separate sections of each chapter. Occasionally, some functions are so intertwined with structural characteristics that the two are discussed together.
   b. Whenever possible, potential methods to measure, sample, and/or monitor each characteristic are introduced or readers are directed to more thorough sources of information. In some cases, not enough information was found while reviewing the literature to make specific recommendations. In these cases, readers are encouraged to use the primary literature cited within the text for methods and additional information.
3. Matrices of the structural and functional characteristics and parameters suggested for use in restoration monitoring
   a. These two matrices are habitat-specific distillations of the *Volume One* matrices
   b. Habitat characteristics are cross-walked with parameters appropriate for monitoring change in that characteristic. Parameters include both those that are direct measures of a particular characteristic as well as those that are indirectly related and may influence a particular characteristic or related parameter. Tables 1 and 2 can be used to illustrate an example. The parameter of salinity in submerged aquatic vegetation is a direct measure of a structural characteristic (salinity, Table 1). In addition, salinity is related to other structural characteristics such as tides and water source. Salinity is also related to functional characteristics such as biodiversity and nutrient cycling and may be appropriate to include in the monitoring of these functions as well (Table 2). Experienced practitioners will note that many characteristics and parameters may be related to one another but are not shown as such in a particular matrix. The matrices are not intended to be all inclusive of each and every possible interaction. The matrices provided and the linkages illustrated are only intended as starting points in the process of developing lists of parameters that may be useful in measuring particular characteristics and understanding some of their interrelationships.
   c. Some parameters and characteristics are noted as being highly recommended for any and all monitoring efforts as they represent critical components of the habitat while others may or may not be appropriate for use depending on the goals of the individual restoration project.
4. Acknowledgement of reviewers
5. Literature Cited

Three appendices are also provided for each habitat chapter. In the online form of *Volume Two,* these appendices download with the rest of the habitat chapter text. In the printed versions of *Volume Two*, each chapter's appendices are provided on a searchable CD-ROM located inside the back cover. Each appendix is organized as follows:

Appendix I - An Annotated Bibliography
a. Overview of case studies of restoration monitoring and general ecological studies pertinent to restoration monitoring
b. Entries are alphabetized by author

Parameters to Monitor the Structural Characteristics of SAV (excerpt)

Parameters to Monitor	Biological	Habitat created by plants	Physical	Sediment grain size[1]	Topography / Bathymetry	Turbidity	Hydrological	Tides / Hydroperiod	Water sources	Current velocity	Wave energy	Chemical	Nutrient concentration	pH, salinity, toxics, redox, DO[2]
Chemical														
Salinity (in tidal areas)								●	●					●

Table 1. Salinity is a parameter that can be used to directly measure a structural component of submerged aquatic vegetation habitats (Chemical/salinity). It is shown with a closed circle indicating that it highly recommended as part of any restoration monitoring program, regardless of project goals. A circle for salinity is also shown under the **Tides/Hydroperiod** and **Water source** columns as salinity levels are related to these structural characteristics as well. (Entire table can be found on page 9.39.)

Parameters to Monitor the Functional Characteristics of SAV (excerpt)

Parameters to Monitor	Biological	Contributes primary production	Supports biomass production	Provides breeding grounds	Provides nursery areas	Provides feeding grounds	Provides refuge from predation	Supports high biodiversity	Supports a complex trophic structure	Provides substrate for attachment	Chemical	Supports nutrient cycling	Modifies chemical water quality	Modifies dissolved oxygen
Chemical														
Salinity (in tidal areas)								○				○		

Table 2. Salinity is related to the functions of **Supporting high biodiversity** and **Supporting nutrient cycling**. It is shown here with an open circle, denoting that it may be useful to monitor if monitoring of these functions is important to the goals of the restoration project. (Entire table can be found on page 9.40.)

[1] Including organic matter content.
[2] Dissolved oxygen.

Appendix II - Review of Technical and Methods Manuals

These include reviews of:

a. Restoration manuals
b. Volunteer monitoring protocols
c. Lab methods
d. Identification keys, and
e. Sampling methods manuals

Whenever possible, web addresses where these resources can be found free of charge are provided.

Appendix III - Contact information for experts who have agreed to be contacted with questions from practitioners

As extensive as these resources are, it is inevitable that some examples, articles, reports, and methods manuals have been omitted. Therefore, these chapters should not be used in isolation. Instead, they should be used as a supplement to and extension of:

- The material presented in *Volume One*
- Resources provided in the appendices
- The advice of regional habitat experts, and
- Research on the local habitat to be restored

WHAT ARE THE HABITATS?

The number and type of habitats available in any given estuary is a product of a complex mixture of the local physical and hydrological characteristics of the water body and the organisms living there. The ERA Estuary Habitat Restoration Strategy (Federal Register 2002) dictates that the Cowardin et al. (1979) classification system should be followed in organizing this restoration monitoring information. The Cowardin system is a national standard for wetland mapping, monitoring, and data reporting, and contains 64 different categories of estuarine and tidally influenced habitats. Definitions, terminology, and the list of habitat types continue to increase in number as the system is modified. Discussion of such a large number of habitat types would be unwieldy. The habitat types presented in this document, therefore, needed to be smaller in number, broad in scope, and flexible in definition. The 13 habitats described in this document are, however, generally based on that of Cowardin et al. (1979).

Restoration practitioners should consider local conditions within their project area to select which general habitat types are present and which monitoring measures might apply. In many cases, a project area will contain more than one habitat type. To appropriately determine the habitats within a project area, the practitioner should gather surveys and aerial photographs of the project area. From this information, he or she will be able to break down the project area into a number of smaller areas that share basic structural characteristics. The practitioner should then determine the habitat type for each of these smaller areas. For example, a practitioner working in a riparian area may find a project area contains a *water column, riverine forest, rocky shoreline*, and *rock bottom*. Similarly, someone working to restore an area associated with a tidal creek or stream may find the project area contains *water column, marshes, soft shoreline, soft bottom*, and *oyster beds*. Virtually all estuary restoration projects will incorporate characteristics of the water column. Therefore, all practitioners should read *Chapter 2: Restoration Monitoring of the Water Column* in addition to any additional chapters necessary.

Habitat Decision Tree

A Habitat Decision Tree has been developed to assist in the easy differentiation among the habitats included in this manual. The decision tree allows readers to overcome the restraints of varying habitat related terminology in deciding which habitat definitions best describe those in their project area. Brief definitions of each habitat are provided at the end of the key.

1. a. Habitat consists of open water and does not include substrate (**Water Column**)
   b. Habitat includes substrate (go to 2)
2. a. Habitat is continually submerged under most conditions (go to 3)
   b. Habitat substrate is exposed to air as a regular part of its hydroperiod (go to 8)
3. a. Habitat is largely unvegetated (go to 4)
   b. Habitat is dominated by vegetation (go to 7)
4. a. Substrate is composed primarily of soft materials, such as mud, silt, sand, or clay (**Soft Bottom**)
   b. Substrate is composed primarily of hard materials, either of biological or geological origin (go to 5)
5. a. Substrate is composed of geologic material, such as boulders, bedrock outcrops, gravel, or cobble (**Rock Bottom**)
   b. Substrate is biological in origin (go to 6)
6. a. Substrate was built primarily by oysters, such as *Crassostrea virginica* (**Oyster Reefs**)
   b. Substrate was built primarily by corals (**Coral Reefs**)
7. a. Habitat is dominated by macroalgae (**Kelp and Other Macroalgae**)
   b. Habitat is dominated by rooted vascular plants (**Submerged Aquatic Vegetation - SAV**)
8. a. Habitat is not predominantly vegetated (go to 9)
   b. Habitat is dominated by vegetation (go to 10)
9. a. Substrate is hard, made up materials such as bedrock outcrops, boulders, and cobble (**Rocky Shoreline**)
   b. Substrate is soft, made up of materials such as sand or mud (**Soft Shoreline**)
10. a. Habitat is dominated by herbaceous, emergent, vascular plants. The water table is at or near the soil surface or the area is shallowly flooded (**Marshes**)
    b. Habitat is dominated by woody plants (go to 11)
11. a. The dominant woody plants present are mangroves, including the genera *Avicennia*, *Rhizophora*, and *Laguncularia* (**Mangrove Swamps**)
    b. The dominant woody plants are other than mangroves (go to 12)
12. a. Forested habitat experiencing prolonged flooding, such as in areas along lakes, rivers, and in large coastal wetland complexes. Typical dominant vegetation includes bald cypress (*Taxodium distichum*), black gum (*Nyssa sylvatica*), and water tupelo (*Nyssa aquatica*). (**Deepwater Swamps**)
    b. Forested habitat along streams and in floodplains that do not experience prolonged flooding (**Riverine Forests**)

Water column - A conceptual volume of water extending from the water surface down to, but not including the substrate. It is found in marine, estuarine, river, and lacustrine systems.

Rock bottom - Includes all wetlands and deepwater habitats with substrates having an aerial cover of stones, boulders, or bedrock 75% or greater and vegetative cover of less than 30% (Cowardin et al. 1979). Water regimes are restricted to subtidal, permanently flooded, intermittently exposed, and semi-permanently flooded. The rock bottom habitats addressed in *Volume Two* include bedrock and rubble.

Coral reefs - Highly diverse ecosystems, found in warm, clear, shallow waters of tropical oceans worldwide. They are composed of marine polyps that secrete a hard calcium carbonate skeleton, which serves as a base or substrate for the colony.

Oyster reefs - Dense, highly structured communities of individual oysters growing on the shells of dead oysters.

Soft bottom - Loose, unconsolidated substrate characterized by fine to coarse-grained sediment.

Kelp and other macroalgae - Relatively shallow (less than 50 m deep) subtidal and intertidal algal communities dominated by very large brown algae. Kelp and other macroalgae grow on hard or consolidated substrates forming extensive three-dimensional structures that support numerous plant and animal communities.

Rocky shoreline - Extensive littoral habitats on high-energy coasts (i.e., subject to erosion from waves) characterized by bedrock, stones, or boulders with a cover of 75% or more and less than 30% cover of vegetation. The substrate is, however, stable enough to permit the attachment and growth of sessile or sedentary invertebrates and attached algae or lichens.

Soft shoreline - Unconsolidated shore includes all habitats having three characteristics: (1) unconsolidated substrates with less than 75% aerial cover of stones, boulders, or bedrock; (2) less than 30% aerial cover of vegetation other than pioneering plants; and (3) any of the following water regimes: irregularly exposed, regularly flooded, irregularly flooded, seasonally flooded, temporarily flooded, intermittently flooded, saturated, or artificially flooded (Cowardin et al. 1979). This definition includes cobble-gravel, sand, and mud. However, for the purpose of this document, cobble-gravel is not addressed.

Submerged aquatic vegetation (SAV; includes marine, brackish, and freshwater) - Seagrasses and other rooted aquatic plants growing on soft sediments in sheltered shallow waters of estuaries, bays, lagoons, rivers, and lakes. Freshwater species are adapted to the short- and long-term water level fluctuations typical of freshwater ecosystems.

Marshes (marine, brackish, and freshwater) - Transitional habitats between terrestrial and aquatic systems where the water table is usually at or near the surface, or the land is covered by shallow water tidally or seasonally. Freshwater species are adapted to the short- and long-term water level fluctuations typical of freshwater ecosystems.

Mangrove swamps - Swamps dominated by shrubs (*Avicenna, Rhizophora*, and *Laguncularia*) that live between the sea and the land in areas that are inundated by tides. Mangroves thrive along protected shores with fine-grained sediments where the mean temperature during the coldest month is greater than 20º C; this limits their northern distribution.

Deepwater swamps - Forested wetlands that develop along edges of lakes, alluvial river swamps, in slow-flowing strands, and in large coastal-wetland complexes. They can be found along the Atlantic and Gulf Coasts and throughout the Mississippi River valley.

They are distinguished from other forested habitats by the tolerance of the dominant vegetation to prolonged flooding.

Riverine forests - Forests found along sluggish streams, drainage depressions, and in large alluvial floodplains. Although associated with deepwater swamps in the southeastern United States, riverine forests are found throughout the United States in areas that do not have prolonged flooding.

THE HUMAN DIMENSIONS CHAPTER

The discussion of human dimensions helps restoration practitioners better understand how to select measurable objectives that allow for the appropriate assessment of the benefits of coastal restoration projects to human communities and economies. Traditionally, consideration of human dimensions issues has not been included as a standard component of most coastal restoration projects. Most restoration programs do not currently integrate social or economic factors into restoration monitoring, and few restoration projects have implemented full-scale human dimensions monitoring. Although some restoration plans are developed in an institutional setting that require more deliberate consideration of human dimensions impacts and goals, this does not generally extend to the monitoring stage. It is becoming increasingly evident, however, that decisions regarding restoration cannot be made solely by using ecological parameters alone but should also involve considerations of impacts on and benefits to human populations, as well. Local communities have a vested interest in coastal restoration and are directly impacted by the outcome of restoration projects in terms of aesthetics, economics, or culture. Human dimensions goals and objectives whether currently available or yet to be developed should reflect societal uses and values of the resource to be restored. Establishing these types of parameters will increase the public's understanding of the potential benefits of a restoration project and will increase public support for restoration activities.

While ecologists work to monitor the restoration of biological, physical, and chemical functional characteristics of coastal ecosystems, human dimensions professionals identify and describe how people value, utilize, and benefit from the restoration of coastal habitats. The monitoring and observation of coastal resource stakeholders allows us to determine who cares about coastal restoration, why coastal restoration is important to them, and how coastal restoration changes people's lives. The human dimensions chapter will help restoration practitioners identify:

1) Human dimensions goals and objectives of a project
2) Measurable parameters that can be monitored to determine if those goals are being met, and
3) Social science research methods, techniques, and data sources available for monitoring these parameters

This chapter includes a discussion of the diverse and dynamic social values that people place on natural resources, and the role these values play in natural resource policy and management. Additionally, some of the general factors to consider in the selection and monitoring of human dimensions goals/objectives of coastal restoration are presented, followed by a discussion of some specific human dimensions goals, objectives, and measurable parameters that may be included in a coastal restoration project. An annotated bibliography of key references and a matrix of human dimensions goals and measurable parameters are provided as appendices at the end of this chapter. Also included, as an appendix, is a list of human dimensions research experts (and their areas of expertise) that you may contact for additional information or advice.

The final four chapters of this manual are designed to provide readers with additional information that should enhance their ability to develop and carry out strong restoration monitoring plans. Chapter 15 reviews methods available for choosing areas or conditions to which a restoration site may be compared both for the purpose of setting goals during project planning and for monitoring the development of the restored site over time. Chapter 16 is a listing of generalized costs of personnel, labor, and equipment to assist in the development of planning preliminary cost estimates of restoration monitoring activities. Some of this information will also be pertinent to estimating costs of implementing a restoration project as well. Chapter 17 provides a brief description of the online review of monitoring programs in the United States. The database can be accessed though the NOAA Restoration Portal (http://restoration.noaa.gov/). This database will allow interested parties to search by parameters and methodologies used in monitoring, find and contact responsible persons, and provide examples that could serve as models for establishment or improvement of their own monitoring efforts. Chapter 18 is a summary of the major United States Acts that support restoration monitoring. This information will provide material important in the development of a monitoring plan. A Glossary of many scientific terms is also provided at the end of the document.

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CHAPTER 2: RESTORATION MONITORING OF THE WATER COLUMN

David Merkey, NOAA Great Lakes Environmental Research Laboratory[1]

INTRODUCTION

The water column, defined as a volume of water that extends from the water surface down to (but not including) the substrate, is a very dynamic habitat subject to waves, currents, tides, and river flow. It is also the only habitat in this guidance document that is associated with all the other habitat types described in the rest of Volume Two. The water column is responsible for transporting materials, nutrients, sediments, and toxins from upland sources into estuarine environments and from one aquatic habitat to another. As such, the water column has direct effects on all other associated habitats (e.g. SAV, coral reefs, riverine forests etc.), and, therefore, must be taken into consideration for any restoration monitoring program.

The hydrodynamics[2] and chemistry within water column habitats are tremendously diverse across different marine, tidally-influenced riverine, and freshwater lacustrine systems. In marine environments, hydrologic patterns are determined by the ebb and flow of ocean tides, the movement of nearshore currents, and freshwater inputs from upland sources. Salinity in estuarine water column habitats in coastal marine areas ranges from seawater (approximately 35 ppt[3]) to fresh water (approximately 0.5 ppt or less). Water level fluctuations in these systems are controlled by both ocean tides and wind events, the relative importance of each varies with location. The hydrodynamics of riverine water columns are dominated by freshwater flows from upland sources. In tidally influenced areas, the surface of the river rises and falls with the tide, allowing for the development of tidal freshwater marshes. In coastal waters of the Great Lakes, hydrodynamics are dominated by seasonal and annual water level fluctuations of the lakes and shorter-term (daily) fluctuations caused by seiches. Seiches (Figure 1) are oscillations of the water's surface and occur in enclosed or semi-enclosed basins. They can be caused by local changes in atmospheric pressure, wind, tidal currents, and earthquakes. Seiches may last from a few minutes to several hours and range in size from a few centimeters to several feet depending on the severity and duration of storms or wind creating them. Seiches are not unique to the Great Lakes and can happen in any body of water with a long enough fetch[4].

In all open water areas (from marine to freshwater) food webs are supported largely by phytoplankton with additional inputs of detritus carried in from upland sources (Day et al. 1989). The relative importance of each food source depends on several factors including: time of year, freshwater inputs, nutrient concentrations, salinity, and oxygen concentration. The presence, absence, and composition of plants and animals in the water column is a result of physical factors related to basin morphology, water quality and chemistry (primarily salinity in marine settings), and to the mixing of communities from adjacent areas.

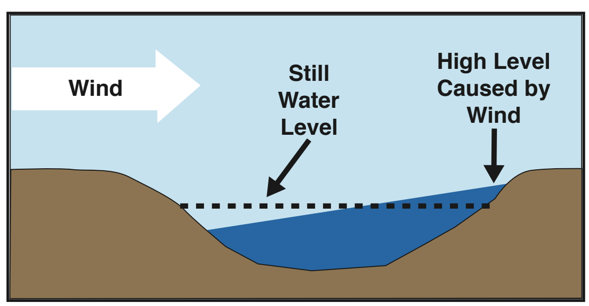

Figure 1. Once the wind driving the seiche stops, the water that has piled up on the right will slosh back toward the left. The effect is similar to water sloshing back and forth in a large bathtub. Graphic by David Merkey, NOAA Great Lakes Enviornmental Research Laboratory (GLERL).

[1] 2205 Commonwealth Boulevard, Ann Arbor, MI 48105.
[2] Water level fluctuations and water movement.
[3] Parts per thousand.
[4] The distance wind can travel over open water. Longer fetches allow for the development of larger waves and seiches.

HUMAN IMPACTS TO THE WATER COLUMN HABITAT

Impacts to estuarine and near shore water quality include but are not limited to: pollutant loading from urban and agricultural runoff, waste discharge, dam construction, dredging, withdraw of water for agriculture and human consumption, logging, and urban development in coastal areas (NOAA 1993). The effects of these impacts varies from one estuary to another but often include increases in nutrient concentrations and associated eutrophication, loss of native plant and animal habitat and diversity, and decreases in commercial and recreational finfish and shellfish stocks (NOAA 1993; Bricker et al. 1999).

This chapter is meant to cover all of the open water coastal habitats of the United States and its protectorates. However, considering the diversity of plants and animals that utilize open water in many different habitat types, we can only provide very general descriptions of water column habitat and associated impacts. Restoration practitioners are strongly encouraged to seek out local and regional experts (Appendix III of this chapter) for assistance in identifying plant and animal species and understanding the complex interrelationships of water chemistry, biology, and physical processes within a particular restoration area. Analysis of restoration monitoring parameters such as salinity, oxygen, and nutrient concentrations requires a "big picture" understanding of systems and processes outside the scope and control of most local restoration efforts. Accurate interpretation of monitoring data is not possible without an understanding of the larger processes at work within an estuary. This is not meant to discourage monitoring water column habitats in estuaries but rather to inform practitioners of the potential complexity involved with such monitoring efforts.

Pollutant Load[5]

There are two sources of pollution that need to be accounted for when calculating pollutant load:

- Point sources, and
- Non-point sources

Point source

Point source pollution is that which is directly discharged from an identifiable pipe or location (Figure 2). While many of these sources have been controlled since the Clean Water Act was passed, some point sources still remain. Sewage treatment plants that are forced to discharge partially treated wastewater into rivers during storm events are one example. Sewage overflows release bacteria and nutrients into rivers and streams that ultimately flow into estuaries. Excess amounts of fecal bacteria and other waste-born pathogens can trigger beach closures and affect human health. Discharged organic matter can lower the dissolved oxygen content of the water column as it is broken down. Certain industrial operations are still permitted to discharge their wastewater into streams and

Figure 2. Point source pollution, such as discharges from this agricultural operation, is one of the major impacts to surface water quality. Photo from the NOAA Photo Library.

[5] The EPA's "Nutrient criteria technical guidance manual: estuarine and coastal marine waters" of 2001 has been extensively used in the writing of this section. It is cited here instead of repeatedly through text. U.S. EPA. 2001a. Nutrient criteria technical guidance manual: estuarine and coastal marine waters. United States Environmental Protection Agency, Office of Water. http://www.epa.gov/waterscience/standards/nutrients/marine/index.html

rivers. This often results in increased turbidity, altered water chemistry, and potential increases in toxic contaminants entering connected estuaries.

Non-point source

One of the largest threats to water quality currently comes from non-point sources such as farms, urban storm water systems, industrial sites, lawns, and golf courses (Figure 3). Non-point source pollution can originate from a variety of activities and take on many forms. Runoff from agricultural land can carry sediments, nutrients, and pollutants such as herbicides and pesticides into streams that eventually flow into estuaries. Logging operations can cause increases in turbidity and water temperature. Runoff from construction sites can also lead to increases in turbidity, water temperature, and toxics, and lead to decreases in dissolved oxygen. Urban runoff can be particularly harmful, causing increases in turbidity, nutrient concentration, water temperature, heavy metals, bacteria, as well as gasoline, oil and other auto-related fluids from parking lot runoff.

Four resources (listed below) have been heavily drawn upon in preparation of this document. In sections where one of these resources has been used extensively, a citation referring the reader to the pertinent reference will appear in the section heading instead of being repeated throughout the text.

American Public Health Association (APHA). 1999. Standard Methods for the Examination of Water and Wastewater, 20th ed. American Public Health Association, Washington, D.C.

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Figure 3. Non-point source runoff from an industrial site in Green Bay, Wisconsin. Photo courtesy of Michigan Sea Grant. http://www.epa.gov/glnpo/image/viz_iss2.html

STRUCTURAL CHARACTERISTICS OF THE WATER COLUMN

As discussed above, monitoring of the water column can be extremely complex. This is due to the interrelationships among the many variables that could be measured. While it is straightforward enough to obtain a water sample for nutrient analysis, if one has not taken into consideration the tidal period, circulation of water through the estuary, loading from upland sources, recent weather patterns, and spatial and temporal changes in characteristics, then the data obtained from a single sample will not provide useful information. The structural characteristics of the water column have been broken into three categories:

Physical
- Turbidity
- Temperature

Hydrological
- Tides/hydroperiod
- Water source
- Gravitational circulation, and
- Wind and wave energy

Chemical
- Nutrient concentration, and
- pH, salinity, redox, and DO

Each of these characteristics is described below. Some of these characteristics, such as nutrient concentration, may be measured directly as part of a restoration monitoring plan. Others such as upland water sources may be outside of the control of restoration efforts but have direct or indirect effects on functional and other structural characteristics suggested for monitoring and therefore need to be considered as well.

PHYSICAL

Turbidity

Turbidity is a measure of how clear the water is. The type and amount of material suspended in the water decreases the depth to which light can penetrate. It also influences the color of light reaching different depths. The color and depth of light penetration determine what species of vascular plants and algae can live there. Suspended materials commonly include: sediment (fine sand, silt, and clay), and zooplankton and phytoplankton. The amount and size of particles depends on how much energy a particular body of water has. Some areas prone to strong tides, large river flows, frequent or strong storms or wave action have more energy and are able to keep more particles in suspension. Areas protected from wave action, with low river flow, and weaker tides and storms tend to have lower amounts of material suspended in the water column. Runoff from agriculture, urban areas, construction sites, and logging operations are all common causes of increased turbidity (Figure 4). Turbidity is often worst shortly after a storm event that washes accumulated dust, dirt, and other material into streams and storm sewers, causes overflows of waste treatment facilities, and increased erosion of stream banks. Estuaries typically have greater amounts of suspended sediment than do other

Figure 4. Turbidity is often worst shortly after storm events that wash accumulated dust, dirt, and other material into streams and storm sewer. Photo from the NOAA Photo Library.

coastal systems. Suspended sediments and other particles are carried in river water and may be re-suspended through tidal currents and wave action. Other coastal features in comparison may have relatively low concentrations of suspended materials and have clearer water due to lower amounts of materials being delivered to and resuspended in them.

Turbidity can also be used as an inexpensive surrogate measure for nutrient concentrations. Krieger (1984, cited in Heath 1992) found that turbidity correlated well with nutrient concentrations entering estuaries with storm water runoff. Nutrients such as ammonia and phosphorus were carried into estuaries on sediments eroded during storm events. Potassium and ammonia were also dissolved in runoff from agricultural fields. Nitrite showed a delayed reaction to storm water loading, implying that it first needed to be mobilized out of the soil and entered the stream as interflow (shallow groundwater inputs to a stream following storm events (Baker 1984, cited in Heath 1992). Other ions such as calcium and magnesium were negatively correlated with turbidity, meaning that they entered the estuary at a constant rate and were diluted by rainwater.

Sampling

The amount of light available for photosynthesis can be directly measured as PAR (photosynthetically available radiation) or indirectly by measuring turbidity[6]. PAR is the portion of visible light between 400 and 700 nm[7] (Kirk 1994). It can be measured using a device called a quantum sensor at the water surface and throughout the water column to determine how much light has been absorbed by the water column. Quantum sensors can be connected to a dataloggers[8] and left in place allowing for the continuous measurement of PAR over time and include random events such as storms or large river flows. These events can temporarily increase turbidity and might be missed with less-frequent, manual sampling.

PAR at various depths can also be measured indirectly using the following equation from Carr et al. (1997):

$$\text{PAR} = I_o * e^{(-kz)}$$

Where I_o equals PAR at the surface, k is the light extinction coefficient of the water and dissolved material, and z is the depth. If PAR is to be inferred in this manner, depth (z) can be estimated by using the mean water level or if more precise measurements are required, continuous monitoring of water level fluctuation in tidal and Great Lakes areas subject to seiches may be needed. These hydrodynamic processes change a key input to the equation (z) and may also affect k by changing the amount and type of dissolved material in the water.

A simpler, less expensive (although not as precise) way to gauge light availability is to measure turbidity using a secchi disc (Figure 5). A secchi disc is a weighted black and white circle, typically made of plastic that can be

Figure 5. A secchi disc can be lowered from the shady side of a boat or dock as a measure of turbidity. Photo courtesy of Aaron Podey, Louisiana State University.

[6] The following information is also presented in Chapter 9: Restoration Monitoring for Submerged Aquatic Vegetation (SAV).
[7] Nanometers, there are 1 million nm in a millimeter.
[8] An electronic device that continually records data over time.

lowered from the shady side of a boat or dock to avoid glare off the water's surface. As light travels through the water column, some of it is absorbed or scattered by phytoplankton and other suspended or dissolved material. The left over light reflects off the secchi disc and travels back through the water column where more is absorbed. The light that remains is what we see as the disc[9]. As the disc is put lower and lower in the water, it gets harder and harder to see as more and more of the light is absorbed. The depth at which the disc disappears from sight, is the depth at which all the light is being absorbed as it passes down and back up through the water column. This is recorded as the secchi disc depth. The frequency of using a secchi disk to sample turbidity should account for tidal regime and hydroperiod and include post-storm measurements whenever possible as these will affect water depth and the amount of suspended and dissolved material carried in the water column. Samples should be taken at a variety of locations in the estuary or water body and at least weekly or biweekly throughout the year for several years to more accurately account for natural variability in the system.

Temperature[10]

Temperature has direct impacts on several variables important to plants and animals and is one of the easiest water characteristics to measure. Every living organism has a range of temperatures to which it is adapted. Water temperatures outside of those ranges can stress organisms and make them more susceptible to parasites and diseases. At higher water temperatures the rate of photosynthesis increases producing more food and oxygen. However, respiration rates are also greater in warmer water resulting in higher consumption of food and oxygen resources. In addition, less oxygen is able to dissolve in warmer water. Low oxygen levels and warm temperatures can harm aquatic plants and animals.

Sampling

The temperature of water in an estuary is a function of water depth, season, amount of mixing from wind and storms, the degree of stratification in the water column, the temperature of water flowing into the estuary, and human influences such as urban runoff from warm parking lots or thermal discharges from factories and power plants. Therefore, water temperatures should be taken at a variety of locations throughout a restoration site, throughout the year, and at different depths in the water column. Since so many factors influence water temperature and water temperature has such a direct impact on the plants and animals of a system, it is recommended that this characteristic be measured at frequent intervals. The availability of inexpensive automated data loggers makes this possible. Data loggers can be set up to record temperatures at any desired interval and store data until it can be retrieved.

HYDROLOGICAL

The hydrologic conditions of open water habitats are produced by the circulation and mixing of freshwater from upland sources with marine or Great Lakes water. Circulation and mixing are affected by the relative amounts and chemical content of upland and receiving waters, the geomorphology of the estuary, water temperature, and wave and tidal action. These factors control much of the variability observed in most restoration monitoring parameters such as nutrient concentrations, dissolved oxygen content, phytoplankton and zooplankton concentrations, turbidity, and fish community dynamics (Day et al. 1989). Three main forces work to circulate and mix freshwater throughout an estuary: tides, water sources (and associated gravitational circulation caused by differences in water densities), and wind and wave energy (Day et al. 1989). Water sources and gravitational circulation will not be

[9] Sunglasses should NOT be worn while taking a secchi disc measurement.

[10] Section developed using material from EPA, U.S. 2001b. Volunteer Estuary Monitoring: a Methods Manual. United States Environmental Protection Agency, Office of Water. http://www.epa.gov/owow/estuaries/monitor/

characteristics that are commonly measured as part of a restoration monitoring program. They are, however, important ecological phenomena that need to be understood when interpreting other hydrologic data.

Tides and Hydroperiod

Understanding the tidal regime or hydroperiod of a particular estuary is important for planning the timing of sampling (i.e., will the sampling location be an exposed mudflat or under several feet of water), and has important implications for the circulation, stratification, and mixing of freshwater and saltwater. In shallow estuaries with a large tidal range (>2 m), tidal circulation can be particularly strong and interact with the geomorphic[11] shape of the estuary to disperse freshwater throughout the estuary (Day et al. 1989). As tides slosh back and forth the two waters get mixed together. In areas of low energy, lack of mixing can lead to vertical stratification of the water column that may require monitoring samples to be taken at several depths, especially for measurements of dissolved oxygen, nutrient concentration, plankton, and salinity (U.S. EPA 2001b) (see Figure 2).

Tidal circulation and mixing are not uniform over time. Neap tides[12] have smaller tidal ranges and less energy and thus produce less mixing. Water columns during neap tides tend to be more stratified than during spring tides that have larger tidal ranges and more energy for mixing (Day et al. 1989). Lunar tides characteristic of marine estuaries are insignificant on the Great Lakes (Day et al. 1989; Schwab and Bedford 1995) with a maximum range of only 3.3 cm (Herdendorf 1990). Seiches, however, can be quite large (e.g., 5.5 m, Herdendorf 1990) and provide many of the same circulation and mixing functions on Great Lakes coastal habitats as lunar tides do in marine areas. Wind/storm driven seiches do not exhibit the same level of predictability as lunar tides. Seasonal seiches also occur in the Gulf of Mexico and are a regular part of the annual water level fluctuations of coastal estuaries there (Gosselink 1984).

Sampling

Tide tables for most of the United States and its protectorates are available from the National Oceanic and Atmospheric Administration (NOAA) at http://tidesonline.nos.noaa.gov/. If the restoration site is reasonably close to the tidal table site, monitoring of the tidal period as part of the restoration monitoring may not be required (U.S. EPA 2001b). The United States Geological Survey also operates a series of gauging stations on rivers throughout the country. Historical and real-time data on hydroperiod and characteristics of the watershed are available for many areas at http://water.usgs.gov/waterwatch/. Smaller coastal rivers may not have a gauging station, however, requiring that restoration practitioners implement other methods to collect this information. A variety of manual gauges are commercially available in different lengths and measurement intervals. These can be attached to metal poles driven into the substrate. Electronic gauges are also available that can be set up and left in place to continually record water level fluctuation. Thus recording data that might otherwise be missed by manual sampling alone.

Water Sources

Inflow from upland sources (i.e., river discharge) is the quantity of freshwater available to dilute seawater. Freshwater discharge influences the relative location of freshwater, brackish and marine habitats within an estuary (Day et al. 1989). The amount of inflow from upland sources affects the chemistry and biology of the water column and is therefore an important component to monitor. When river discharge is high, (e.g. in the spring), more freshwater is delivered to the estuary and freshwater habitats may extend out toward the ocean. During droughts or other seasons with normally low

[11]The form or shape of features on the earth's surface.
[12]A tide of minimum range occurring at the first and the third quarters of the moon.

precipitation, riverine discharge is low and freshwater habitats may be pushed inland by the relatively greater amounts of seawater in the estuary (Day et al. 1989; Mitsch and Gosselink 2000).

Gravitational Circulation

Gravitational circulation is another factor that influences the structure of the water column. Gravitational circulation results from differences in the density of river water and that of the receiving body. Density differences can be caused by difference in salinity or temperature. In marine habitats, gravitational circulation is controlled primarily by the density difference between riverine freshwater and marine salt water, though there are usually differences in temperature as well. In estuaries of the Great Lakes, where riverine freshwater mixes with freshwater of the lakes, seasonal temperature differences are responsible for gravitational circulation.

Freshwater is less dense than salt water and floats on the top of the water column when rivers discharge into marine estuaries and freshwater spreads out over the estuary. This often results in a highly stratified water column (Figure 6). Wind, waves, and tides reduce stratification by mixing the freshwater with the saltwater. The amount of wind and wave action, strength of the tide, and quantity of freshwater discharged combined determine whether or not the estuarine water column remains highly stratified, becomes moderately stratified, or is vertically well mixed. Stratification and degree of mixing are critical to almost all other characteristics that can be measured in the water column including dissolved oxygen, nutrient concentrations, and diversity and abundance of plankton and fish communities. Stratification of the water column requires that sampling be conducted frequently and at a variety of depths.

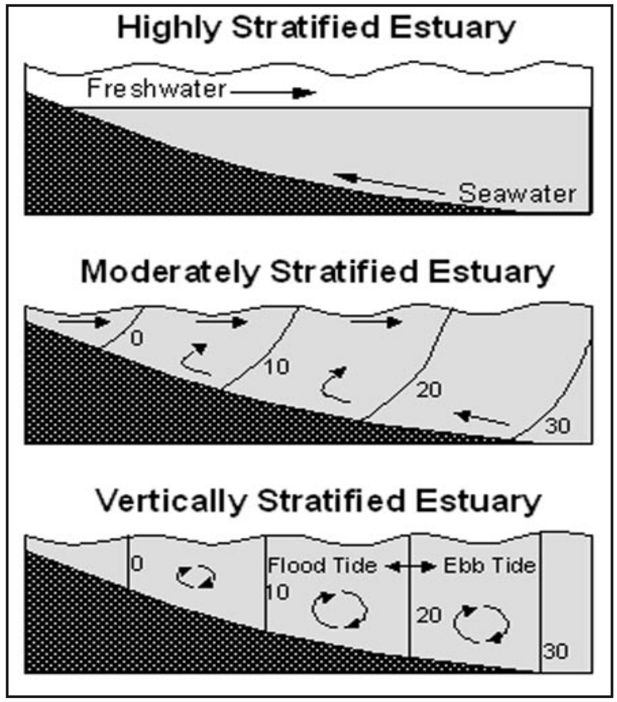

Figure 6. Density gradients caused by differences in salinity. Numbers refer to salinity in parts per thousand. Modified from U.S. EPA 2001b.

Gravitational circulation in freshwater systems of the Great Lakes is caused by seasonal temperature differences between river and lake water. This makes gravitational circulation in freshwater estuaries more complex and ephemeral than in marine estuaries. Although not a lot of research has been conducted on temperature gradients across seasons, in theory, they should works as follows (Bedford 1992). Runoff from upland sources responds to changes in air temperature faster than deeper lake water, making it colder in winter and warmer in summer relative to lake water. In the early spring, when the surface of the lakes is still frozen, water from upland sources is slightly warmer and denser[13] and slips under lake water. As rivers continue to warm faster than lakes in the spring they eventually reach temperatures above 4 degrees. At this point river water is less dense than lake water and is stratified on top of the lake water. As heating of the two water

[13]Freshwater reaches maximum density at 4° C, water between 0 and 4° C is less dense and rises to the surface of the water column.

bodies reaches equilibrium in the summer, this effect is minimized. In the fall, the reverse happens. River water is cooled faster than lake water and reaches maximum density sooner. Again riverine flow slips under lake water. As the lake continues to cool to 4 degrees C, river water is by then colder and floats on top. These effects have been measured, but are completely dependent on climate and, as such, vary from place to place and year to year (Bedford 1992).

Gravitational circulation based on salinity gradients does not exhibit seasonal variability and is of greater importance in understanding the chemistry and biology of marine estuary water columns. Large freshwater inputs during storm events may also deliver large quantities of nutrients to estuaries that may lead to algal blooms and eutrophic conditions. If density gradients are strong, hypoxic[14] conditions at lower depths may occur. This can happen even in estuaries without significant human inputs of nutrients (Day et al. 1989).

Wind and Wave Energy

Wind and waves are important forces for mixing riverine and receiving waters (Figure 7). Wind generates surface waves, internal waves[15], seiches, and Langmuir wind rows/cells[16], all of which significantly enhance the mixing of estuary water columns (Day et al. 1989). In the absence of strong tides or wind and waves to mix estuarine waters, water columns tend to remain stratified. In addition to mixing of freshwater and saltwater and breaking up density gradients, wind and wave action is also responsible for the resuspension of sediments. This increases turbidity and brings once deposited nutrients back into the water column. Water samples taken after a storm event will differ significantly (in a variety of characteristics) from samples obtained during a relatively calm period. Therefore, recent weather patterns (as an indication of wind and wave effect) need to be recorded as part of the routine sampling protocol for coastal restoration monitoring.

Figure 7. Winds from a winter storm make large waves that mix the water column. Photo courtesy of Peter Dyrynda.

Sampling

The Army Corps of Engineer's Shore Protection Manual (U.S. Army Coastal Engineering Research Center 1984) is an extensive document that explains many wave characteristics and mathematical formulae for predicting them. Using equations from that document, it is possible to calculate the depth at which waves reach the sediment surface (i.e., touch the bottom). Simplified equations that may be of use in some coastal areas are provided in Appendix IV of this chapter. Electronic devices to measure wave energy (such as pressure sensors) are also commercially available.

CHEMICAL

Nutrient Concentration[17]

In general, estuaries tend to be relatively nutrient rich environments compared to other

[14] Low oxygen levels (DO ~ 0.5 ppt).
[15] Waves within the water column, between layers of water of different densities. Often seen in areas where fresh- and saltwater meet.
[16] Three-dimensional circulation of water within the water column, created by constant, unidirectional winds.
[17] Section developed using material from U.S. EPA 2001a. Nutrient criteria technical guidance manual: estuarine and coastal marine waters. United States Environmental Protection Agency, Office of Water. http://www.epa.gov/waterscience/standards/nutrients/marine/index.html

types of coastal systems. High nutrient levels lead to high primary productivity. High nutrient levels and high productivity are due, in part, to the constant inflow of materials such as sediments, nutrients, and organic matter from upland sources. Although they are generally rich in nutrients, the maximum productivity of any coastal habitat is determined by one or more key limiting nutrients. In marine ecosystems nitrogen is typically the limiting nutrient, while in freshwater systems phosphorus tends to be the limiting nutrient. At certain times of the year other nutrients, such as silica, may also become limiting in either freshwater or marine settings (Conley et al. 1993). The ratio of these three nutrients (nitrogen, phosphorus, and silica) to one another dictates what species of algae dominate the plankton community. If a nutrient that is limiting is added to the water column, phytoplankton productivity can increase and the entire community composition may be altered. Since phytoplankton are the base of the food web in estuarine water columns, this can have serious and possibly detrimental consequences such as altering the species composition of higher levels in the food chain (Burkholder 1998).

Monitoring nutrient levels is an important part of a restoration monitoring plan because of the effect high nutrient levels have on phytoplankton productivity. Nutrient concentrations tend to be high in estuaries (both freshwater and marine) in the spring and after rain events. High levels of nutrients can lead to increases in algae productivity and can lead to excessive production, called blooms. When algae dies it sinks to the bottom of the estuary where bacteria break it down. In the process, bacteria use up the oxygen in the water column, sometimes faster than it can be replenished by diffusion or physical mixing induced by waves. Hypoxic or anoxic conditions (low to no oxygen) can result, killing fish and other wildlife and altering the biochemical cycling of nutrients and other compounds.

Estuaries are highly dynamic environments, and nutrient concentrations can vary widely on an annual, weekly, or even daily basis. For example, after a rainstorm large amounts of nutrients are delivered to an estuary. These excess nutrients are quickly absorbed by the phytoplankton. Depending on the frequency and spatial location of sampling that pulse of nutrients to the estuary may be missed. Nutrients also have complex interactions with hydrology (freshwater vs. saltwater) and dissolved oxygen concentrations both of which can also be affected by seasonal weather patterns and isolated storm events. Therefore, it is recommended that nutrient sampling be conducted on at least a weekly or biweekly schedule over several years and at enough points throughout the restoration area to be effective.

Fecal coliforms[18]

Increased nutrient loading and resulting eutrophication is not just an aesthetic issue or a problem for bottom dwelling organisms,

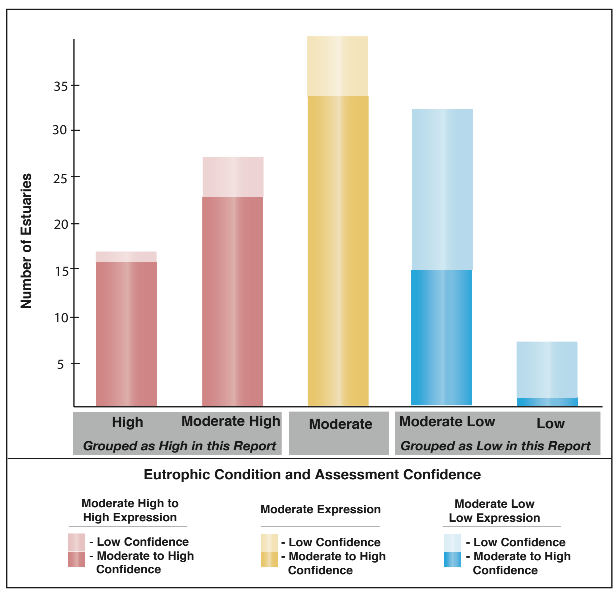

Figure 8. Approximately 65% of estuaries sampled as part of a nation-wide NOAA study were found to be moderately to highly impaired from high levels of nutrient inputs. Figure courtesy of Suzanne Bricker, NOAA National Centers for Coastal and Ocean Science.

[18]Section developed using material from U.S. EPA. 2001b. Volunteer Estuary Monitoring: a Methods Manual. United States Environmental Protection Agency, Office of Water. http://www.epa.gov/owow/estuaries/monitor/.

it has human health implications as well. A variety of human diseases have been associated with nutrient enrichment in coastal waters. Increases in *Escherichia coli* (*E. coli*) and other disease causing organisms, concentration of trihalomethanes[19], frequency of hazardous algal blooms, and cholera outbreaks in relationship to algal blooms in coastal waters have all been linked to increased nutrient concentrations in coastal waters. Approximately 65% of the estuaries of the United States (out of 138 surveyed) have moderate to serious nutrient enrichment problems (Figure 8 - Bricker et al. 1999).

Pathogenic microorganisms (bacteria, viruses, and protozoans) that cause illnesses such as typhoid, cholera, giardiasis, and hepatitis are often associated with fecal waste. These microorganisms are particularly important to monitor in recreational and water supply areas. Since the pathogens that cause such illnesses are rare and difficult to sample, indicator organisms are often used to determine if contamination with fecal material has occurred. Four indicators are commonly used: total coliforms, fecal coliforms, *E. coli*, and enterococci. Total coliforms include organisms naturally occurring in plant material and soil and therefore are not the best indicator of contamination from sewage treatment plants, leaky septic tanks, industrial discharges, or livestock feed lots. Measurement of enterococci requires an expensive growth media that is toxic to humans. Fecal coliforms (and *E. coli* specifically) make better indicators of sewage contamination in terms of getting the best information for the time and money invested. Natural populations can, however, be found in areas with large wildlife populations or where waters tend to be warm and have high organic content. If biological contamination is suspected, it is important to sample in a variety of locations, frequently (i.e., weekly or bi-weekly), and near suspected contamination sites. It is also important to sample for these bacteria during and after storm events, as this is when discharges from sewage treatment plants and stockyards are most likely to occur. When sampling is conducted to monitor the restoration of a recreational area, sampling can be limited to warmer months when people are likely to use the area for swimming and boating. If sampling is being conducted to monitor oyster or clam beds, it must be continued throughout the year.

Sampling

Sampling, handling, and processing nutrient and bacterial samples of any sort requires special instrumentation and reagents. Detailed information on equipment requirements and laboratory procedures is found in the American Public Health Association's (1999) *Standard Methods for the Examination of Water and Wastewater*. The U.S. Environmental Protection Agency (U.S. EPA 2001a) has also published a useful document on monitoring nutrient concentrations in estuarine habitats. More information on this document is available at: www.epa.gov/owow/estuaries/monitor/.

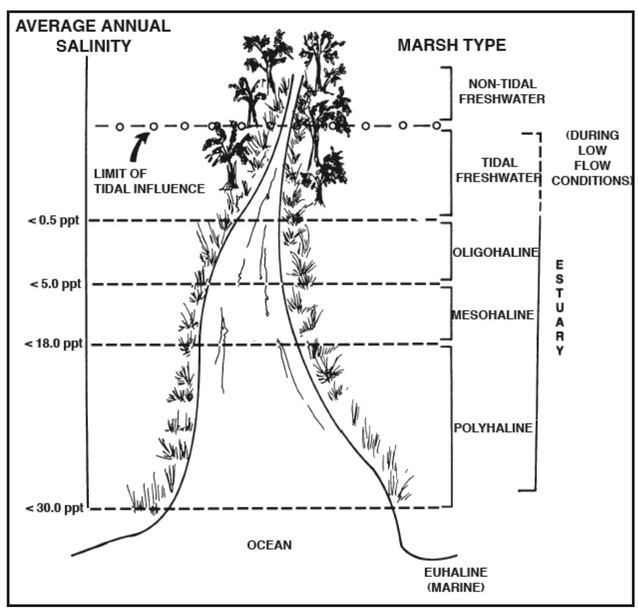

Figure 9. The Venice classification of estuarine salinity. Taken from Odum et al. 1984.

[19]A carcinogenic byproduct of chlorine based waste water treatment.

Salinity (tidal systems only)

Salinity is the key determinant in the distribution and abundance of estuarine flora and fauna (Gibson et al. 2000). Some species may be restricted to the freshwater portion of the estuary (< 0.5 ppt), while others are restricted to more saline environments, yet others are able to tolerate a range of conditions. Classification of salinity levels is often broken down according to the Venice system, illustrated in Figure 9. A salinity level below 0.5 ppt is considered freshwater, a level between 0.5 and 5.0 ppt is called oligohaline (also referred to as brackish), between 5.0 and 18.0 ppt is mesohaline, between 18.0 and 30.0 ppt polyhaline, and anything over 30.0 ppt euhaline or marine (Gibson et al. 2000).

Salinity also has direct effects on other chemical and physical parameters of the water column. For example, the total concentration of oxygen able to dissolve in saltwater is less than that for freshwater. This places a lower natural limit on the supply of oxygen in the estuary water column compared to freshwater systems, particularly at lower depths. The impact of lower oxygen levels near the sediment surface can be compounded during calm weather when mixing of the upper water column is reduced or if eutrophic conditions are present in the estuary. In order to be properly calibrated, most oxygen meters also require a measurement of salinity (U.S. EPA 2001b). Salinity also affects turbidity, which, in turn, affects primary production by limiting the depth at which photosynthesis by phytoplankton and submerged aquatic vegetation can occur. Material that is dissolved in freshwater can clump together in saltwater. These clumps increase turbidity thereby decreasing the depth to which light can penetrate in the water column (EPA 2001).

The segregation of estuarine fish species based on salinity gradients is illustrated in Figure 10. Restricted to freshwater areas are such species as:

Bluegill (*Lepomis macrochirus*)
Largemouth bass (*Micropterus salmoides*)
Sunfish (*Lepomis gibbosus*)

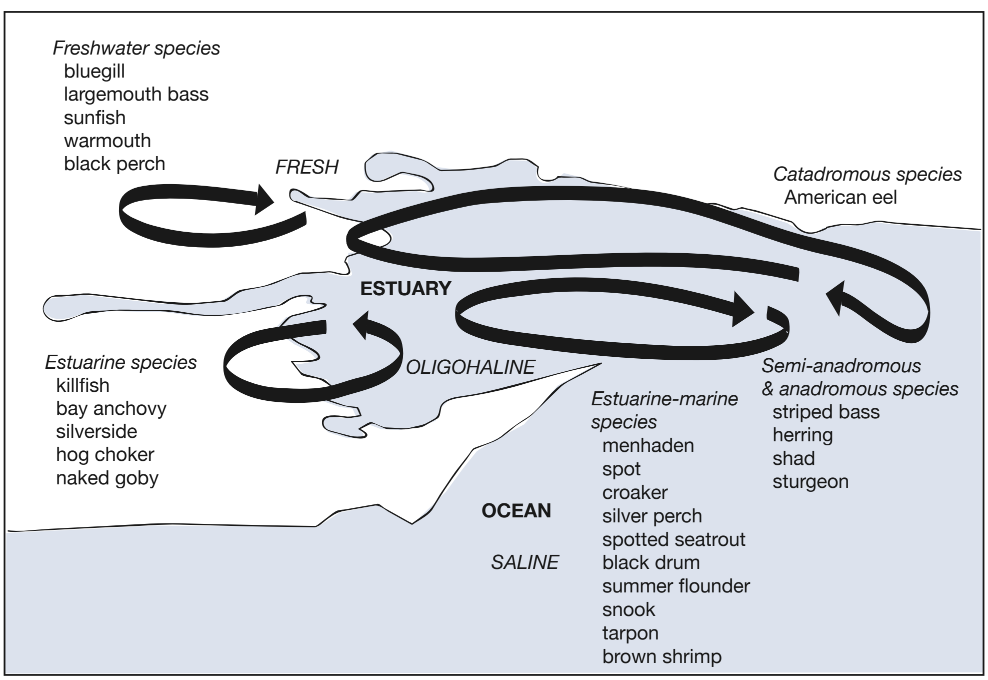

Figure 10. Fish species distribution in an estuary is dependent upon salinity. Modified from Mitsch and Gosselink 2000.

Species adapted to oligohaline conditions include:

Killifish (*Fundulus confluentus*)
Bay anchovy (*Engraulis mordax*
Naked goby (*Gobiosoma bosc*)

Other species are able to tolerate a variety of conditions. As salinity concentrations shift back and forth across the estuary due to freshwater inflow from upland sources, plant and animal communities adapt to those ever-changing conditions (Mitsch and Gosselink 2000).

Sampling

A variety of electronic meters are commercially available for measuring salinity and range in price from tens to several hundreds of dollars. Most meters are designed for use within a given range of salinity. Use outside of this range will result in the collection of incorrect data if salinity levels are below that which the meter is designed for or permanent damage to the meter if salinity levels are too high.

Dissolved Oxygen (concentration, spatial coverage, frequency of low oxygen events)[20]

Nearly all aquatic life requires dissolved oxygen (DO) to survive. Lack of oxygen can become a significant problem. In addition to its use in respiration by higher organisms such as fish, DO is used by bacteria in the process of breaking down organic matter. In nutrient-rich waters, where algal production is high, bacteria can use up practically all of the oxygen dissolved in the water to decompose the algae once it dies. Normally, aquatic organisms require at least 5 mg/L DO to survive and reproduce. If the DO concentration falls below 3 mg/L (referred to as hypoxia), organisms become stressed. Below 2 mg/L most fish species die. If DO levels go below 0.5 mg/L (anoxia), all but anaerobic organisms will be killed (U.S. EPA 2001b). Anoxia resulting from eutrophication and excess oxygen consumption has resulted in massive fish die-offs in Lake Erie (Czapla et al. 1995) and is currently causing the large 'dead zone' in the Gulf of Mexico (Mitsch et al. 2001).

DO also affects the concentration and availability of nutrients and some toxic chemicals. In the presence of oxygen, phosphorus is bound to sediments. Under anoxic conditions, phosphorus becomes soluble and is available for uptake by plants, furthering the process of eutrophication (Mortimer 1941; Mortimer 1942). During periods of low oxygen concentration, nitrogen is transformed from nitrate and nitrite (NO_3 and NO_2) to ammonia (NH_4) which, like soluble phosphorus, is readily taken up by plants. At low oxygen concentrations, hydrogen sulfide and some metals also become soluble. Both are toxic to plants and animals (U.S. EPA 2001a).

Dissolved oxygen enters the water column through gas exchange with the atmosphere and by photosynthesis of aquatic plants. Concentrations vary with time of day, season, temperature, and salinity. DO measures, therefore, need to be taken at regular intervals, as a single measure will not provide meaningful information. On bright, sunny days adequate nutrients lead to high rates of photosynthesis. Under these conditions it is possible to achieve supersaturated DO concentrations. By early morning, DO levels can reach critical lows as plants and animals use up dissolved oxygen over night. DO concentrations tend to be highest during the winter since more oxygen can dissolve in cold water than in warm water and biological activity (i.e., respiration) is lower. As mentioned above, salinity level also affects DO concentrations (i.e., freshwater has higher concentrations than salt water). Warm, seawater then, can have low oxygen concentrations even in absence of any adverse human impacts.

[20]Section developed using material from EPA, U.S. 2001. Volunteer Estuary Monitoring: a Methods Manual. United States Environmental Protection Agency, Office of Water. http://www.epa.gov/owow/estuaries/monitor/

Sampling

DO measurements should be taken at least weekly and twice during the same day, in the early morning and mid-afternoon (always at the same times). This frequency should provide useful maximum and minimum DO values for monitoring purposes. Measurements should also be taken at varying depths in the water column in relation to changes in salinity and temperature. Measurements should be taken year-round where- and whenever possible. At a minimum they should be taken throughout the growing season, as this is when plant communities will have their greatest affect on oxygen concentrations.

The American Public Health Association (APHA) *Standard Methods for the Examination of Water and Wastewater* describes, in detail, a number of chemical and electronic methods for measuring dissolved oxygen concentration in fresh- and salt waters. A variety of electronic oxygen sensors are also commercially available. These have the benefit of allowing measurements to be taken in the field, thus decreasing the chance that handling and transporting the sample will change oxygen concentration before it can be processed in the laboratory.

FUNCTIONAL CHARACTERISTICS OF THE WATER COLUMN

The water column performs a variety of biological and physical functions. As water is the common link between all of the habitats in Volume Two, these functions are often performed within and between other habitats. These functions include:

Biological
- Contributes to primary production
- Supports biomass production
- Provides breeding grounds
- Provides feeding grounds

Physical
- Affects transport of suspended/dissolved material

Chemical
- Affects nutrient and chemical concentrations

Much of the information on the physical and chemical functions of the water column (transporting suspended and dissolved material) has been covered in the associated structural characteristics above. The biological functions listed, along with specific parameters that may be monitored to assess them during restoration projects, are described below.

BIOLOGICAL

Contributes to Primary Production

Primary production is the amount of plant tissue created as a result of photosynthesis over time. As previously discussed, many coastal ecosystems are nutrient rich and thus have high rates of primary production. The primary productivity of the water column in coastal water columns is predominantly measured using two different indicators: the diversity and abundance of phytoplankton and the amount of chlorophyll *a*. The presence and frequency of harmful algal blooms can also be a measure of productivity and is also an indicator of eutrophic conditions as well.

Plankton diversity and abundance[21]

The term plankton refers to plants and animals suspended in the water column that are unable to prevent being moved around by currents. There are three types of plankton:

- bacterioplankton[22]
- phytoplankton[23]
- zooplankton[24]

The most commonly measured types of plankton are phyto- and zooplankton. Phytoplankton and the associated measurement of chlorophyll *a* content of the water are discussed here. The importance of zooplankton (which are animals) is discussed under the section on biomass production below.

Phytoplankton
Phytoplankton are the primary food producers in freshwater, marine, and estuarine water columns. As plants, they produce food through photosynthesis then are eaten by zooplankton that are in turn eaten by larger zooplankton and small fish that are then eaten by larger fish and so on up the food chain. If toxic compounds are present in the water they can be absorbed by phytoplankton, and these chemicals can accumulate in the food chain until harmful concentrations are reached at higher levels (bioaccumulation).

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[21] Section developed using material from APHA. 1999. American Public Health Association, Standard Methods for the Examination of Water & Wastewater. 20 ed. American Public Health Association, Washington, D.C.
[22] Bacteria.
[23] Unicellular, colonial, or filamentous algae.
[24] Animals, both those that live full time as plankton and the larval stages of organisms such as fish and crustaceans.

Phytoplankton make excellent indicators of nutrient loads because they respond very quickly to changes in nutrient concentrations. This aspect also makes them useful for picking up isolated, nutrient-loading events that may be missed by chemical sampling alone. For example, a storm event may deliver a surge of nutrients to a water body. Phytoplankton communities respond to the presence of the excess nutrients by growing and reproducing rapidly. When practitioners return for chemical sampling, nutrient concentrations dissolved in the water column may have become more dilute but the algae will still be visible, indicating that excess nutrients had been available.

High nutrient concentrations can also affect algal species composition. Algal blooms, following high nutrient inputs have lower species diversity than under lower nutrient conditions (Sanders and Kuenzler 1979). Nutrient rich conditions also favor a shift from diatom dominated phytoplankton communities to communities dominated by non-siliceous[25] algae, altering the base of estuarine food webs (Béthoux et al. 2002). Thus the change in phytoplankton community as it pertains to nutrient enrichment can be measured through overall production, loss in phytoplankton diversity (Rabalais et al. 1996), or by a change in community structure.

The complexity of the relationship between nutrients, phytoplankton and the rest of the estuarine food web is illustrated in Figure 11. As the diagram indicates, phytoplankton, zooplankton, microbes, and nutrient concentrations are all closely inter-related. One could also include varying concentrations

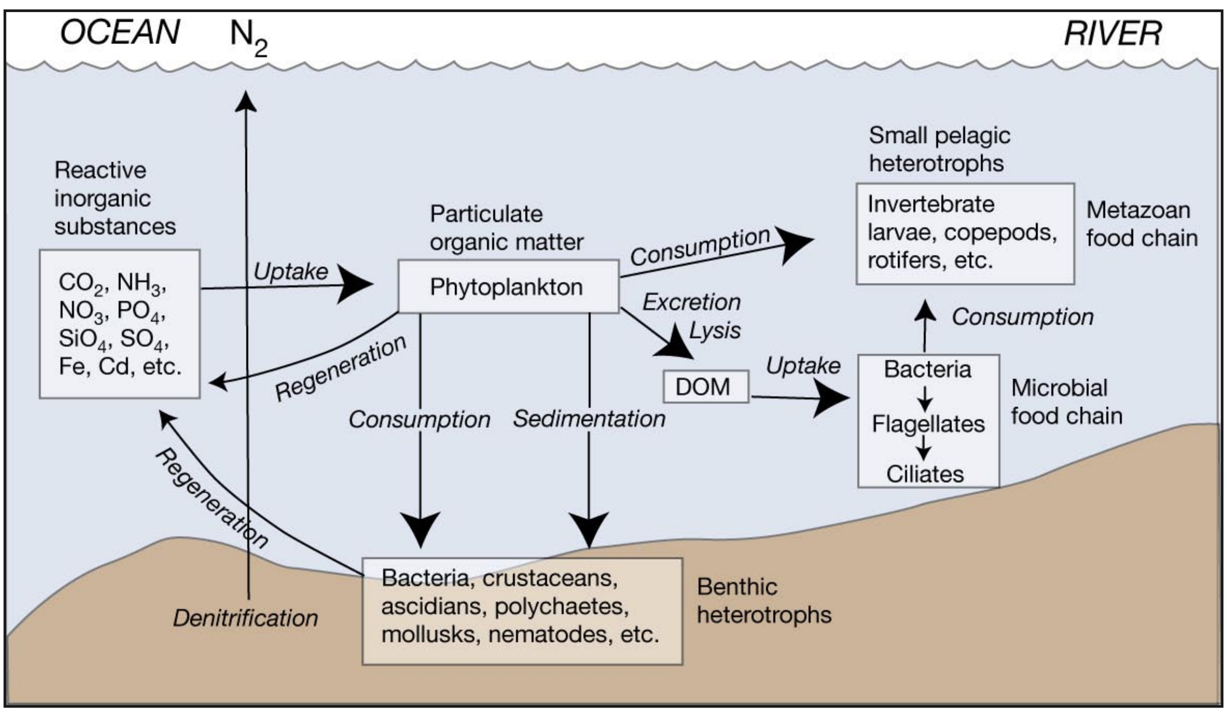

Figure 11. The central role phytoplankton play as agents of nutrient transformation in shallow open water systems. Phytoplankton take up nutrients (reactive inorganic substances) and convert these into particulate (POM) and dissolved organic matter (DOM). Each of these supports the production of pelagic and benthic zooplankton and fish. The arrows indicate material exchanges between these different ecosystem components. Denitrification has also been added to the figure. Modified from Cloern 1996.

[25]Diatoms are unicellular algae that make hard shells out of silica (SiO_2). Algae with shells (also called tests) made of something other than silica or those that lack shells entirely are 'non-siliceous'.

of salt and oxygen to add further detail (and complexity) to this diagram. Monitoring just one component of the system provides only a small piece of the overall picture and may not provide all of the information needed to properly assess the success or failure of a restoration effort. Many qualitative and quantitative methods exist for monitoring plankton communities. Practitioners interested in using plankton as part of a restoration monitoring effort are referred to the American Public Health Association (1999) "Standard Methods for the Examination of Water and Wastewater" for a thorough explanation of sampling methods and analysis techniques.

Figure 12.1 Microcystis, toxic to zooplankton and thus harmful to fish, is one type of algae responsible for harmful algal blooms. This concentrated sample was taken in Lake Erie off the northwest Ohio coast. Photo courtesy of Tom Bridgeman, University of Toledo.

Chlorophyll a[26]

All green plants, including phytoplankton, produce chlorophyll *a*[27]. Chlorophyll *a* concentration is often used to determine how much phytoplankton is in the water column. There are two main methods for measuring chlorophyll *a*, depending on the type of system you are monitoring. In freshwater systems, chlorophyll *a* is measured using the spectrophotometric method. In marine systems, the fluorometric method produces better information. As with phytoplankton, readers are again referred to American Public Health Association (1999) *Standard Methods for the Examination of Water and Wastewater* for a thorough explanation of sampling methods and analysis techniques.

Figure 12. A harmful algal bloom in a Lake Erie estuary in northwest Ohio. Photo courtesy of OhioLink. http://www.biosci.ohio-state.edu/~eeob/limnologylab/photoslesatellite.htm

Harmful algal blooms (concentration, frequency, duration)[28]

Some phytoplankton produces toxins that can cause illness or death in fish, shellfish, and marine mammals. Humans can be affected as well if infected shellfish are eaten. In recent years, there has been an increase in the number and frequency of harmful algal blooms (HABs)

[26]Section developed using material from APHA. 1999. American Public Health Association, Standard Methods for the Examination of Water & Wastewater. 20 ed. American Public Health Association, Washington, D.C..

[27]A green pigment that gives most plants their color and enables them to perform photosynthesis.

[28]Section developed using material from EPA, U.S. 2001. Volunteer Estuary Monitoring: a Methods Manual. United States Environmental Protection Agency, Office of Water. http://www.epa.gov/owow/estuaries/monitor/

in the United States and globally. Some HABs are naturally occurring (i.e., red tides) while others are caused by humans and linked to nutrient enrichment of estuaries and coastal waters (Figures 12 and 12.1). Increased monitoring efforts are being conducted for improved forecasting and early detection of harmful blooms that may save human suffering and lives. If reduction of nuisance and toxic algal blooms is a goal of a restoration project, monitoring can help discern whether or not nutrient abatement projects are achieving the desired results. Representatives from several federal agencies[29] have teamed together with various state agencies to coordinate a national HAB research and monitoring strategy[30]. Additional information on these and other research and monitoring activity can be found at http://www.cop.noaa.gov/Fact_Sheets/MERHAB.html. The U.S. Environmental Protection Agency has formed a network of volunteers to monitor the occurrence of harmful algal blooms in the nation's estuaries. Information on sampling techniques and particular species of concern can be found in *The Volunteer Monitor* (volume 10, number 2 fall 1998). This issue is available on-line at http://www.epa.gov/owow/estuaries/monitor/.

Manual monitoring of algal toxins in specific areas can, however, be expensive and time consuming. This has led to the use of remote sensing techniques such as aerial and satellite imagery to detect potentially harmful algal blooms over larger areas (Boesch et al. 1997).

Supports biomass production and provides breeding and feeding grounds

Biomass production is different than primary production. Biomass is the total weight of all living material (plant and animal) produced in a particular area. Methods for sampling primary plant productivity were discussed above. Parameters for monitoring animal production are presented here. There are two main groups of organisms can be useful in monitoring the functions of biomass production, breeding, and feeding grounds in water column habitats: fish and zooplankton. The community composition, diversity, and abundance of fish and zooplankton as well as the health (body condition) of fish may all be useful parameters to monitor depending on the goals of a restoration project.

Figure 13. Striped bass (shown here) and other predators feed on smaller fish that feed on zooplankton. Photo courtesy of the US Environmental Protection Agency. http://www.epa.gov/gmpo/education/photo/birds-animals.html

Fish community composition, diversity, and body condition

Fish can be useful indicators of estuarine health and are important for restoration monitoring. Since they are near the top of the aquatic food web, fish community composition and health incorporate a variety of information related to overall water quality and conditions at lower trophic levels (APHA 1999). Fish represent an important link in the food web between invertebrates and piscivorous birds and mammals, including humans. Smaller feeder fish, such as menhaden, mummichog, and bay anchovies (*Anchoa mitchilli*) feed on phyto- and zooplankton, the first organisms in the food web to absorb toxins. These small fish are then eaten by larger fish such as striped bass (Figure 13 - *Morone saxatilis*) that are eventually eaten

[29]U.S. Department of the Interior, Centers for Disease Control, U.S. Food and Drug Administration, U.S. Department of Agriculture, U.S. Environmental Protection Agency, National Oceanic and Atmospheric Administration, and the National Institute for Environmental Health Services.

[30]www.redtide.whoi.edu/hab/announcements/pfiesteria/pfiesteriastrategy.html

by larger fish or people. Thus fish at all levels bioaccumulate toxins that may eventually impact human populations (U.S. EPA 1998; Gibson et al. 2000).

Although tremendous diversity in environmental preference, tolerance to disturbance, and pollution exists, most fish species are sensitive to increased turbidity, low oxygen levels, contaminants, and loss of habitat. Certain species are very intolerant of these conditions and are thus useful indicators of disturbance. Atlantic menhaden (*Brevoortia tyrannus*), an important estuarine feeder fish, is one example of a pollution intolerant fish. The presence of trout (family Salmonidae) or sculpin (family Cottidae) also often indicates good water quality in freshwater systems. On the other hand, some fish are quite tolerant of a variety of conditions. Mummichogs (*Fundulus heteroclitus)*, channel catfish (*Ictalurus punctatus*), and the common carp (*Cyprinus carpio*) are examples of more tolerant estuarine and freshwater fishes. Fish are also generally long-lived and useful in indicating long-term factors that may be missed by short-term periodic sampling of other parts of the ecosystem. There are, however, no universal indicators that can be used to measure the same thing in all locations, as species sensitivities often vary by the specific type and location of disturbance (U.S. EPA 1998; APHA 1999; Gibson et al. 2000).

Other characteristics of fish communities and health may also be useful in monitoring restoration projects. Fish are mobile and are therefore able to move away from stressful environments. Thus presence/absence alone can be a useful measure of whether or not a restoration activity is having the desired effect (U.S. EPA 1998; Gibson et al. 2000). Fish also exhibit a variety of physiological, morphological, and behavioral responses to stress. Deformities such as tumors, lesions, parasites, fin rot, skin ulcers, abnormal growths, and skeletal deformities can be used to determine the presence of contamination (Blazer et al. 1994) before costly chemical sampling needs to be conducted (U.S. EPA 1999). Where commercially or recreationally valuable species are involved, long-term data sets may be available from state and federal agencies for comparison to data collected for restoration purposes or may even be substituted for additional data collected as part of a restoration monitoring effort (U.S. EPA 1998; Gibson et al. 2000).

Despite these advantages, there are limitations to using fish to monitor restoration progress. Because some fish are higher in the food chain, other organisms lower on the food web may respond to environmental stressors and restoration activities faster. The mobility of fish can also add complications to monitoring programs. While some species of fish may spend their entire life cycle within one estuary, others such as bluefish (*Potatomus saltatrix*) migrate along the Atlantic coast of the U.S. and move in and out of estuaries with the availability of food resources. The use of some migratory species for restoration monitoring can be further complicated because the location of their normal occurrence varies by season. In addition, the presence of fish deformities may not necessarily indicate adverse conditions

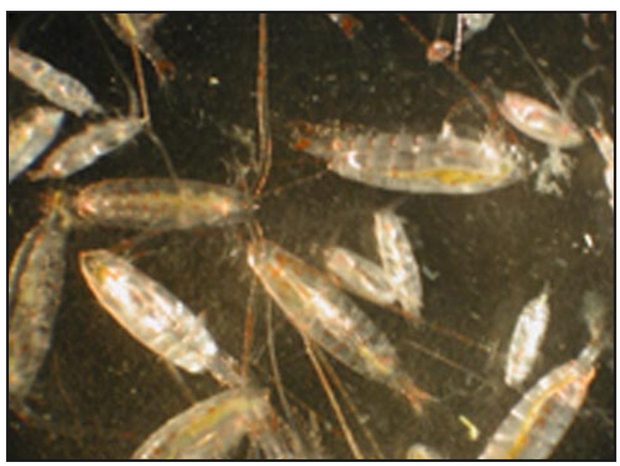

Figure 14. Calanoids, one of the three main types of copepods, are a zooplankton commonly eaten by fish. Photo courtesy of the NOAA Photo Library. http://www.photolib.noaa.gov/fish/images/big/fish3251.jpg

within the restoration area since the fish may have migrated in from elsewhere.

Sampling

A tremendous diversity of sampling approaches and techniques are available to sample fish. The optimum method depends upon the goal of a particular restoration effort and the specific location to be sampled. Restoration practitioners interested in sampling fish populations as part of a monitoring program are referred to two resources: 1) APHA (1999) "Standard Methods for the Examination of Water & Wastewater" and 2) American Fisheries Society "Fisheries Techniques" (Murphy and Willis 1996).

Zooplankton community composition, diversity, and abundance

Zooplankton are small (< 2 mm) invertebrates that float in the water column of all estuaries, freshwater and saltwater (Figure 14). Some are able to weakly swim up and down through the water column to feed on suspended phytoplankton or detritus and escape predation from larger invertebrates or fish (Day et al. 1989). Zooplankton are generally short lived, have high reproductive rates and are very responsive to a number of environmental factors (Deibel 2001) such as water temperature, light, chemistry (pH, oxygen, salinity, and toxic chemicals), food availability, and predation (Paterson 2001). Therefore, zooplankton diversity and abundance may be useful to monitor during a restoration-monitoring program because they are sensitive to so many important environmental factors.

Zooplankton communities can also be very robust and rebound relatively quickly after disturbance. Osbourne and Kovacic (1993) studied the zooplankton community of a freshwater lake in Polk County, Florida. They found that the zooplankton community underwent significant changes in composition, diversity, and abundance during hydraulic dredging of the lake. Though initially wiped out by dredging activities, the zooplankton community had begun to return within one year after dredging was completed.

Zooplankton communities can be very diverse and upwards of 20 species in any one body of water is not uncommon (Paterson 2001). While this diversity may allow for the use of particular species as indicators in certain areas, it also adds considerable complexity to designing a sampling protocol to accurately reflect the entire zooplankton community. Since zooplankton come in a variety of sizes (from microscopic up to 2 mm), the mesh size of the net used to sample them will directly affect which types of animals are caught (Deibel 2001; Paterson 2001).

Sampling

Zooplankton diversity and abundance vary spatially and temporally (i.e., daily, seasonally) within an estuary. In the presence of planktivorous fish, many plankton will swim to lower depths during the day to evade predators and then move up in the water column at night to take advantage of richer food sources in the top of the water column. Due to seasonal population fluctuations sampling at only one spot at one time may underestimate actual community size and structure by as much as 67% (Paterson 2001). Restoration practitioners interested in using zooplankton for monitoring are encouraged to consult with local experts, look for previous studies of the area (if available), and conduct pilot studies to determine what types of animals are found in their system. This will lead to more efficient restoration sampling. Quantitative and qualitative methods to monitor plankton are presented in the American Public Health Association's (1999) *Standard Methods for the Examination of Water and Wastewater*.

PHYSICAL

The importance and monitoring of the physical functions of the water column have been discussed within the Structural Characterics above, under the section titled “Hydrological.”

CHEMICAL

The importance and monitoring of the chemical functions of the water column have been discussed within the structural characteristics above under sections titled “Water Sources”, “Nutrient Concentration”, and “Dissolved Oxygen”.

PARAMETERS FOR MONITORING STRUCTURAL/FUNCTIONAL CHARACTERISTICS

The matrices of structural and functional parameters for restoration monitoring provided below were developed through extensive review of the restoration and ecological monitoring-related literature. Additional input was received from recognized experts in the field of water column ecology. This listing of parameters is not exhaustive, it is merely intended as a starting point to help restoration practitioners develop monitoring plans for this habitat. Parameters with a closed circle (●) are those that, at a minimum, should be considered in monitoring restoration progress. Parameters with an open circle (❍) may also be monitored depending on specific restoration goals. Information on why these parameters are important for monitoring and how they relate to structural and functional characteristics as well as to one another is found throughout the preceeding text. Literature directing readers toward additional information on the ecology of the water column, restoration case studies, and sampling strategies and techniques can be found in the Annotated Bibliography of the Water Column and the associated Review of Technical Methods Manuals.

Parameters to Monitor the Structural Characteristics of the Water Column

Parameters to Monitor	**Physical**	Turbidity	**Hydrological**	Tides / Hydroperiod	Water sources	Current velocity	Wave energy	**Chemical**	Nutrient concentration	pH, salinity, toxics, redox, DO[31]
Geographical										
Acreage of habitat types				●						
Biological										
Plants										
Phytoplankton diversity and abundance		❍								
Hydrological										
Physical										
Chlorophyll concentration		●								
PAR[32]		❍								
Seiche disc depth		❍								
Shear force at sediment surface						❍	❍			
Temperature				❍	❍					
Upstream land use					●					
Water column current velocity						❍				
Water level fluctuation over time				●	●					
Chemical										
Dissolved oxygen										●
Groundwater indicator chemicals[33]					●					
Nitrogen and phosphorus									❍	
pH										❍
Salinity (in tidal areas)				●	●					●
Silicon									❍	
Toxics										❍

[31]Dissolved oxygen.
[32]Photosynthetically active radiation, measured at canopy height and substrate surface.
[33]Calcium and magnesium.

Parameters to Monitor the Functional Characteristics of the Water Column

Parameters to Monitor	Biological: Contributes primary production	Biological: Supports biomass production	Biological: Provides breeding grounds	Biological: Provides feeding grounds	Physical: Affects transport of suspended/dissolved material
Geographical					
Acreage of habitat types	●	●	●	●	●
Biological					
Plants					
Interspersion of habitat types		❍	❍	❍	❍
Nutrient levels in algal tissues (N and P)	❍	❍			
Phytoplankton diversity and abundance	❍	❍		❍	
Biological					
Animals					
Species, composition, and abundance of:					
Fish		❍	❍	❍	
Invasives		❍		❍	
Invertebrates		❍	❍	❍	
Fecal coliforms					❍
Hydrological					
Physical					
Secchi disc depth	❍	❍			❍
Trash					❍
Upstream land use					●
Water column current velocity					❍
Water level fluctuation over time			●	●	●
Chemical					
Chlorophyll concentration	●	●		●	●
Dissolved oxygen			●		
Groundwater indicator chemicals					❍
Nitrogen and phosphorus	❍	❍			
pH			❍	❍	❍
Salinity (in tidal areas)			●	●	●
Silicon	❍	❍			
Toxics			❍	❍	

Acknowledgments

The author would like to thank Suzanne Bricker, Jon Hare, Pete Sheridan, and Mike Weinstein for the comment and review of this chapter.

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Gosselink, J. G. 1984. The ecology of delta marshes of coastal Louisiana: a community profile, 134 pp. FWS/OBS-84/09, U.S. Fish and Wildlife Service.

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APPENDIX I: WATER COLUMN ANNOTATED BIBLIOGRAPHY

This annotated bibliography contains summaries of restoration case studies and basic ecological literature. It is designed to provide restoration practitioners with examples of previous restoration projects as well as overviews of papers from the ecological literature that offer more detail than that covered in the associated chapter. Entries are presented from both peer reviewed and grey literature. They were selected through extensive literature and Internet searches as well as input from reviewers. They are not, however, a complete listing of all of the available literature. Entries are arranged alphabetically. Wherever possible, web addresses or other contact information has been included in the reference to assist readers in easily obtaining the original resource. Summaries preceded by the terms '*Author Abstract*' or '*Publisher Introduction*' or similar descriptors were taken directly from their original source. Summaries without such descriptors were written by the author of the associated chapter.

Bedford, K. W. 1992. The physical effects of the Great Lakes on tributaries and wetlands. *Journal of Great Lakes Research* 18:571-589.

Author Abstract. Wetlands and tributary confluences are susceptible to physical influences imposed by the Great Lakes, particularly through the effects of short and long-term water level fluctuations and accompanying transport disruptions including flow and transport reversals. With there being few, if any, direct observations of these disruptions based upon velocity measurements, the objective of this paper is to review the possible physical effects on these regions by first, reviewing the relevant contributing physics known about the Great Lakes; second, contrasting possible marine estuary transport mechanisms with was little is published about the Great Lakes circumstances; and third, summarizing modeled results exemplifying these behaviors from a study of Sandusky Bay, Lake Erie. Because it exhibits the strongest response to storms and the clearest measurable signals resulting from them, attention is centered on Lake Erie. In contrast to a typical research paper, the objective herein is to provide a summary of what is known and commonly accepted about these physics which can serve as a backdrop for the other papers in this special issue.

Davies, J., J. Baxter, M. Bradley, D. Connor, J. Khan, E. Murray, W. Sanderson, C. Turnbull and M. Vincent. 2001. Marine Monitoring Handbook. 405 pp. UK Marine Science Project, and Scottish Association of Marine Science. Joint Nature conservation Committee, English Nature, Scottish Natural Heritage, Environment and Heritage Services. http://www.jncc.gov.uk/marine/mmh/contents.htm

The United Kingdom Marine Science Project developed this handbook to provide guidelines for recording, monitoring, and reporting characteristics and conditions of marine habitats. Methodologies will need to be modified to suit the structural characteristics of habitats in the United States. This manual addresses the fundamentals and procedures for monitoring different parameters in marine habitats, management tools, and benefits and costs for developing a monitoring project. Topics presented in this document include establishing marine monitoring programs highlighting what needs to be measured and methods to use; provides guidance when developing a monitoring program; selecting proper monitoring techniques to attain precision and accuracy; and procedural guidelines for monitoring a specific marine habitat. Detailed information on the tools needed for monitoring marine habitats are described within this handbook.

Day, J. W., Jr., C. A. S. Hall, W. M. Kemp and A. Y.-A. (eds.). 1989. Estuarine Ecology. John Wiley and Sons, NewYork.

Editors Comments. Estuaries are critical to the life cycles of fish and other aquatic animals. This book is a comprehensive synthesis of the field of estuarine ecology, incorporating much new research not covered by other books. The authors provide up-to-date information on the structure and function of estuaries, integrating the various components and processes of these key ecosystems. They also present a classification of estuaries bases on ecological principles. *Estuarine Ecology* is suitable as a text, for it presents all relevant background material – and it is complete and well-referenced enough to serve as a standard reference. Specific environmental impacts are addressed and classified.

Initial chapters describe the physical and chemical aspects of estuaries, with emphasis on nutrient cycling, and show how these fundamental factors provide a setting for the study of estuarine ecology. Middle chapters address estuarine plants, microbial ecology, estuarine consumers, and fish life-history patterns. Considerable information is provided on rates, patterns, and factors controlling primary production; the role of detritus in coastal systems (a topic that has been important in estuarine ecology for thirty years); and estuarine consumers (zooplankton, benthos, nekton, and wildlife). Of special note is the importance of estuaries in supporting fisheries.

Estuarine Ecology also deals with the effects of civilization on estuaries, including commercial fishing, and the side effects of industry and development. The authors examine traditional approaches to fisheries management, then present a modern ecological viewpoint. In the final chapter they present a general classification of the effects of human activities on estuarine ecology and give examples of each.

Estuarine Ecology is a thorough introduction to the subject – it presents an acceptable synthesis of modern estuarine science for those new to the field and develops sophisticated analysis for the professional.

Johnson, G. E., B. D. Ebberts, R. M. Thom, N. M. Ricci, A. H. Whiting, J. A. Southard, G. B. Sutherland, J. D. Wilcox and T. Berquam. 2003. An ecosystem-based approach to habitat restoration projects with emphasis on salmonids in the Columbia River Estuary, 154 pp., Pacific Northwest National Laboratory, Richland, WA.

Author Overview. The intent of this document is to provide a scientific basis and implementation guidelines for a habitat restoration program designed to improve ecosystem functions and enhance juvenile salmonid survival in the Columbia River estuary (CRE). The document does not address economic, social, or political aspects of habitat restoration in the CRE. The focus here is on habitat for listed salmon, although the ecosystem-based approach necessarily affects other species as well. Salmon habitat restoration is best undertaken within the context of other biota and physical processes using an ecosystem perspective. The anticipated audience includes entities responsible for, interested in, or affected by habitat restoration in the CRE. Timeframes to apply this document extend from the immediate (2003-2004) to the near-term (2005-2006) to the long-term (2007 and beyond). We anticipate and encourage that the document be revised as new knowledge and experience are attained.

Lewis, R. R., III, P. A. Clark, W. K. Fehring, H. S. Greening, R. O. Johansson and R. T. Paul. 1998. The rehabilitation of the Tampa Bay estuary, Florida, USA, as an example of successful integrated coastal management. *Marine Pollution Bulletin* 37:468-473.

Author Abstract. The Tampa Bay Ecosystem is located in the state of Florida, USA. The 6739 km^2 ecosystem has undergone major changes due to coastal development, including dredging for maintenance and expansion of the 10th largest port in the USA. Approximately 44% of the historic emergent coastal wetlands and 81% of the historic submergent seagrass meadows had been lost through 1981. Declines in commercial and recreational fisheries harvests and coastal wildlife populations followed similar trends in declines. Beginning three decades ago, an informal Integrated Coastal Management (ICM) program initiated by citizen groups has progressed to a formal ICM program that has initiated restoration of the ecosystem and management through a unique multi-county umbrella organization, the Tampa Bay Estuary Program.

Osborne, J. A. and M. R. Egan. 1997. The impact of lake restoration on the zooplankton community in Banana Lake, Polk County, Florida. *Florida Scientist* 60(2):104–111.

Author Abstract: Zooplankton were monitored in Banana Lake between January, 1990 and March, 1992 to evaluate the impact of lake restoration by hydraulic dredging. Zooplankters were collected on a monthly basis at eight stations using an 8.1 L Kemmerer water sampler. The samples were concentrated by straining the samples through a #20 nylon bolting cloth zooplankton net. Microscopic enumeration was employed to determine abundance of rotifers and microcrustaceans. Dredging was conducted within Banana Lake between August, 1990 and August, 1991. During and after dredging, all species of zooplankters had decreasing trends except for *Asplanchna* sp., a predatory rotifer. Most species started to decline in January, 1991 and by October, 1991 all of the cladocerans and copepods had disappeared. Recovery had begun by March, 1992.

Poulakis, G. R., J. M. Shenker and D. S. Taylor. 2002. Habitat use by fishes after tidal reconnection of an impounded estuarine wetland in the Indian River Lagoon, Florida (USA). *Wetlands Ecology and Management* 10:51-69.

Author Abstract. Most of the wetlands located along the Indian River Lagoon (IRL) in east-central Florida (USA) have been impounded since the 1950's and 1960's to reduce mosquito reproduction. Impounded marsh (i.e., impoundment) dikes physically separate the wetlands from the estuary to allow artificial flooding of the impoundments during the mosquito breeding period (May to October). Presently, Rotational Impoundment Management (RIM) is the preferred impoundment management technique in the IRL. Impoundments maintained under RIM have culverts installed through the dikes which are kept closed during the mosquito breeding season (to control mosquitos) and are allowed to remain open for the remainder of the year (to allow tidal flow). A 24.3 ha impoundment 8 km north of Sebastian Inlet that had been isolated from the IRL for over 39 years was studied for 12 months to determine habitat use by fishes after tidal reconnection and the implementation of RIM. Fish sampling was conducted with a seine in the perimeter ditch and with clover and minnow traps in the upper marsh and tidal creek areas of the impoundment. Water level, impoundment bottom topography, and the seasonal nursery function of the impoundment were factors that contributed to observed patterns of fish habitat use during the study. Within the first 15 weeks of perimeter ditch sampling, an increase from 9 to 40 species was observed. Transient species used the perimeter ditch almost exclusively and entered the impoundment primarily during the spring open period. Juvenile

Pogonias cromis (Linnaeus), *Elops saurus* Linnaeus, *Centropomus undecimalis* (Bloch), and *Megalops atlanticus* Valenciennes were the most abundant recreationally important species, respectively. Habitat use by the most abundant resident species (*Gambusia holbrooki* Girard, *Poecilia latipinna* (Lesueur), *Cyprinodon variegatus* Lacepède, and *Fundulus confluentus* Goode & Bean) was influenced primarily by water level fluctuations. Resident species used the upper marsh and tidal creek habitats during summer flooded periods and the cyprinodontids left the interior surface of the impoundment last as water levels decreased. This study is the first to document the recovery of fish populations in a reconnected impoundment north of Sebastian Inlet using both active and passive sampling techniques.

Smakhtin, V. U. 2004. Simulating the hydrology and mouth conditions of small, temporarily closed/open estuaries. *Wetlands* 24:123-132.

Author Abstract. Many small estuaries and coastal lagoons in different parts of the world may be classified as temporarily closed/open ecosystems. They are blocked off from the sea for varying lengths of time by a sand bar, which forms at the estuarine mouth. The lengths of the closed and open phases, which are determined primarily by the interaction of river inflow and the sea in the mouth region, affect the structure and functioning of the estuarine biotic community. Freshwater inflow to such estuaries is normally not measured, and observations on the duration of estuarine mouth openings / closures are very scarce. As a result, relevant management decisions are often made on the basis of general experience and intuitive judgment. This paper describes an innovative approach for linking hydrologic data to mouth state in ungauged estuaries. A key characteristic in the method is the stream/river flow duration curve. It is first established for a daily index, which reflects the upstream catchment wetness and is calculated using rainfall information from the nearest rain gauge(s). This duration curve is then used to convert the current precipitation index time series into a continuous daily inflow time series at the ungauged estuarine mouth location. The conversion is based on the assumption that precipitation index values in a small catchment, and daily inflows to the estuarine mouth correspond to similar probabilities on their respective duration curves. The paper further illustrates how the generated inflow data could be used for the simulation of a continuous time series of estuary mouth openings/closures. Inflows are routed through a reservoir model, and the estuary mouth is considered open on days when the spillage from an estuarine "reservoir" occurs. The approach is illustrated using limited observed data on estuary mouth conditions from the South African coastline.

Weinstein, M. P., J. M. Teal, J. H. Balletto and K. A. Strait. 2001. Restoration principles emerging from one of the world's largest tidal marsh restoration projects. *Wetlands Ecology and Management* 9:387-407.

One of the world's largest tidal wetland restoration projects was conceived to offset the loss of nekton to once through cooling at a power plant on Delaware Bay, USA. An aggregated food chain model was employed to estimate the area of tidal salt marsh required to replace these losses. The 5040 ha was comprised of two degraded marsh types - *Phragmites*-dominated marshes and diked salt hay farms - at eleven locations in oligo-mesohaline and polyhaline reaches of the estuary. At a series of 'summits' convened with noted experts in the field, it was decided to apply an ecological engineering approach (i.e., 'self design', and minimal intrusion) in a landscape ecology framework to the restoration designs while at the same time monitoring long-term success of the project in the context of a 'bound of expectation'. The latter encompassed a range of reference marsh planforms and acceptable end-points established interactively with two advisory committees, numerous resource agencies, the permitting agency and multiple-stakeholder groups. In addition to the technical recommendations provided by the project's advisors, public health and safety, property protection and public access to the restored sites were a constant part of the dialogue between the utility, its consulting scientists and the resource/permitting agencies. Adaptive management was used to maintain the restoration trajectories, ensure that success criteria were met in a timely fashion, and to protect the public against potential effects of salt intrusion into wells and septic systems, and against upland flooding. Herbicide spray, followed by prescribed burns and altered microtopography were used at *Phragmites*-dominated sites, and excavation of higher order channels and dike breaching were the methods used to initiate the restorations at the diked salt hay farms. Monitoring consisted of evaluating the rate of re-vegetation and redevelopment of natural drainage networks, nekton response to the restorations, and focused research on nutrient flux, nekton movements, condition factors, trophic linkages, and other specific topics. Because of its size and uniqueness, the Estuary Enhancement Program as this project is known, has become an important case study for scientists engaged in restoration ecology and the application of ecological engineering principles. The history of this project, and ultimately the Restoration Principles that emerged from it, are the subjects of this paper. By documenting the pathways to success, it is hoped that other restoration ecologists and practitioners will benefit from the experiences we have gained.

West, T. L., L. M. Clough and W. G. Ambrose, Jr. 2000. Assessment of function in an oligohaline environment: Lessons learned by comparing created and natural habitats. *Ecological Engineering* 15:303-321.

Author Abstract. Assessments of nursery area function were carried out over a 10-year period in a 3-ha oligohaline marsh and creek system (`Project Area 2') and four natural `control' creeks (Drinkwater, Jacks, Jacobs, and Tooley) located in the Pamlico River estuary, North Carolina. Habitat function was assessed by comparing (1) growth and survival of fish; (2) long-term monitoring of water quality, sediment organic carbon, and the benthic infaunal community; and (3) measurement of benthic food availability. Growth (weight gain) and survival of the fish *Leiostomus xanthurus* held within enclosures were similar in both created and natural habitats. Species composition, total fauna density, and species richness of the infaunal community of the Project Area and the natural creeks were comparable within 3 years after construction of the Project Area. However, the sediments of the Project Area lacked the woody detrital cover, high peat content, and predominance of silt and clay characteristic of the natural creek sediments. There was no evidence of significant accretion of total organic carbon in the Project Area during the course of the study. This study has heuristically inspired four recommendations concerning assessment criteria of mitigation success. (1) Direct experimentation is needed to assess habitat function for motile species such as fish. (2) Studies of community structure need to be carried out long enough to permit testing of community stability, especially when working in areas exposed to stochastic abiotic and biotic stressors. (3) Measurements of nutritional content of the sediments should include estimates of overall organic quantity and nutritional quality. (4) Site design or restoration techniques should be included in the experimental design of each mitigation effort. Specifically, the lack of replication in these aspects of the mitigation process limits the inferential potential of the study, constrains the ability to make accurate predictions about the probability of success of future mitigation endeavors, and impedes our understanding of the critical mechanisms governing successful habitat creation, restoration, and enhancement.

APPENDIX II: WATER COLUMN
REVIEW OF TECHNICAL METHODS MANUALS

This Review of Technical Methods Manuals includes a variety of sampling manuals, Quality Assurance/Quality Control (QA/QC) documents, standardized protocols, or other technical resources that may provide practitioners with the level of detail needed when developing a monitoring plan for a coastal restoration project. Examples from both peer reviewed and grey literature are presented. Entries were selected through extensive literature and Internet searches as well as input from reviewers. As with the Annotated Bibliographies, these entries are not, however, a complete list. Entries are arranged alphabetically by author. Wherever possible, web addresses or other contact information is included in the reference to assist readers in easily obtaining the original resource. Summaries preceded by the terms '*Author Abstract'* or *'Publisher Introduction*' or similar descriptors were taken directly from their original source. Summaries without such descriptors were written by the authors of the associated chapters.

Alliance for the Chesapeake Bay. 2002. Chesapeake Bay citizen monitoring program manual, 25 pp. Methods Manual, Alliance for the Chesapeak Bay, Richmond, VA. http://www.acb-online.org/pubs/projects/deliverables-206-1-2003.PDF

Author Abstract. This manual was prepared to assist volunteers performing chemical water quality monitoring and is a revision of the original manual prepared by Kathleen K. Ellett. This manual contains background material and instructions for measuring air and water temperature, dissolved oxygen, water clarity and pH. A sample data sheet is also included.

American Public Health Association. 1999. Standard Methods for Examination of Water & Wastewater. 20 ed. American Public Health Association, Washington, D.C.

Standard Methods for Examination of Water and Wastewater is an essential resource for any laboratory performing every imaginable analysis on water samples whether they be for chemical or biological components. Procedures for the sampling of zooplankton, phytoplankton, periphyton, macrophytes, benthic macroinvertebrates, and fish are also included as well as general identification keys to these organisms. Each procedure is explained in step-by-step detail with information on the strengths and weaknesses of various measurement methods. To a general practitioner, this resource would be useful to explain the chemical and biological components they are sampling, what the analysis entails, and the meaning of the final value obtained from each analysis. Various editions should be available at most any laboratory, or scientific or university library.

Anderson, D. M., P. Andersen, V. M. Bricelj, J. J. Cullen and J. E. Rensel. 2001. Monitoring and Management Strategies for Harmful Algal Blooms in Coastal Waters, APEC #201-MR-01.1, 235 pp. Technical Series 59, Asia Pacific Economic Program, Singapore, and Intergovernmental Oceanographic Commission, Paris. www.whoi.edu/redtide/Monitoring_Mgt_Report.html

In response to a red tide event in Hong Kong in 1998 that devastated the local fishing industry, the government of Hong Kong launched a program to study the effects of Harmful Algal Blooms (HABs) and develop methods to monitor their occurrence. The report by Anderson et al. is an edited version of the information supplied to the Hong Kong government and is a thorough inventory and assessment of HAB monitoring and management practices from around the world as of 1999. Research into HABs is a very dynamic field and much has been learned in the last few years, particularly with advancements in technology for detecting HABs remotely using satellite imagery. The scope of this report, however, would make it a valuable resource to anyone interested in the effects of HAB, efforts to monitor them, and strategies to minimize there impact on human and coastal fisheries.

Campbell, G. and S. Wildberger. 1992. The Monitor's Handbook. Lamotte Company ENC-016429, Chestertown MD. Contact information: Phone # (410) 778-3100, (800) 344-3100 or Fax # (410) 778-6394. Reference No.1507.

Author Abstract. This handbook provides the background and testing procedures for individuals who want to learn more about their local waterways or are involved in a water monitoring program. Aquatic ecosystems, such as streams, rivers, and lakes, are explained and a pre-monitoring sequence of activities is discussed. The handbook outlines sampling techniques and the equipment involved. Information for each of the water quality factors covered in the book (such as hardness, pH, and coliform bacteria levels) include: how to measure the factors, what the significant levels are, and what the measured levels indicate. Tips are provided for assuring the test results' accuracy for each test method. Quality assurance practices that contain calibration procedures and audits are suggested. Readers can find discussions of data analysis and presentation methods. A glossary, bibliography, and conversion table is included in the document. Appendices provide an overview of management concerns for a volunteer water monitoring program and lists of additional resources. Black and white photographs and drawings are found throughout the book.

Cook Inlet Keeper. 1998. Volunteer Training Manual. Contact information: Cook Inlet Keeper, P. O. Box 3269, Homer, AK 99603, Phone # (907) 235-4068 and Fax # (907) 235-4069. http://www.inletkeeper.org/training.htm.

This Manual provides Cook Inlet Keeper volunteers with information needed to monitor water quality in the Cook Inlet watershed. It also provides guidelines for monitoring procedures that are currently included in the Keeper's Citizens' Environmental Monitoring Program (CEMP). Outlined in this document are safety and access issues; a monitoring overview which discusses areas such as water quality test methods, test parameters and sampling schedule; monitoring procedures which include: field procedure checklist, field observations, collecting the samples, testing procedures, sample custody and completing data sheets; equipment care and waste disposal; data management and reporting; and quality control. Additional information for methods and procedures used can be obtained from this manual.

Deibel, D. 2001. Marine biodiversity monitoring: monitoring protocol for zooplankton, 14 pp. A report by the Marine Biodiversity Monitoring Committee (Atlantic Maritime Ecological Science Cooperative, Huntsman Marine Science Centre) to the Ecological Monitoring and Assessment Network of Environment Canada, Environment Canada, St. John's, Newfoundland, Canada. http://www.eman-rese.ca/eman/ecotools/protocols/marine/zooplankton/zooplankton_marine_e.pdf

Diebel explains many of the reasons why zooplankton are an important component of aquatic systems to monitor, many stemming from the relationship zooplankton play in the food web linking phytoplankton to fish communities. He also highlights many of the problems associated with zooplankton sampling calling for a more standardized approach. Sampling zooplankton with nylon nets is highly selective and biased. Biases are caused by the size of mesh in relation to the varying size of animals (i.e. smaller animals get extruded through larger mesh nets), larger animals being able to avoid the net by swimming away, and the physical destruction of soft-bodied animals. Diebel points out that different types of sampling gear (i.e. different mesh sizes, different materials, different size openings) will all have different biases making comparison of data from one sample type to the next impossible.

Diebel also points out that the distribution and abundance of zooplankton species is greatly influenced by light, water depth, temperature, salinity, tides, and time of year and that these measurements too should be taken along with the zooplankton sample. He suggested that a stratified random sample design would be an appropriate sampling technique to account for the spatial variability of zooplankton communities. The strata should be subdivided on the abiotic characteristics listed above, which are also correlated to three general vertical layers in the water column: the upper mixed layer, the thermocline/pycnocline, and the bottom mixed layer. It has also been shown that zooplankton communities segregate out in vertical bands within these larger zones, indicating that a vertical tow may be useful in deeper waters. Since zooplankton communities vary depth, an onshore-offshore gradient could also be added as an addition stratum if a large area is to be sampled. Diebel also states that any zooplankton sampling scheme is a trade off between the length of tow and clogging. Ideally, the longest tow possible before the net is clogged more accurately samples the zooplankton community. Calculations for finding the ideal tow length are provided.

Zooplankton populations also vary according to different time scales. Sampling may thus need to be stratified on a daily time scale (day vs. night), a medium time scale (i.e. before and after storms), seasonal time scales, and decadal scales related to climate change. The choice of the appropriate time scale for measure depends on the question being answered by the practitioner. It is generally suggested that the frequency of samples should be greater while the zooplankton abundance is changing most rapidly and is thus most variable. Fewer samples can be taken when populations are more stable.

Eddy, S. and J. C. Underhill. 1978. How to Know the Freshwater Fishes. Third ed. Wm. C. Brown Company Publishers, Debuque, IA.

The Pictured Key Nature Series has a variety of identification keys available for a host of freshwater and terrestrial plants and animals. This particular volume is geared toward the identification of freshwater fishes found throughout the United States. Some marine fishes that occasionally found in estuarine environments are also included. The key provides accurate and detailed, yet easily understood drawings of representatives from each family as well as specific features that can be used to identify individuals to species. Brief summaries of preferred habitat and extent of range are also provided for most individual species to aid in identification.

Environment and Natural Resources Institute. 2002. Quality assurance project plan, 59 pp. Alaska Biological Monitoring and Assessment Program, Anchorage, AK. http://www.uaa.alaska.edu/enri/bmap/pdfs/ENRI_QAPP_2-02.pdf

This quality assurance project plan (QAPP) is designed for use in collecting data to assess wadable streams in Alaska focusing on the collection of benthic invertebrates and chemical water quality parameters. It can be used by practitioners restoring and monitoring other coastal habitats as a template of the types of information and level of detail required for a QAPP. QAPPs are important documents for any monitoring effort to have readily available. They are used by to ensure that data are collected in a comparable and consistent fashion regardless of who is obtaining the sampling. Some of the topics included in this QAPP include the identification of responsible parties; procedures for properly selecting sample locations and reference conditions; the collection, handling, and preservation of biological and chemical samples; methods to analyze samples and record data; data management; contingency plans for foreseeable mistakes and accidents; and methods to verify and validate the accuracy of data. Example data sheets and procedures for using specific types of equipment are also included.

Findlay, D. L. and H. J. Kling. 2002. Protocols for measuring biodiversity: phytoplankton in freshwater. Ecological Monitoring and Assessment Network Coordinating Office, Knowledge Integration Directorate of Environment Canada. http://www.eman-rese.ca/eman/ecotools/protocols/freshwater/phytoplankton/intro.html

This manual briefly describes the importance and use of phytoplankton in water quality monitoring. Abiotic factors that effect phytoplankton populations are also briefly described. Procedures for selecting sample sites and frequency of measurement, use of qualitative and quantitative sampling methods, and sample handling are also provided. Examples are used to illustrate laboratory procedures and data analysis techniques. As with the other volumes in this series, a list of persons to contact (in Canada) for additional information and assistance is also included.

Garrison, G. 2002. Monitoring water quality, 31 pp. Protocol, Florida Caribbean Science Center, St. John, US Virgin Islands. http://science.nature.nps.gov/im/monitor/protocols/WQPR0719.doc

This manual was designed specifically for monitoring the low-nutrient waters around the United State's Virgin Islands of St. John, Buck Island, and Dry Tortugas. They may also be applicable to other coastal areas with low nutrient concentrations. These areas had historically of low nutrient concentrations that benefited the coral reefs, seagrass beds, and other marine organisms found there. Recent development in the area has, however, led to decreases in water quality. Field and laboratory protocols for the monitoring of temperature, dissolved oxygen, salinity, conductivity, pH, light transmission, visibility, turbidity, suspended solids, photosynthetically reactive radiation (PAR), and nutrients are discussed.

Gibson, G. R., M. L. Bowman, J. Gerritsen and B. D. Snyder. 2000. Estuarine and coastal marine waters: bioassessment and biocriteria technical guidance, 300 pp. EPA 822-B-00-024, U.S. Environmental Protection Agency, Office of Water, Washington, D.C. http://www.epa.gov/ost/biocriteria/States/estuaries/estuaries1.html

Biological assessment can be a cost-effective tool for evaluating water quality, determining water resource status and trends, and following the progress of restoration projects. This technical guidance document is designed to assist managers and biologists in developing methods and approaches for implementing biological assessment and criteria projects. The guidance offered in this manual provides descriptions of the physical and chemical measures needed to properly classify sites for assessment as well as detailed descriptions of the biological measurements themselves. The document describes four levels of monitoring intensity that may be used depending on the particular project in question, and availability of monitoring funds available, and the investigative intensity required.

- Tier 0 is a preliminary review of existing literature and data on the site in question.
- Tier I is a one-time site visit to gather additional data and refine information collected in Tier 0.
- Tier II repeats and expands Tier I measurements. These measurements will be used to establish the reference condition against which comparisons can be made.
- Tier III requires the most intensive sampling to help determine why certain sites are not meeting biological criteria goals.

When using biological criteria to monitor a habitat, it is critical that physical and chemical measurements are also obtained and documented so that adequate comparisons of biological communities can occur. Salinity, depth, sediment grain size, and water quality (i.e. pH, temperature, DO, nutrients, and toxicants) can all affect biological communities and therefore must be taken into consideration when comparing one site to another for assessment of general system health or monitoring the progress of restoration efforts. In addition to discussion of the physical and chemical parameters listed above, use of and techniques to measure benthos, fish, submersed aquatic vegetation, phytoplankton, zooplankton, and epibenthos are described. The classification and characterization of reference conditions is also detailed and several case studies are provided as examples.

Griffith, L. M., R. C. Ward, G. B. McBride and J. C. Loftis. 2001. Data analysis considerations in producing 'comparable' information for water quality management purposes, 44 pp. Technical Report 01-01, U.S. Geological Survey, National Water Quality Monitoring Council. http://water.usgs.gov/wicp/acwi/monitoring/pubs/tr/nwqmc0101.pdf

Water quality monitoring is being used in local, regional, and national scales to measure how water quality variables behave in the natural environment. A common problem, which arises from monitoring, is how to relate information contained in data to the information needed by water resource management for decision-making. This is generally attempted through statistical analysis of the monitoring data. However, how the selection of methods with which to routinely analyze the data affects the quality and comparability of information produced is not as well understood as may first appear.

To help understand the connectivity between the selection of methods for routine data analysis and the information produced to support management, the following three tasks were performed.

- An examination of the methods that are currently being used to analyze water quality monitoring data, including published criticisms of them.
- An exploration of how the selection of methods to analyze water quality data can impact the comparability of information used for water quality management purposes.
- Development of options by which data analysis methods employed in water quality management can be made more transparent and auditable.

These tasks were accomplished through a literature review of texts, guidance and journals related to water quality. Then, the common analysis methods found were applied to portions of a river water quality dataset from New Zealand. The purpose of this was to establish how information changes as analysis methods change, and to determine if the information produced from different analysis methods is comparable.

The results of the literature review and data analysis are then discussed and recommendations are made addressing problems with current data analysis procedures. Options are listed through which to begin solving these problems and produce better information for water quality management.

It was found that null hypothesis testing is the most popular method through which to produce information, yet assumptions and hypotheses are loosely explained and alternatives rarely explored to determine the validity and comparability of the results. Other data analysis methods (using graphical, non-null hypotheses or Bayesian methods) that might be more appropriate for producing more comparable information are discussed, along with recommendations for further research and cooperative efforts to establish water quality data analysis protocols for producing information for

Hubbs, C. H. and K. F. Lagler. 1983. Fishes of the Great Lakes Region. The University of Michigan Press, Ann Arbor, MI.

Fishes of the Great Lakes Region offers detailed descriptions and identification tips for all 172 species of fish found throughout the Great Lakes Basin. Brief introductions to the general characteristics of each family are also provided. Very detailed descriptions of characteristic traits and accompanying pictures facilitate accurate identification of individuals to species. The geographic extent of each species is also presented as an additional aid to proper identification.

Lindbo, D. T. and S. L. Renfro. 2003. Riparian and Aquatic Ecosystem Monitoring: A Manual of Field and Lab Procedures. 4th ed. Saturday Academy's Student Watershed Research Project, Beaverton, OR.

The Student Research Watershed Project has developed a set of field and lab data collection procedures that has successfully translated scientific methodologies for use by non-scientists. The procedures were designed for use by students (grades 8 – 12) and can easily be adapted for volunteer efforts to collect baseline and restoration monitoring data for streamside and aquatic (in-stream) habitats. Methods for the collection of physical, chemical, and biological criteria are included. The manual covers the steps necessary to design a monitoring plan as well as a quality assurance project plan. Rationale behind and the steps involved in monitoring the following parameters are also included: stream flow, temperature, dissolved oxygen, pH, alkalinity, solids and turbidity, conductivity, phosphorus, nitrogen, chlorine, microbes, and macroinvertebrates. Information on the collection of information on in-stream habitat, riparian vegetation, stream reach mapping, photo monitoring, and soils is also included. Example data sheets are provided to assist in the systematic and complete recording of monitoring results by different parties.

Marcogliese, D. J. 2002. Protocols for measuring diversity: parasites of fishes in freshwater. Ecological Monitoring and Assessment Network Coordinating Office, Knowledge Integration Directorate of Environment Canada. http://www.eman-rese.ca/eman/ecotools/protocols/freshwater/parasites/intro.html

Parasites typically have complex life cycles and can often be used to indicate different aspects of host biology including diet, migration, recruitment, health, and phylogeny. They can also be used as indicators of stress and environmental contaminants. Parasites can be microscopic such as bacteria, fungi, protozoans, and myxozoans or macroscopic such as flukes, tapeworms, nematoads, and copepods. The lamprey eel is a large, famous parasite that had a devastating effect on large sportfishes of the Great Lakes. The protocols listed in this on-line resource include methods for sampling parasite host populations (i.e., fish). Information includes procedures for collecting, handling, and storing samples, identification keys, quality assessment/quality control (QA/QC) documentation, recommendations for using volunteers, and methods to analyze data. There is also a list of experts (in Canada) for those who require additional information and assistance.

Martin, J. L. 2001. Marine biodiversity monitoring: protocol for monitoring phytoplankton, 13 pp. A report by the Marine Biodiversity Monitoring Committee (Atlantic Maritime Ecological Science Cooperative, Huntsman Marine Science Centre) to the Ecological Monitoring and Assessment Network of Environment Canada, Environment Canada, St. Andrews, New Brunswick, Canada. http://www.eman-rese.ca/eman/ecotools/protocols/marine/phytoplankton/phyto_marine_e.pdf

Martin's report covers a variety of aspects concerning phytoplankton sampling in marine waters. She covers the some of the general ecology of marine phytoplankton including the abiotic factors that dictate species presence, absence, and abundance. These include water exchange throughout the area to be sampled, depth, water column stability, proximity to aquaculture sites, or other agriculture and industry. She also gives suggestions on certain places where sampling should be avoided as well as sampling frequency. Martin also covers several methods for obtaining quantitative and qualitative samples including some strengths and limitations of each sampling type. There is also a section on sample treatment and processing and several methods for preserving samples. Also of use to practitioners interested in using phytoplankton for monitoring, a variety of methods and equipment needed in the identification process are also introduced including references to identification manuals for different types of these microscopic algae.

McCobb, T. D. and P. K. Wieskel. 2003. Long-Term Hydrologic Monitoring Protocol for Coastal Ecosystems. United States Geological Survey Open-File Report 02-497. 97 pp. http://water.usgs.gov/pubs/of/2002/ofr02497/

The United States Geological Survey (USGS) and the National Park Service have designed and tested monitoring protocols implemented at Cape Cod National Seashore. The monitoring protocols are divided into two parts. Part one of the protocol discusses the objectives of the monitoring protocol and presents rationale for the recommended sampling program. The second part describes the field, data-analysis, and data-management, and variables that are to be taken into consideration when monitoring (e.g., sea level rise, climate change and urbanization). This protocol provides consistency when monitoring changes in ground-water levels, pond levels, and stream discharge. The monitoring protocol not only establishes a hydrologic sampling network but provides reasoning for measurement methods selected and spatial and temporal sampling frequency. Data collected during the first year of monitoring and hydrologic analyses for selected sites are presented. Long-term hydrologic monitoring procedures performed at the Cape Cod National Seashore may also assist set a template for deciphering findings of other monitoring programs.

Merritt, R. W. and K. W. Cummins, (eds.). 1996. An Introduction to the Aquatic Insects of North America. Third edition ed. Kendall/Hunt Publishing Company, Dubuque, IA, USA.

While the bulk of Merritt and Cummins is on identification of aquatic insects of North America, they include several chapters useful in project planning as well. Various experts in the field of aquatic insect collection and identification have submitted chapters on: the general morphology of aquatic insects, designing studies, collection techniques, aquatic insect respiration, habitat and life history, and the ecology and distribution of aquatic insects. The rest of the manual is devoted to identification keys for each family of aquatic insect found in North America with many detailed and useful pictures of identifying characteristics.

Since this book is continental in scope, it is suggested that practitioners first look for identification keys prepared for their local or regional waterways. This will reduce much confusion in the identification process by eliminating species that are not found locally. Any local aquatics expert or science librarian should be able to locate these materials. If local materials are not available, then Merritt and Cummins will be useful, however, be sure to check the distribution of species identified whenever possible.

Mueller, D. K., J. D. Martin and T. J. Lopes. 1997. Quality-control design for surface-water sampling in the national water-quality assessment program, 8 pp plus appendices. Open-File Report 97-223, U.S. Geological Survey, Denver, CO. http://water.usgs.gov/nawqa/protocols/OFR97-223/ofr97-223.pdf

This brief report summarizes the quality control methods employed for sampling under the national water-quality assessment program. Although this document is not a complete quality assurance program plan (QAPP), the information included may be useful for monitoring programs developing sampling protocols for contaminated areas. The use of field blanks, trip blanks, field-matrix spikes, and analysis replicates are discussed.

Murphy, B. R. and D. W. Willis, (eds.). 1996. Fisheries Techniques: Second edition. American Fisheries Society, Bethesda, MD, USA.

Murphy and Willis have edited the industry standard for fisheries sampling techniques. A variety of experts in the field have written chapters that cover all aspects of how to sample and measure fish. Topics include: planning for sampling, data management and statistical techniques, safety, habitat measurements, care and handling of samples, passive and active capture techniques, collection and identification of eggs and larvae, sampling with toxics, invertebrates, tagging and marking, acoustic assessment, field examination and measurements, age and growth rate determination, diet, underwater observation, creel sampling, commercial surveys, and socioeconomic measurements.

Ossinger, M. 1999. Success standards for wetland mitigation projects - a guideline, 31 pp. Washington State Department of Transportation, Environmental Affairs Office. http://pnw.sws.org/forum/success.PDF

This report offers guidance and examples on how to write specific success criteria for mitigation and restoration projects. Though it was designed to address mitigation projects in the Pacific Northwest, its information and approach make it useful throughout the United States. It outlines the steps necessary for planning the monitoring and management of a mitigation/restoration project. Guidance in writing the following program elements is provided: how to set project goals, how to select specific project objectives (i.e. what functions or values will the mitigation/restoration provide), how to select performance objectives (i.e. what structural characteristics need to be in place to provide desired functions), selection of success standards (measurable benchmarks used to determine success of performance objectives), monitoring method (how will the success standard be measured), contingency measure (what to do if the success standards are not met). Several examples are provided of each of these steps. These examples, while not all-inclusive, facilitate the application of this method to diverse areas and project types.

Paterson, M. 2001. Protocols for measuring biodiversity: zooplankton in freshwaters. Ecological Monitoring and Assessment Network Coordinating Office, Knowledge Integration Directorate of Environment Canada. http://www.eman-rese.ca/eman/ecotools/protocols/freshwater/zooplankton/intro.html

Patterson has compiled an extensive literature review on the topic of zooplankton sampling in freshwater environments. This review covers the topics of selecting sample sites within a water body, preparing a site description, sampling frequency, and includes a list of other environmental factors that need to be measured that affect zooplankton and should be measured in conjunction with it. There is also a brief review of field sampling protocols for various sizes of zooplankton and methods for sample preservation as well as a list of literature reviewing sampling methods in greater detail. Patterson also lists laboratory techniques for identification and biomass estimation directing readers to additional literature as needed. Data analysis techniques for comparing abundance, community measures, and multivariate methods for community analysis are also described. One of the most useful sections of this document for restoration practitioners developing monitoring programs will be the extensive literature review Patterson has conducted as well as the thorough list of references available for freshwater zooplankton identification.

Ribic, C. A., T. R. Dixon and I. Vining. 1992. Marine debris survey manual, 92 pp. NOAA Technical Report NMFS 108, NOAA National Marine Fisheries Service, Seattle, Washington.

Author Introduction. Over the last several years, concern has increased about the amount of man-made materials lost or discarded at sea and the potential impacts to the environment. The scope of the problem depends on the amounts and types of debris. Once problem in making a regional comparison is the lack of a standard methodology. The objective of this manual is to discuss designs and methodologies for assessment studies of marine debris.

This manual has been written for managers, researchers, and others who are just entering this area of study who seek guidance in designing marine debris surveys. Active researchers will be able to use this manual along with applicable references herein as a source for design improvement. To this end, the authors have synthesized their work and reviewed survey techniques that have been used in the past for assessing marine debris, such as sighting surveys, beach surveys, and trawl surveys, and have considered new methods (e.g., aerial photography). All techniques have been put into a general survey planning framework to assist in developing different marine debris surveys.

Steyer, G. D., R. C. Raynie, D. L. Steller, D. Fuller and E. Swenson. 1995. Quality management plan for Coastal Wetlands Planning, Protection, and Restoration Act **monitoring** program, 8 pp. Open-File Report 95-01, Louisiana Department of Natural Resources, Coastal Restoration Division, Baton Rouge, LA. http://www.lacoast.gov/cwppra/reports/MonitoringPlan/index.htm

This document is a Quality Assurance Project Plan (QAPP) used for all restoration projects conducted under the Coastal Wetlands Planning, Protection, and Restoration Act (CWPPRA) and similar legislation for coastal Louisiana. Though it does not explain how to develop a QAPP for new wetland restoration monitoring projects, it can be used as a template by which monitoring plans can be developed. Detailed explanations of how to data is to be collected, acceptable error rates, and methods to ensure high quality data is collected, recorded, and analyzed are included. Quality assurance guidelines are provided for field data collection, remote sensing and airphoto interpretation, computer systems to be used, data entry procedures, data review, laboratory procedures, and documentation and reporting. Any restoration practitioner attempting to develop a monitoring plan or preparing a QAPP for their project may find this document a valuable example to follow.

Trippel, E. A. 2001. Marine biodiversity monitoring: protocol for monitoring of fish communities, 10 pp. A report by the Marine Biodiversity Monitoring Committee (Atlantic Maritime Ecological Science Cooperative, Huntsman Marine Science Centre) to the Ecological Monitoring and Assessment Network of Environment Canada, Environment Canada, St. Andrews, New Brunswick, Canada. http://www.eman-rese.ca/eman/ecotools/protocols/marine/fishes/intro.html

Trippel reviews the standard protocols used in sampling fish communities in marine environments for biodiversity and abundance studies performed by Environment Canada. Trippel cites a preference for stratified random sampling as it increases the homogeneity of catches within each stratum sampled compared to a purely random or fixed station sampling strategy. The need for a stratified approach is re-enforced through the measurement of depth, temperature, salinity and other abiotic factors that affect fish species presence and abundance. Trippel also addresses the issue of sampling frequency, as some migratory species may only be present in a certain area for a short period of time. Knowledge of the life cycle and migratory patterns of target species must be taken into consideration when designed any sampling effort. Additionally, frequent sampling in early years may allow for the determination of patterns in the timing of target species presence so that sampling may be cost effectively scaled back in later years. The Canadian sampling efforts also prefer the use of bottom trawls as opposed to gill nets or baited hooks as the trawls capture a greater diversity of species and body sizes as well as allowing for the calculation of abundance since the area of the trawl is known. However, topographically diverse areas may exclude the use of bottom trawls. Additionally, bottom trawls can be expensive, as they require the use of a large vessel with numerous scientific and technical crewmembers.

In addition to fish-related measurements such as number of individuals, length, weight, sex, and species, abiotic factors must also be measured for each trawl to ensure the proper comparison of strata. These include: cruise, set, vessel, stratum, sample (or station) number, date, positions, time, distance, speed, depth (minimum, maximum), auxiliary equipment, warp, wind force, current, and water temperature and salinity at specific depths.

U.S. EPA. 1996. The volunteer monitor's guide to quality assurance project plans, 59 pp. EPA 841-B-96-003, U.S. Environmental Protection Agency, Washington, D.C. http://www.epa.gov/volunteer/qapp/vol_qapp.pdf

Author Abstract. The Quality Assurance Project Plan, or QAPP, is a written document that outlines the procedures a monitoring project will use to ensure that the samples participants collect and analyze, the data they store and manage, and the reports they write are of high enough quality to meet project needs.

U.S. Environmental Protection Agency-funded monitoring programs must have an EPA-approved QAPP before sample collection begins. However, even programs that do not receive EPA money should consider developing a QAPP, especially if data might be used by state, federal, or local resource managers. A QAPP helps the data user and monitoring project leaders ensure that the collected data meet their needs and that the quality control steps needed to verify this are built into the project from the beginning.

Volunteer monitoring programs have long recognized the importance of well-designed monitoring projects; written field, lab, and data management protocols; trained volunteers; and effective presentation of results. Relatively few programs, however, have tackled the task of preparing a comprehensive QAPP that documents these important
elements. This document is designed to help volunteer program coordinators develop such a QAPP.

U.S. EPA. 2002. Assessing and monitoring floatable debris, 49 pp. EPA-842-B-02-002, Oceans and Coastal Protection Division, U.S. Environmental Protection Agency, Washington, D.C.

This manual is designed to help states, tribes, and local units of government develop assessment and monitoring programs for floating debris (trash) in coastal waterways. The manual is broken into five parts with appendices. Part 1 introduces the impacts of floating debris on the aquatic environment and describes current legislation to address the issue. Part 2 discusses the types and origins of trash in coastal waters. Part 3 describes a variety of plans and programs that have been developed and implemented in various coastal areas to assess and monitor trash. Part 4 provides recommendations for developing assessment and monitoring programs that were originally presented in NOAA's *Marine Debris Survey Manual* and the EPA's *Volunteer Estuary Monitoring: A Methods Manual*. Part 5 provides methods to prevent and mitigate the problems associated with floating debris. The Appendices include information on international coastal cleanup efforts, a National Marine Debris Monitoring Program data card, storm drain stenciling cards, and surveys from the *Marine Debris Survey Manual*.

U.S. EPA. 2002. Guidance for quality assurance project plans, 57 pp. EPA QA/G-5, U.S. Environmental Protection Agency, Washington, D.C. http://www.epa.gov/swerust1/cat/epaqag5.pdf

This document is designed to guide those involved with Quality Assurance Project Plan (QAPP) development for environmental monitoring and data analysis. It describes various issues to be addressed when preparing a QAPP, with an emphasis on systematic planning. The report is divided into three chapters. An introduction that describes the target audience and the importance of systematic sampling. A second chapter describes all of the pieces of a QAPP, focusing on environmental data collection and analysis. The third chapter describes methods for developing QAPPs for projects that use previously collected data.

The importance of having high quality, reliable data cannot be over estimated. Use of this document or the EPA's *Volunteer Monitor's Guide to Quality Assurance Project Plans*, will help restoration practitioners develop monitoring plans that will provide the high quality, reliable data necessary to monitor and manage restoration projects. The step-by-step approach of this document takes restoration practitioners through the entire planning, data collection, data analysis, and reporting process from start to finish. Ensuring that all aspects of the monitoring project are well thought out ahead of time and that contingency plans are in place.

U.S. EPA. 2001. National coastal assessment: field operations manual, 72 pp. EPA 620/R-01/003, U.S. Environmental Protection Agency, Office of Research and Development, National Health and Environmental Effects Research Laboratory, Gulf Ecology Division, Gulf Breeze, Florida. http://www.epa.gov/emap/nca/html/docs/c2kfm.pdf

This manual presents a standard set of field data and sample collection techniques for the EPA's National Coastal Assessment, the current state of the EPA's Environmental Assessment Program (EMAP). Though the methods collected here are geared specifically toward this program, some restoration practitioners may find them useful particularly in areas where restoration projects overlap existing monitoring activities, as this will facilitate the comparison of current data with historic trends. The measurement protocols described in this manual include:

- sediment contaminant concentrations
- sediment toxicity
- benthic species composition
- sediment characteristics
- water column dissolved nutrients
- chlorophyll *a* concentrations
- total suspended solids
- surface and bottom dissolved oxygen, salinity, temperature, and pH
- water clarity
- contaminant levels in fish and shellfish
- external pathological condition of fish
- fish community structure

A suggested monitoring routine is presented for data collection at each site to maximize sampling efficiency while in the field. Of particular use to the beginning restoration-monitoring practitioner, a list of necessary field and laboratory equipment is also provided in an appendix.

U.S. EPA. 2001. Nutrient criteria technical guidance manual: estuarine and coastal marine waters. United States Environmental Protection Agency, Office of Water. http://www.epa.gov/waterscience/standards/nutrients/marine/index.html

This manual provides and introduction and definition to estuaries and coastal systems of the United States, focusing primarily on marine-estuarine systems and the problem and scope of nutrient over-enrichment in America's estuaries. Techniques for classifying estuaries for comparison of one system to another are outlined. Variables and measurement methods to assess and monitor estuarine and marine conditions are provided and divided into two groups: causal and response. This allows practitioners to choose which types of measurements are best suited toward their needs and abilities. Measurements discussed include: nutrients (nitrogen and phosphorus), water clarity, dissolved oxygen, benthic macrofauna, phytoplankton, sediments, primary productivity, macroalgae, seagrasses and SAV. An overview of existing databases from across the US is given along with guidance on the development of sampling designs, quality assurance and control, and statistical analyses. Methods to determine reference condition, nutrient and algal monitoring criteria, and methods for using this information to help protect water quality are also discussed in detail. Several case studies are included as examples of how these criteria have been implemented in estuaries in California, New York, Florida, Washington state, and areas around the Chesapeake Bay.

U.S. EPA. 2001. Volunteer Estuary Monitoring: a Methods Manual. United States Environmental Protection Agency, Office of Water. http://www.epa.gov/owow/estuaries/monitor/

Partial Author Abstract. This document presents information and methodologies specific to estuarine water quality. The first eight chapters of the manual deal with typical issues that a new or established volunteer estuary monitoring program might face:

- Understanding estuaries, what makes them unique, the problems they face, and the role of humans in solving the problems
- Establishing and maintaining a volunteer monitoring program
- Working with volunteers and making certain that they are well-positioned to collect water quality data safely and effectively
- Ensuring that the program consistently produces data of high quality, and
- Managing the data and making it available to data users

The remaining chapters focus on several water quality parameters that are important in determining the health of an estuary. These chapters are divided into three units, which characterize the parameters as measures of the chemical, physical, or biological environment of the estuary.

The significance of each parameter and specific methods to monitor it are detailed in a step-by-step fashion. The manual stresses proper quality assurance and quality control techniques to ensure that the data are useful to state agencies and any other data users.
References are listed at the end of each chapter. Appendices containing additional resources are also supplied. These references should prove a valuable source of detailed information to anyone interested in establishing a new volunteer program or a background resource to those with already established programs.

U.S. Geological Survey. variously dated. National field manual for the collection of water-quality data: U.S. Geological Survey Techniques of Water-Resources Investigations. Book 9, chapts. A1-A9. http://pubs.water.usgs.gov/twri9A

The U.S.G.S. National Field Manual was designed to promote the consistency of scientific methods and procedures used to collect water quality data. Individual chapters from this electronically available document can be downloaded from the government website listed above. The manual includes information on methods to plan and prepare for water sampling, selection and cleaning of equipment, collection and processing of water samples, and appropriate field methods for collection of temperature, dissolved oxygen, conductivity, pH, redox potential, alkalinity, and turbidity. Methods for collecting and analyzing biological indicators of water quality such as bacterial and viral indicators of fecal contamination are also included as are guidelines for analysis of bottom materials and field safety practices.

Virginia Citizen Water Quality Monitoring Program. 2003. Virginia citizen water quality monitoring program methods manual, 81 pp plus appendices. Methods Manual, Virginia Department of Environmental Quality, Richmond, VA. http://www.deq.state.va.us/cmonitor/pdf/cmonman.pdf

This document provides guidance on the selection and use of available water quality monitoring methods commonly used by citizen volunteer groups in the state of Virginia. It is not a comprehensive list of every available method, it is intended as an introduction to sampling for the uninitiated. The manual opens with information on planning a monitoring program and developing a quality assurance project plan (QAPP). The following sections explain the pros and cons of various methods to monitor chemical, biological, and physical parameters of the water column and associated habitats such as submerged aquatic vegetation and riverine forests. A variety of appendices also provide lists of contacts, equipment suppliers, and other resources useful to citizen monitoring efforts. Although this manual is designed for use in Virginia, monitoring volunteers in other areas may also find it useful.

Walk, M. F. 2003. Lake volunteer water quality monitoring manual, 91 pp. Massachusetts Water Watch Partnership, University of Massachusetts, Amherst, MA. http://www.umass.edu/tei/mwwp/acrobat/lake%20manual.pdf

The Massachusetts Water Watch Partnership (MassWWP) has developed this guidebook to introduce individuals and/or lake associations to water quality monitoring. It contains instructions on how to start a successful monitoring program including information on proper study design, building community support for the monitoring program, field and lab techniques, and quality control. Detailed sampling and measuring protocols are provided for water temperature and transparency, dissolved oxygen, pH, alkalinity, total phosphorus, and chlorophyll. These protocols reflect MassWWP's suggested data quality requirements and may not be appropriate for every monitoring effort. The manual is divided into two main parts with appendices. Part One provides background information on watershed ecology and how to design a monitoring program. Part Two describes each of the water quality indicators covered and procedures for analysis in the field and laboratory. The appendices include references for further reading, a copy of the 2000 Massachusetts Surface Water Quality Standards, a list of agencies and organizations that can provide monitoring assistance, a list of recommended equipment and supplies, and examples of typical lake surveys. Protocols for chemical and physical parameters as well as suggested biological parameters (including some for rivers) can be accessed directly at: http://www.umass.edu/tei/mwwp/protocols.html.

Wenner, E. L. and M. Geist. 2001. The National Estuarine Research Reserves Program to Monitor and Preserve Estuarine Waters. *Coastal Management* 29: 1-17.

The National Estuarine Research Reserve (NERR) sites in 1992 coordinated a program that would attempt to identify and track short-term variability and long-term changes in representative estuarine ecosystems and coastal watersheds. Water quality parameters that were monitored include: pH, conductivity, temperature, dissolved oxygen, turbidity, and water level. Standardized protocols were also used at each site so that sampling, processing, and data management techniques were consistent among sites. Statistical techniques are being used to identify periodicity in water quality variables. Periodic regression analysis indicated that diel periodicity in dissolved oxygen is a larger source of variation than tidal periodicity at sites with less tidal amplitude. Authors of this document stress how understanding the functions of estuaries and how they change over time will help predict how these systems respond to change in climate and anthropogenic sources.

APPENDIX III: LIST OF WATER COLUMN EXPERTS

The experts listed below have provided their contact information so practitioners may contact them with questions pertaining to the restoration or restoration monitoring of this habitat. Contact information is up-to-date as of the printing of this volume. The list below includes only those experts who were 1) contacted by the authors and 2) agreed to submit their contact information. Some of those listed also reviewed the associated habitat chapter. In addition to these resources, practitioners are encouraged to seek out the advice of local experts as well faculty members and researchers at colleges and universities. Engineering, planning, and landscape architecture firms also have experts on staff or contract out the services of botanists, biologists, ecologists, and other experts whose skills are needed in restoration monitoring. These people are in the business of providing assistance in restoration and restoration monitoring and are often extremely knowledgeable in local habitats and how to implement projects on the ground. Finally local, state, and Federal environmental agencies also house many experts who monitor and manage coastal habitats. In addition to the National Oceanic and Atmospheric Administration (NOAA), the Environmental Protection Agency (EPA), the Army Corps of Engineers (ACE), Fish and Wildlife Service (FWS), and the United States Geologic Survey (USGS) are important Federal agencies to contact for assistance in designing restoration and monitoring projects as well as potential sources of funding and permits to conduct work in coastal waterways.

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CHAPTER 3: RESTORATION MONITORING OF CORAL REEFS

Andrew Bruckner, NOAA National Marine Fisheries Service[1]
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INTRODUCTION

Shallow-water coral reefs (Figure 1) are diverse ecosystems found in warm, clear, shallow tropical and sub-tropical oceans, primarily between the latitudes of 30˚ north and south, in the Western Atlantic, Indian, and Pacific Oceans. The United States has jurisdiction over an estimated 19,700 km^2 of coral reefs, not including the Freely Associated States (Turgeon et al. 2002). U.S. reefs are found in the:

- Western Atlantic
- Caribbean
- Gulf of Mexico off Florida (Florida Keys, east coast of Florida and Florida Middle grounds)
- Puerto Rico
- U.S. Virgin Islands
- Navassa Island, and
- On the continental shelf about 100 miles south of the Texas/Louisiana border (e.g., the Flower Garden Banks National Marine Sanctuary).

U.S. Pacific reefs are found off the:

- Hawaiian Archipelago
- American Samoa
- Commonwealth of the Northern Mariana Islands, and
- Guam

In the U.S. Pacific Remote Island areas, coral reefs include:

- Baker
- Howland
- Jarvis Islands (i.e. table reefs)
- Johnston
- Kingman
- Palmyra
- Rose, and
- Wake Atolls

In addition, well-developed coral reefs are associated with the Freely Associated States (Palau, Marshall Islands, and the Federated States of Micronesia).

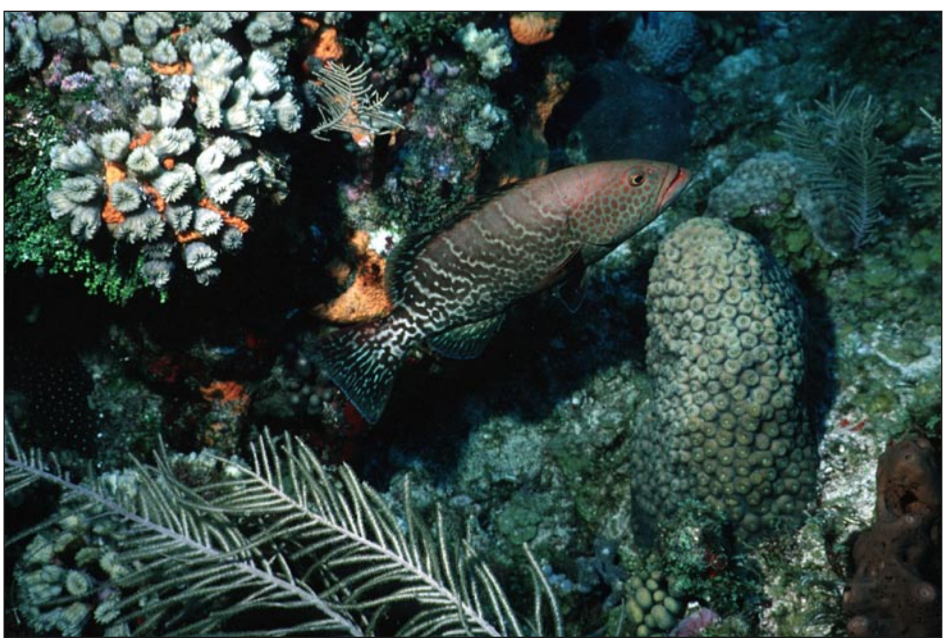

Figure 1. Star coral reef (*Montastrea cavernosa*) with a tiger grouper (*Mycteroperca tigris*). Photo courtesy of Andrew Bruckner, NOAA National Marine Fisheries Service.

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Coral reefs discussed in this chapter consist of consolidated limestone or unconsolidated rubble constructed primarily from the skeletal remains of invertebrates and algae. Living corals and other benthic organisms form a thin veneer that overlies a limestone framework deposited over thousands of years by their ancestors, and solidified by the combined processes of cementing coralline algae, mechanical action of waves, bioerosion from boring sponges and other organisms, and the chemical action of rainwater. Reef-building scleractinian corals are the dominant organisms responsible for most of the framework growth, followed by coralline algae on wave-exposed reef slopes, and green algae (e.g., *Halimeda*) in backreef and lagoonal depositional zones. Other important organisms contributing sediments to reef structure include mollusks, foraminiferans, and echinoderms.

Reefs can be classified according to their geological history, shape, position relative to land masses, and materials from which they are constructed. Although there is continual variation from one reef type to another, most coral reefs can be merged into three broad categories: fringing reefs, barrier reefs, and atolls. There are also several specialized reef types such as platform reefs, patch reefs, table reefs, and bank reefs. Fringing reefs are mostly located close to shore, while barrier reefs are typically offshore, at the edge of the continental shelf. Barrier reefs are separated from land by a lagoon that may contain patch reefs, mangrove islands, grass beds, and soft bottom algal flats. Most atolls are annular reefs enclosing a central lagoon that develop at or near the surface of the sea, beginning as fringing reefs around high islands and gradually becoming more distant from land as the island subsides and reefs grow upward. Bank reefs are common in the Caribbean, and formed on offshore banks or platforms in response to sea level fluctuations over the last 8,000 years since the last ice age. Table reefs are similar to atolls except they do not enclose a central lagoon.

Coral reefs contain several zones such as the backreef, reef crest, and fore reef slope that are characterized by their depth, wave exposure, structure, and biotic communities. The dominant sessile invertebrates found in all zones, except in areas of extreme wave exposure, are scleractinian corals. Scleractinian corals are similar in structure to sea anemones, with each polyp having six or multiples of six tentacles. They are unique, however, in that they produce an external calcium carbonate skeleton and often form colonies consisting of thousands of interconnected polyps. Scleractinian coral colonies may be hundreds to thousands of years old and form massive structures several to tens of meters in height. Other dominant cnidarians found on coral reefs are the octocorals, which include:

Gorgonians (e.g., sea fans)
Soft corals (leather corals)
Blue coral (*Heliopora*)
Organ pipe coral (*Tubipora*), and
Sea pens

Unlike scleractinian corals, octocorals have eight pinnately-branched tentacles, and most lack an external skeleton. *Heliopora* is the only shallow-water octocoral that forms a massive aragonite skeleton similar in structure to scleractinian corals, and *Tubipora* has a skeleton that consists of a series of parallel polyps encased in calcareous tubes of fused sclerites. Gorgonians have an internal skeleton consisting of a proteinaceous (gorgonin) central axial skeletal rod and separate embedded calcareous spicules, while soft corals possess soft, fleshy, or leathery bodies with embedded calcareous spicules. Other sessile organisms, such as sponges (Figure 2), tunicates, and bryozoans also contribute to the complexity of the reef's structure (Holliday 1989; Sorokin 1993).

The major factors controlling the global distribution of coral reefs are light and temperature, with water turbidity currents, storms, wave exposure, sedimentation, and salinity affecting

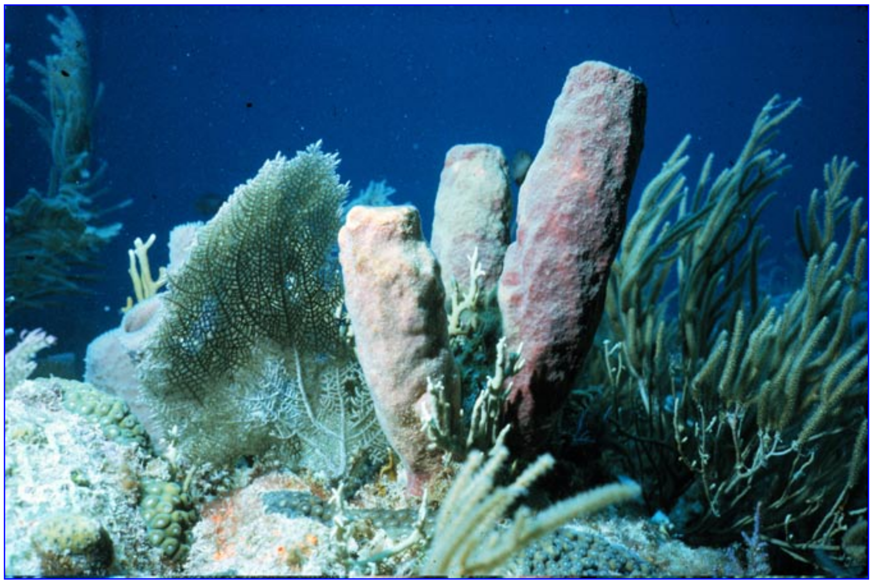

Figure 2. Sponge (Porifera) and sea fan (Gorgonia) on a coral. Photo courtesy of B. Walden, NOAA Research-National Undersea Research Program. Publication of NOAA Central Library. http://www.photolib.noaa.gov/nurp/nur03002.htm

species diversity and abundance within specific coral reef habitats. Because of the dependence of zooxanthellae on light for photosynthesis, reef-building corals are restricted to depths of about 70 m in clear water. Water temperature on most coral reefs remains fairly constant throughout the year, with optimal growth at temperatures of 22-30°C. Temperatures on some subtropical reefs, such as in the Florida Keys and Flower Gardens, will drop to 16°C in winter, and in some extreme shallow environments such as tidepools, temperatures may increase to over 34°C. While certain corals can tolerate even lower temperatures for short periods, rapid declines in temperature or prolonged colder than normal temperatures may result in extensive coral mortality. Heat stress can also lead to colony death. Temperature increases of 1-2°C above the long-term average for one to two weeks is known to trigger bleaching, causing corals to turn white due to the loss of the symbiotic zooxanthellae (Hoegh-Guldberg 1999; Westmacott et al. 2000; Salm and Coles 2001). Other stressors such as high levels of ultraviolet (UV) radiation, reduced salinity, and low temperatures also cause localized bleaching, although temperature increases are believed to be the most critical factor responsible for global and regional bleaching events (Wilkinson 2004). Although corals can recover from bleaching, prolonged higher than normal temperatures and other stressors may increase susceptibility to disease and can result in partial to total colony mortality.

ECONOMIC VALUE OF CORAL REEFS

Coral reefs provide economic and environmental services to millions of people by protecting shorelines; providing sources of food, building materials, and pharmaceuticals; and creating employment, recreational, and tourism opportunities. The estimated global economic value of coral reef ecosystems is about $375 billion per year (Costanza et al. 1997). In 2000, an estimated 10.5 million people resided in U.S. coastal areas adjacent to shallow-water corals reefs and another 45 million tourists visited these reefs (Turgeon et al. 2002). In addition, the annual ex-vessel[3] value of commercial fisheries associated with U.S. coral reefs is estimated at over $137.1 million (NMFS 2001). In southeast Florida, 18 million people participated in reef-related activities during 2001, and these reefs are estimated to have an asset value of $7.6 billion (Johns et al. 2001). Recreational fishers, divers, and snorkelers that use the natural reef in Broward County, Florida are willing to pay $83.6 million per year to maintain their natural reefs, $55.9 million per year to maintain the

[3] When a commercial fishing boat lands or unloads a catch. For example, the price received by a captain for the catch is known as the ex-vessel price.

existing artificial reefs, and $15.7 million per year to add new artificial reefs (Johns et al. 2001).

HUMAN IMPACTS TO CORAL REEFS

Coral reefs are declining in many areas of the world due to steadily increasing threats from direct human pressures and indirect effects of global climate change. The three major human stressors to corals reefs worldwide are overfishing, sedimentation, and land-based sources of pollution, exacerbated locally by other stressors such as:

- Destructive fishing practices
- Oil, metal, and/or chemical pollution
- Coral mining
- Uncontrolled tourism, and
- Physical damage from ship groundings and anchors

There are various natural stressors that also impact coral reefs and are discussed primarily in the structural and functional characteristics sections of this chapter. Some of these natural stressors include outbreaks of coral eating predators (e.g., crown-of-thorns sea star), coral diseases, bleaching, tropical storms and hurricanes, and unusual rainfall events. Until recently, most reefs recovered fairly rapidly from these natural stressors. When combined with cumulative human pressures, however, recovery may be significantly delayed or prevented. Once human impacts are removed ecological recovery may still take many years, depending on the extent and type of damage, duration of the impact, and diversity and complexity of the affected ecosystem.

Despite the longevity and apparent natural resilience of corals and the reefs they construct, both are extremely vulnerable to destruction by human activities, either gradually through degraded habitat quality, or suddenly through catastrophic damage from vessel groundings, toxic spills, or habitat destruction. In some cases, degraded reefs have undergone phase shifts from highly productive coral-dominated systems to algal reefs that persisted for more than 20 years. In these situations, ecological recovery may be facilitated through mitigation or restoration efforts. However, for restoration to be effective, it is imperative that resource managers:

1) Understand the causes and effects of human-induced disturbances
2) Properly assess these damages
3) Eliminate or reduce the stressors that contribute to the decline, and
4) Develop a subsequent restoration approach that addresses the specific needs of the particular site, prior to undertaking restoration efforts

Finding appropriate solutions to a particular damage scenario is often hampered by an incomplete understanding of the ecological effects of human impacts as well as processes and factors that contribute to natural reef recovery. Hypothesis-driven ecological studies and quantitative, long-term monitoring programs are important to answer these critical questions. Baseline monitoring data can be used to help identify and develop appropriate components of the restoration approach, develop quantifiable success criteria, and evaluate the efficacy of the restoration effort. This chapter presents a brief overview of human-induced stressors that impact reefs, management and restoration actions that may be undertaken to mitigate the impacts associated with these stressors, and monitoring approaches that are currently being used to document coral reef condition and effectiveness of management and restoration actions.

Pollution

Land-based sources of pollution

Pollution, including eutrophication and sedimentation associated with land-based activities, has been associated with the degradation of water quality and coral reef health and diversity (Lapointe et al. 2000). Some of the sources of pollution include improper coastal development; dredging and beach renourishment; land clearing for agriculture; discharge of untreated sewage, industrial waste, agrochemicals, and pharmaceuticals; and chemical and oil spills. Potential impacts to coral reef ecosystems from these stressors include:

- Poisoning sensitive species
- Altering species composition and distribution due to smothering and reduced light penetration
- Disrupting critical ecological and endocrine functions such as reproduction, coral/zooxanthellae symbiosis, and photosynthesis
- Impeding the settlement, growth, and survival of stony corals and other benthic invertebrates
- Enhancing the growth of competitive macroalgae and phytoplankton, and
- Increasing the prevalence and virulence of disease-causing pathogens and reducing the resistance and resilience of reef-building corals

Marine-based sources of pollution

In addition to land-based sources of pollution, marine pollution can kill existing benthic communities and retard recruitment. Excessive sedimentation generated by offshore dredging; ocean dumping; oil, gas, and mineral extraction; and certain types of fishing gear such as bottom trawls can cause increased turbidity as well as physical injuries, burial, and smothering of corals (Blair et al. 1990; Lirman et al. 2003). Numerous chemicals can enter coral reef habitats through industrial effluent, vessel discharge, and oil and chemical spills. Many reefs are also inundated by large amounts of human-made debris lost by commercial fishing operations or emanating from other marine and terrestrial sources. These objects degrade reef health by abrading, smothering, and dislodging benthic organisms and entangle marine mammals, turtles, birds, and pelagic fishes.

Coral reefs are increasingly vulnerable to invasion by alien species introduced via discharge of ballast water, releases from aquaria and aquaculture operations, and fouling organisms on ships hulls and marine debris. Alien species invasions have led to fundamental changes in natural communities as a result of their superior competitive ability, lack of predators, and introduction of parasites and diseases that commonly accompany them. One of the best examples of alien introductions into coral reef communities is in Hawaii, where several species of invasive, nonindigenous marine algae were introduced for commercial aquaculture and subsequently abandoned, yet are proliferating throughout shallow environments and pose a severe threat to nearshore reefs (Squair et al. 2003). As alien algae spreads, it smothers areas dominated by corals and native algae, and reef habitats rapidly shift from diverse coral communities to monotypic stands of alien algae. The loss of corals may affect fish diversity and abundance, and without intervention, a once healthy reef may become a highly degraded system with few surviving corals and fish (Stimson et al. 2001).

Overfishing and Destructive Fishing

Coral reef fisheries support and sustain communities by providing food and income, and play a central social and cultural role in many island communities. Recently, many fisheries have become unsustainable due to human population growth, the emergence of export fisheries, and use of more efficient fishing equipment. Overfishing of high-value species has been documented on nearly all U.S. inshore reefs. Localized depletions of key species such as groupers, snappers, and parrotfish may have impacts on other members of the reef community. In particular, overfishing of herbivorous fish has been linked to "phase-shifts" from high-diversity, coral-dominated systems to low-productivity, algal-dominated communities (Fossaa et al. 2002; Turgeon et al. 2002). Excessive fishing pressure on predatory fish may also accelerate bioerosion of corals by releasing their invertebrate prey (e.g., corallivorous snails and sea stars) from predation pressure. Destructive practices, such as cyanide and dynamite fishing and the use of small mesh gill nets and bottom trawls, can damage reef habitats by breaking and dislodging corals and other sessile invertebrates, resuspending sediments, and increasing turbidity.

Recreational Overuse

Coral reefs are a major water attraction for tourists visiting the tropics and subtropics, and their presence contributes significantly to the economy of many coastal communities. In many countries, including the United States, coral reefs have been exploited to support the growth in tourism. The impacts include increased development in the form of hotels, marinas, restaurants, roads, airports, and consequently increased sedimentation as a result of beach nourishment and channel dredging projects, and nutrient input from septic systems, golf courses, and gardens associated with hotels (Sudara and Nateekarnchanalap 1988; Hawkins and Roberts 1994; Turgeon et al. 2002). Most tourists also visit popular dive, snorkel, and fishing sites, which may lead to increased boating accidents, habitat damage from anchors, trampling and diver contact, illegal and damaging fishing practices (e.g., spearfishing), increased trash, and removal of shells and corals for souvenirs and curios.

Physical Damage

Commercial and recreational vessels striking coral reefs cause localized damage to shallow coral reefs. Impacts include fracturing and removal of the three-dimensional reef structure, thereby crushing and dislodging corals and other sessile invertebrates, uprooting seagrasses and displacing resident fishes (Precht et al. 2001). Propeller scarring and other physical impacts from small recreational and fishing boats and anchors is more frequent and, cumulative damage to corals and associated seagrass beds can be significant in areas of high recreational use. Although less frequent, large vessel groundings cause more insidious damage, including the fracturing of the underlying reef structure as well as collateral damage during salvage and removal of the vessel which may increase the footprint of the original scar. Secondary impacts may also include scarring and abrading of previously uninjured resources and increased sedimentation (sedimentation discussed in 'Marine Pollution' section) as waves and currents disperse rubble produced in the original grounding. Some affected habitats will not recover without direct, and often expensive, human intervention, for activities such as direct removal of debris or vessels, emergency triage of injured animals, and other restoration strategies to enhance recovery of benthic communities (Precht et al. 2001).

RESTORATION EFFORTS

Most previous restoration projects in the United States have focused on physical damage caused by humans, including vessel groundings, harbor dredging, and other discrete shoreline modification projects. Emergency restoration efforts associated with vessel groundings should be taken as soon as possible following an incident to reduce the overall extent of the injury. This may include righting and reattachment of displaced and broken coral (Figure 3), removal and stabilization of loose rubble, and repair of

Figure 3. A diver prepares to reattach an elkhorn coral fragment on Mona Island, Puerto Rico. Photo courtesy of Erik Zobrist, NOAA Restoration Center. http://www.photolib.noaa.gov/habrest/r0000732.htm

structural fractures (Precht 1998). The degree of damage by ship groundings or other physical disturbances may set practical limits on the scope of the restoration. Factors that should be considered when designing a restoration strategy include the:

- Costs to conduct various alternative approaches
- Extent to which each alternative will prevent future injury
- Likelihood of success of each alternative, and
- Extent to which each alternative is likely to return the injured natural resource and services to pre-damage state (Precht et al. 2001)

As Federal resource trustees for United States coral reef environments, the National Oceanic and Atmospheric Administration (NOAA) has been involved in a number of major ship grounding restoration efforts within Federal waters (especially in national marine sanctuaries). NOAA's Office of Response and Restoration and the NOAA Restoration Center, in partnership with Federal, state, and local agencies as well as non-governmental and non-profit organizations, have also assessed damaged reefs caused by hazardous material spills, recreational and commercial vessel groundings, and anchor damage, and implemented coral reef restoration projects in attempt to speed up recovery of the structure and function of the reef after these impacts. These efforts have often spanned years and required large sums of money that may be recovered from responsible parties. Restoration efforts involve activities ranging from initial response to damage assessment, litigation or cooperative settlement for damages, restoration planning, emergency repairs, and subsequent compensatory restoration activities. NOAA continues to provide financial and technical assistance for various restoration efforts in coral reef and other coastal habitats throughout the United States and its territories.

Several Federal statutes provide the United States government with the authority to recover resource damages caused by the grounding of vessels on coral reefs. A natural resource damage assessment (NRDA) process is used to identify and quantify natural resource injury, determine damages, and implement appropriate restoration actions (Mauseth and Kane 1995). Monitoring data can provide a defensible basis upon which to document the extent of injury and loss of natural resources and ecological services (impact assessment), set restoration goals, implement a restoration plan, and gauge the overall success at restoring ecosystem structure and function (Hudson and Goodwin 2001; Precht et al. 2001). One of the weaknesses of NRDA settlements associated with ship groundings, however, is that monitoring is not required by law to be part of the settlement, and is therefore not typically included. Responsible parties tend to be apprehensive to include monitoring in the settlement because they fear that additional compensation could be sought based on monitoring results. Thus, it has been difficult to gauge the effectiveness of these types of restoration efforts and the outcome is often unknown or inadequately studied (Miller and Rogers 2000). Because coral reef restoration is in its infancy, greater emphasis needs to be placed on hypothesis-driven restoration projects with detailed monitoring to determine the most cost-effective and ecologically beneficial approaches to restore the environment. The following section provides an overview of scientific monitoring approaches for coral reefs, with emphasis on application of these approaches to coral reef management and restoration.

MONITORING

The overall success in conserving coral reef ecosystems depends on the ability of managers to apply proactive, precautionary management measures that are successful in mitigating stressors, halting decline, and improving the overall health of the ecosystem. In some cases, this may require active restoration of reefs to prevent further degradation or to advance the natural recovery process in injured or damaged habitats. Developing the best strategy for conservation requires an understanding of the status of reefs, causes of decline, and impacts of natural and anthropogenic stressors. Because each reef is unique and cumulative stressors differ among sites, this information can only be acquired through monitoring and research at the specific sites of interest.

Coral reef monitoring involves the repeated surveys of organisms and environmental parameters (ecological monitoring) and the people who use coral reef resources (human dimensions monitoring) to provide information on abundance, diversity, and condition of particular species or their habitats, human use patterns, and changes to the ecosystem over time. Monitoring is fundamental to understanding the history, documenting the current state, and predicting the future condition of coral reef ecosystems. In addition to basic information on status and trends of coral reef resources and where they are located, long-term monitoring data can be used to guide decisions on whether and how the coral reef community needs to be managed or restored. A monitoring program can provide data to support effective management by:

- Providing baselines to enable early detection of change in coral reefs over time
- Identifying the controlling factors contributing to the stability, decline, or recovery of coral reefs
- Distinguishing the effects of human activities on ecological processes from natural changes
- Determining the response of coral reefs to management actions undertaken to reduce threats
- Evaluating the natural recovery and restoration of injured or degraded reefs, and
- Providing information necessary to adapt restoration and management activities to maximize recovery potential and conservation benefits

The design of a monitoring program will vary depending on the specific objectives and information needed to maintain, conserve, or restore particular coral reefs. The objectives may be very specific or more general, as determined on a case by case basis. A manager, for instance, may have a general objective to compare the condition of a reef under stress from human activities with a remote, undisturbed reef, or a more specific objective of determining the impact of a particular stressor, such as sedimentation associated with a coastal development or dredging project. Carefully thought-out objectives will help guide decisions on monitoring locations, frequency and duration of the monitoring program, specific biological and physical variables that need to be examined, detail (e.g., taxonomic resolution) of those variables, and appropriate scale of measurement. The most appropriate monitoring method will also depend on the available time, financial resources, equipment, and skills. Prior to undertaking monitoring, the restoration practitioners also need to consider how they will validate, analyze, and archive the data and communicate the results (Hill and Wilkinson 2004).

The primary ecological monitoring methods emphasize assessment of water quality, benthic communities (living and non-living components), motile invertebrates, and fishes. Baseline data are used to characterize the condition of a reef as it currently exists and address two questions:

1) What is the composition of the community? (This includes measures of species composition and abundance, total cover, cover of individual species, population densities and size frequency distribution, dispersion patterns, etc.), and
2) Are different communities, habitats, or populations correlated with or being affected by specific environmental and anthropogenic parameters?

Quantitative data on the ecological characteristics allow more standardized and accurate descriptions of the reef community, including comparisons of different reef areas and various zones within a reef. In addition, this type of information will provide a baseline against which to identify and quantify natural resource injury associated with physical impacts or other disturbances.

The primary focus for a monitoring program designed to evaluate a coral reef restoration project is to determine if the restorative measures are performing to an identified standard. For instance, at Western Sambo in the Florida Keys, a 200 m^2 reef crest environment dominated by elkhorn coral (*Acropora palmata*) was damaged by ship grounding. Detached corals were placed into cylindrical cement reef crowns and attached to the substrate which occupied a total of 20 m^2. After three years, the size, condition, and survivorship of restored fragments were examined and the resulting live cover was compared with surrounding unrestored habitat and a neighboring undamaged reference site (NOAA 2005). Using these monitoring data, the undamaged reference site could be compared with the restored area using the Bray-Curtis similarity coefficient (Bray and Curtis 1957) to determine whether the restored area has recovered to the pre-damaged condition.

Restoration efforts following impacts from the *Fortuna Reefer* ship grounding off Mona Island, Puerto Rico further illustrate the importance of monitoring in guiding future actions. Emergency restoration involved securing fragments of elkhorn coral (*Acropora palmata*) to the reef and to dead standing elkhorn skeletons using wire (NOAA 1997). A comprehensive monitoring program initiated two years after the grounding incident identified a major weakness that manifested over time - chronic failure of the stainless steel wire used to initially secure the fragments (Bruckner and Bruckner 2001). Data collection and analysis helped identify a mid-course correction to restabilize remaining fragments, resulting in maintenance of restored coral fragments on site that would have otherwise been lost. In addition, monitoring data on elkhorn coral survivorship over time are contributing to the development of new and improved techniques for restoring this species, including optimal placement, size, and orientation of fragments to maximize survivorship (Bruckner and Bruckner (a), *in press*).

STRUCTURAL CHARACTERISTICS OF CORAL REEFS

Although there are numerous reef types, such as fringing, barrier and atoll, they show certain similarities in structure and profile determined primarily by the physical environment, underlying topography, geological history, and the type of structure-forming (e.g., framework) organisms present. On the seaward side of the reef, the reef front or fore reef slope rises from lower depths to a shallow reef flat or reef crest. The inclination of the reef slope varies from gentle to steep, may be interrupted by one or more terraces, and often forms a vertical wall in deeper areas referred to as the drop-off. The shallow fore reef often has a series of finger-like projections that extend seaward and alternate with deeper sand channels (e.g., spur and groove formation). The reef crest is typically the area exposed to highest wave energy and may be partially exposed, especially at low tide. The reef crest separates fore reef habitats from calmer back reef environments.

The occurrence of particular scleractinian coral species and their development into coral reef communities is dependent on the availability of suitable substrata, thermal and light regimes, variations in salinity, levels of sedimentation and nutrient input, and local oceanographic conditions (e.g., wave exposure, storm frequency and intensity, and current patterns). Environmental factors, and consequently the species of corals and other animals found within a coral reef, vary depending on the reef zone. For instance, branching acroporids and pocilloporids typically dominate on the shallow fore reef and reef flat in areas of low to intermediate wave exposure. On the reef slope at intermediate depths, there is a high diversity of massive and columnar species, while plate-like species predominate in deep reef environments (Goreau 1959). In addition to the presence of distinct assemblages within reef zones, some species will overlap but exhibit wide variations in morphology. Because of these unique differences among zones, an understanding of the environmental attributes, structural features, and species composition is integral to the design of a restoration project as well as the particular method chosen to monitor the efficacy of the project. Factors that influence the structure and diversity of coral reefs may affect the design and assessment of a restoration project and include:

Biological

- Habitat created by animals[4]
- Biological controls
- Coral recruitment
- Diseases

Physical

- Bathymetry/topography
- Sediment (e.g., sedimentation rate)
- Turbidity and light availability
- Temperature

Hydrological

- Currents and wave energy
- Water sources (e.g., upwelling nutrients, land-based sources, etc.)

Chemical

- Nutrients (i.e., nutrients provided by algae and epiphytes)

Since many of these parameters can influence coral recruitment, survival, and growth, causes of site degradation must be understood and remediated as a first step in restoration. Appropriate species and growth forms must be carefully considered based on the physical attributes optimal for the target organisms.

BIOLOGICAL

Habitats Created by Animals

Scleractinian corals are considered foundation species, as they are a major source of three-

[4] Animals that form these habitat types are corals.

Figure 4. Shallow reef environment dominated by *Acropora palmata* and *A. cervicornis*. Photo courtesy of Andrew Bruckner, NOAA National Marine Fisheries Service.

dimensional structure and topographic complexity which provides habitat for diverse community assemblages (Bruno and Bertness 2001). Reefs are also colonized by other sessile organisms that contribute to the reef's topographic complexity and diversity, such as:

- Algae (crustose coralline, macroalgae, turf algae, and cyanobacteria)
- Sponges
- Other cnidarians (e.g., octocorals, hydrozoan corals, anemones, and false corals)
- Tunicates, and
- Bryozoans

Scleractinian corals secrete skeletons of calcium carbonate to form the basis of the reef structure (Wells 1956; Zann and Bolton 1985; Sorokin 1993). Rates of expansion of coral reefs require constant deposition of calcium carbonate, infilling of pores by sediment, and cementation by coralline algae at rates that exceed physical, chemical, and biological destructive processes.

Most reef-building corals as well as other cnidarians, tridacnid bivalves, and a number of other reef organisms have a symbiotic relationship with single-celled algae or dinoflagellates called zooxanthellae. The zooxanthellae give corals their characteristic yellow, green, golden brown, or brown coloration and they contribute to coral growth, calcification, and processes of physiology and reproduction (Glynn 1996; Brown 1997). Coral colonies are modular organisms composed of many interconnected polyps of identical genetic composition. Colonies grow by progressively accreting more skeleton. Corals have a wide range of life histories that allow them to inhabit specific zones, and modify the habitat to support other organisms. At one extreme are relatively short-lived and fast-growing corals such as the branching *Acropora* spp. (Figure 4) and *Pocillopora* spp. These species allocate considerable energy to growth and reproduction, but little towards maintenance. Growth (linear branch extension) rates can average 10-15 cm per year, but colonies are particularly susceptible to physical disturbances (e.g., hurricanes) and are preferred prey of *Drupella*, *Acanthaster,* and other corallivores. Other corals, such as *Porites* and *Agaricia* are opportunistic species. These exhibit high rates of recruitment and are among the first species to recolonize an area after a disturbance, but they are poor at repairing injuries and have short life spans. Massive faviids (e.g., *Montastraea* spp.) are long-lived and slow growing (1 cm per year), and can form colonies several meters in height. These species often exhibit low reproductive success, but they are resistant to many stressors and devote much of their energy towards colony maintenance.

Corals can build complex structures variable in shape, size, and designed to meet the demands of the reef's variable environmental conditions. Their differently shaped skeletons also influence the distribution of other organisms that co-occur in reef environments. Corals can be classified into ten general growth forms (branching, digitate, encrusting, table, foliose, massive, submassive, mushroom, flower, and solitary). Specific growth forms are primarily species specific, although the exact kind of coral can look very different from one place to the next. Some of the variation is genetically programmed, while the degree of light attenuation and symbionts clade[5] occupying the coral host, the biological environment (e.g., degree of competition), and other environmental factors such as wave exposure also cause variation. Corals on the upper slope and reef crest of exposed windward reefs are small, often encrusting or massive, and solidly constructed. In deeper reef environments, as wave action declines, corals become progressively larger and more delicate, and include diverse growth forms. In addition, many massive corals, such as *Montastraea annularis* (species complex), *M. cavernosa*, *Diploria strigosa,* and *Colpophyllia natans* that form hemispherical heads in shallow water have a plating morphology in deeper, low light environments as a strategy to maximize light absorption and particle capture.

Coral Recruitment

Regional recruitment patterns are controlled by a number of biological and physical factors such as larval supply, dispersal patterns during the planktonic period, substrate availability, and post settlement survival, as well as the local abundance, fecundity, and life history strategies of adults (Edmunds 2000). Patterns of settlement and survival of coral recruits may provide an indication of the vitality of reef communities and the potential for natural recovery of degraded areas (see Figure 5 for coral recruitment). In addition, knowledge of the effects of depth, physical relief, and various environmental parameters on juvenile coral survival may further explain the dominance of species in certain habitats (Bak and Engel 1979; Chiappone and Sullivan 1996) and assist in selecting appropriate species for transplantation.

Most studies of coral recruitment involve either field surveys of natural substrates or

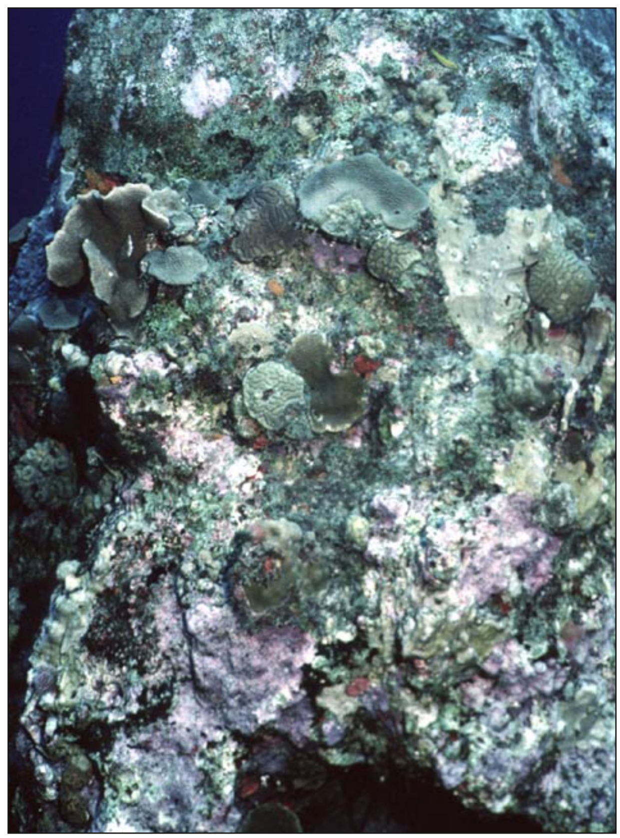

Figure 5. A Mountainous star coral (*Montastrea faveolata*) colony that experienced about 90% mortality from disease. Exposed skeletal surfaces were subsequently colonized by coral recruits. Photo courtesy of Andrew Bruckner, NOAA National Marine Fisheries Service.

[5] A group of species with a common evolutionary ancestry.

the use of settlement plates deployed before major reproductive periods and subsequently removed and analyzed several months later in a laboratory. Most field surveys target juvenile corals that are 0.5-4 cm in diameter and several months old because of limitations in identifying recruits due to:

1) The small size and low visual contrast of newly settled coral recruits; and
2) The difficulty in detecting small juvenile corals in more cryptic and architecturally complex habitats.

An emerging technology that may facilitate characterization of early patterns of coral recruitment involves the use of fluorescence to locate coral recruits because most corals contain pigments that fluoresce in a color differing from background algae fluorescence.

Biological Controls

There are a number of biotic agents that affect the settlement, growth, and survival of scleractinian corals, including coral diseases, bleaching, and predation by corallivores, competitors, and bioeroders (e.g., grazers, etchers, and borers). Biotic agents often weaken the substrate and make it more susceptible to physical and chemical erosion. Grazers, including echinoids and fishes, graze live or dead coral substrates, encrusting coralline algae, and filamentous algae. These activities typically generate large amounts of new sediment that may fill in spaces in the reef structure and become cemented in place, or be carried from reef substrates into sand channels and lagoons. Annual rates of parrotfish bioerosion in the Caribbean are estimated to be 40-490 g/m^2 (Ogden 1977; Frydl and Stearn 1978). Other community effects of predation include increased species diversity due to the removal of dominant preferred taxa. For instance, corallivores often feed on fast growing corals such as *Acropora*, and their removal may enhance the persistence of slower growing corals. Coral predators may also prevent recovery after a hurricane or other disturbance due to a concentration of predators on remaining prey, or they may open up substrata that are rapidly colonized by non-calcifying organisms, thereby reducing the potential for larval settlement and recruitment (Glynn 1988).

Diseases

Since the early 1990s, scientists have documented a rapid emergence of diseases among corals, with increases in the number of diseases reported, coral species affected, geographic extent, prevalence and incidence, and rates of associated coral mortality (Richardson 1998; Epstein et. al. 1999; Knowlton 2001; Sutherland et al. 2004). A survey of the coral disease literature conducted by Green and Bruckner (1999) described 29 differently named diseases on 102 scleractinian coral species. At least 12 new syndromes have since been reported, with a dramatic increase in observations from the Indo-Pacific. More than 150 species of zooxanthellate corals, including scleractinian, gorgonian, and hydrozoan taxa are now known to be susceptible to diseases (Green and Bruckner 2000; Sutherland et al. 2004).

Coral diseases may be caused by:

- Pathogens such as bacteria and fungi (infectious diseases)
- Stresses like elevated seawater temperatures and increased UV radiation
- Poor nutrition
- Genetic mutations (non-infectious diseases), or
- Possibly a combination of these factors

Increased sedimentation, nutrients, and pollutants may also be responsible for the proliferation of pathogens, or they may alter coral defense mechanisms and immune responses. Some disease-causing pathogens are thought to have been introduced into the marine environment as a result of human activities such as improper treatment and discharge of sewage, runoff associated with land clearing, dredging, ballast water exchange, and introduction of non-native species. This includes a soil fungus that is responsible for a disease in sea fans, and a bacterium found in the human intestine that has been identified as the causative agent of white pox, a disease affecting elkhorn coral (Sutherland et al. 2004). Alarmingly, more and more reefs in unpopulated areas are also being impacted by diseases, despite the absence of most major human impacts in these areas.

The most common diseases that affect scleractinian corals include black-band disease, white-band disease, white plague and yellow-band disease. In addition, a number of other conditions have been recently observed. The characteristics of the four major diseases are presented below to aid in the identification and monitoring of these conditions.

Black-band disease

Black-band disease (BBD) (Figure 6) forms a crescent-shaped or circular band that separates live, normally colored green, brown, or yellow-brown coral tissue from white, exposed skeleton. The band is maroon to black in color due to the photosynthetic pigments of the cyanobacteria (blue-green algae), it often has a white dusting of filamentous (sulfide-oxidizing) bacteria, and it is loosely anchored in living tissue and is easily dislodged by water motion. The band can range from a few millimeters to several centimeters wide, and may be over 2 m in length on large colonies. Over days to months, BBD slowly spreads in a line across the coral, advancing 2-3 mm per day or more, to a maximum of 2 cm per day. In the western Atlantic, 16 species of massive and plating corals are affected, as well as other types of stony coral, sea fans, and branching gorgonians. Boulder star coral (*Montastraea annularis* complex) and brain corals (*Diploria* spp. and *Colpophyllia natans*) are most commonly infected, while staghorn and elkhorn coral have not been observed with BBD.

White-band disease

White-band disease (WBD) (Figure 7) typically starts at the base of a colony and progresses towards its branch tips, causing tissue to peel off the skeleton at a fairly uniform rate. WBD occasionally initiates in the middle of a colony, especially where a colony branches, and then advances toward the branch tips or the base of the branch. Affected colonies have a distinct

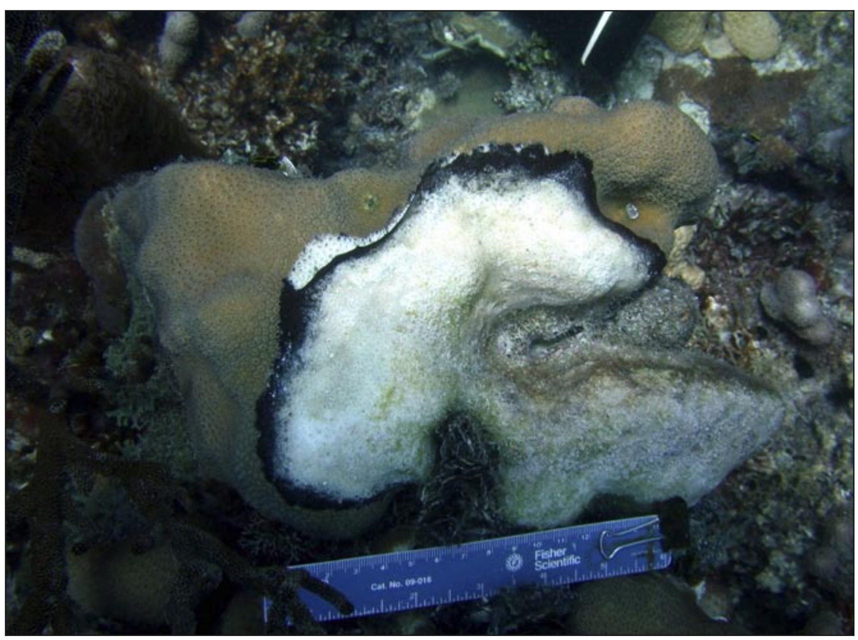

Figure 6. Coral infected by black band disease. Photo courtesy of Andrew Bruckner, NOAA National Marine Fisheries Service.

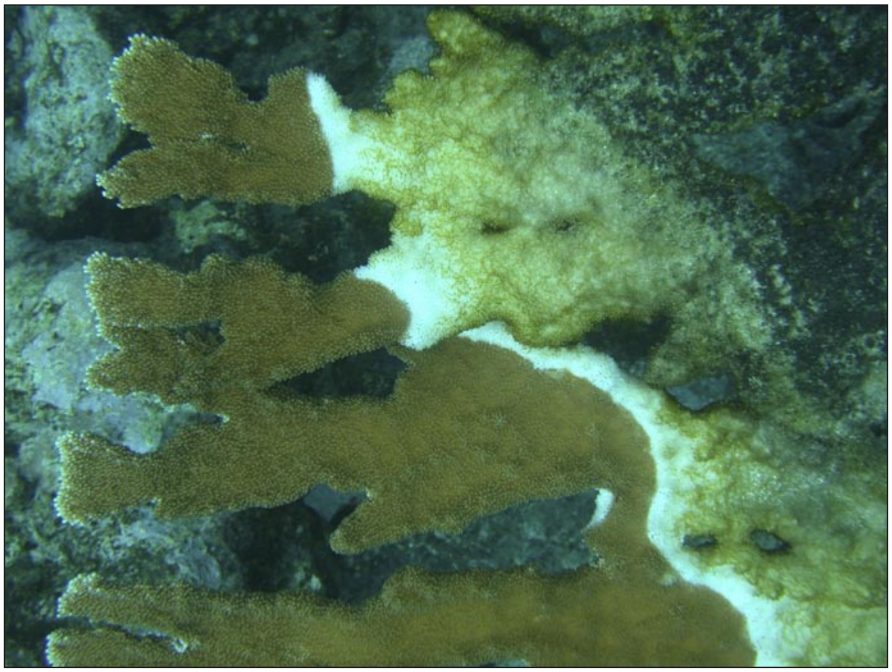

Figure 7. Coral infected with white-band disease. Photo courtesy of Andrew Bruckner, NOAA National Marine Fisheries Service.

margin or band of white, recently exposed skeleton ranging from a few millimeters to about 10 cm in width. Exposed skeleton is colonized by green filamentous algae within days, and this band progressively grades into other algal successional stages towards the base of the colony. Tissue loss averages at about 5 mm per day, but it can occur much faster. In some cases, tissue adjacent to the exposed skeleton forms a jagged margin as small patches of tissue are sloughed off into the water. WBD is known to affect only the acroporids in the Caribbean and is believed to be largely responsible for the decline of two of the dominant reef-building corals on shallow western Atlantic reefs (*Acropora palmata* and *A. cervicornis*) during the 1970s and 1980s (Antonius 1981 (a); Gladfelter 1982; Aronson and Precht 2000). In most locations, populations of *A. palmata* and *A. cervicornis* have failed to recover and remaining colonies are being affected by a host of new diseases including white pox. Due to the threats that these species face, and their potential for extinction, both species are now being considered for listing on the Federal Endangered Species Act (Bruckner 2002).

White plague

White plague (WP), a disease first reported from Florida in 1977, emerged in a more virulent form (Type II) in 1995 on the same reefs and is now recognized as one of the most destructive diseases in the western Atlantic. WP Type II causes tissue losses at a rate of 1-10 cm per day and can kill several meter tall colonies within weeks to months (Dustan 1977; Antonius 1981 (a) and (b); Harvell et al. 1999). WP is similar in appearance to WBD, but it affects massive and plating corals rather than branching acroporids. Tissue loss begins at the base or margin of a colony, or next to a previously killed area, and quickly spreads upward or outward in a band. In affected corals there is the appearance of a sharp line separating healthy coral tissue and bare coral skeleton, but there is no visible mat of organisms at the disease front as is observed with BBD (Richardson 1998). It now affects nearly 40 species of reef-building corals in the western Atlantic, with outbreaks observed in the Florida Keys, southwestern Puerto Rico, U.S. Virgin Islands, Bonaire, Curacao, Panama, Colombia, and other locations.

Yellow-band disease

Yellow-band disease (YBD) (Figure 8) begins as a pale yellow, circular blotch of tissue in the middle of normal, dark green to brown tissue, or as a narrow band at the edge of a colony. Affected tissue is translucent, and still contains symbiotic algae (zooxanthellae), although the algae are reduced in number. As YBD advances, the leading edge of the band (area closest to the normal tissue) becomes a light pale yellow or lemon color, while tissue behind the disease front gradually darkens and then dies. The band advances at up to 1 cm per month. Because the spread is relatively slow, colonies with YBD rarely have a prominent area of white, exposed skeleton. Typically, recent tissue mortality is restricted to small (5-10 cm^2) irregular blotches. Although the rate of tissue loss is much less than that observed in other coral diseases, this disease can affect individual corals for many years and will eventually kill them. Boulder star corals (*Montastraea annularis* complex) are most frequently affected by this condition, but cavernous star coral (*M. cavernosa*) and boulder brain coral (*C. natans*) have also been seen with YBD (Bruckner and Bruckner (b), *in press*).

Diseases can affect coral reef organisms directly and indirectly by altering both reef community structure and function. Coral diseases are playing an increasingly important role in regulating coral population size, diversity, and demographic and other structural characteristics (Antonius 1985; Aronson and Precht 2000 and 2001; Porter and Tougas 2001; Bruckner 2004). *Acropora palmata* and *A. cervicornis* were the two dominant space occupants and most important framework builders in reef crest and fore reef habitats on Caribbean reefs until the late 1970s, when outbreaks of WBD, hurricanes, and other factors decimated populations, leading to large losses of live coral cover throughout the region (Richardson and Aronson 2002). More recently, boulder star coral (*Montastraea annularis* complex) populations are experiencing significant declines as a result of multiple diseases including BBD, YBD, and WP (Antonius 1973; Santavy et al. 2001; Garzon-Ferriera et al. 2001; Kuta and Richardson 2002; Bruckner and Bruckner 2003 and 2004).

Measuring and Monitoring Methods

Sessile Invertebrates and Algae

Sessile benthic invertebrates and algae can be assessed using transects, quadrats, manta tows, and other methods including line intercept, point intercept or belt transects, visual or

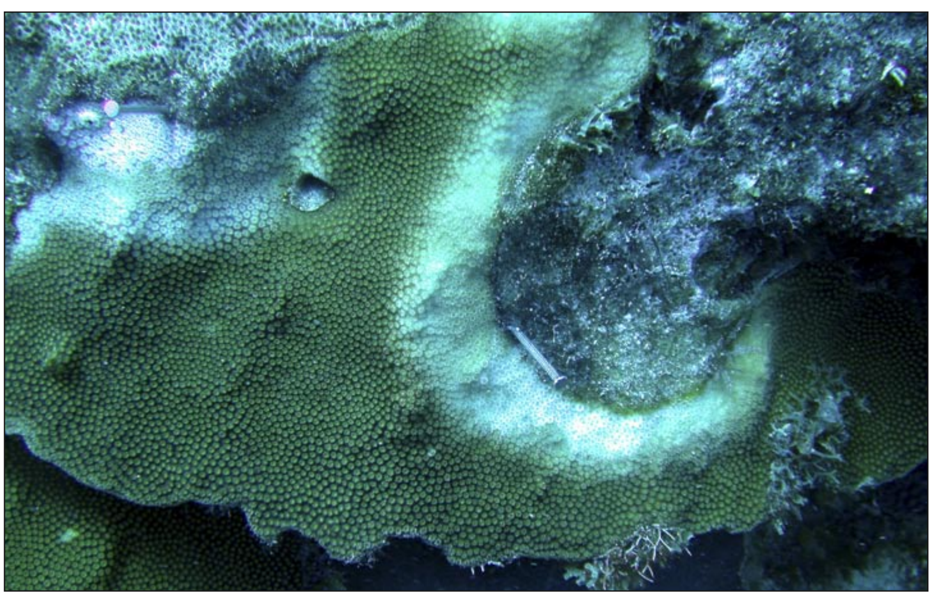

Figure 8. Coral infected with yellow-band disease. Photo courtesy of Andrew Bruckner, NOAA National Marine Fisheries Service.

photoquadrats, video transects, or colony-level monitoring (Table 1). The method chosen depends on the level of detail desired. Broad-scale methods such as a manta tow or timed swim are most useful for assessing broad changes in benthic communities over large areas at lower resolutions. The manta tow technique enables visual assessment of large areas of reef in a short amount of time, and can be used to determine the effects and large-scale disturbances. Manta tows can also assist in identifying sites of interest for more detailed monitoring. Medium-scale methods, such as visual or video transects, are typically used to monitor at the scale of an entire reef. Quadrats are typically used to measure smaller areas in more detail and can provide high resolution data on coral recruitment and growth, as well as biomass of various algal groups (Hill and Wilkinson 2004).

Once the method is selected, one must determine the appropriate scale of measurement, such as the length of transect and size of quadrat, as well as the number of replicates and placement of these replicates (e.g., random or haphazard placement). The chosen monitoring method and protocol depends on the scale of the area to be monitored, level of detail desired, type of reef habitat, and precision of data required. The appropriate size and amount of replication can be determined through a pilot study that examines the size, spatial abundance, and diversity of organisms. Typically, abundant, large organisms located within a smaller area and/or sites with low diversity or low spatial heterogeneity require fewer and shorter transects, while detection of rare or smaller organisms or assessment of high diversity sites require additional, longer transects that cover a larger sampling area. Sufficient replication is also necessary to understand the extent of variability within a coral reef ecosystem and to collect information that is representative of the area of interest and/or abundance of the target organism.

Linear transects - Linear transects (Figure 9) are used to collect baseline information on sessile benthic community structure and changes over time. Linear transects are generally extended parallel to the reef crest along depth contours, although they may be extended perpendicular to depth contours to characterize different habitat types and changes in species composition along a gradient extending from the shore to deeper

Figure 9. Linear transect running through staghorn coral (*Acropora cervicornis*). Photo courtesy of Andrew Bruckner, NOAA National Marine Fisheries Service.

water. Data collection can include substrate types (hard substrate, rubble, sand, dead coral, etc.) and major life forms or growth forms of corals and other organisms, although identification (rather than collection) of each organism to the species level is preferred.

Line intercept transects - Line intercept transects focus on the horizontal plane of the reef and data are collected along the entire length of the line. The cover of a particular organism is defined by the fraction of the line that is intercepted by that organism. A variation of this is the point intercept method, where biotic or abiotic components are recorded at specific intervals below the line (Chiappone et al. 2001). If a researcher uses replicate 30 m transects and records the substrate type or organism every 0.5 m, then a total of 60 data points will be collected per transect. The total number of points occupied by a certain species divided by the total points examined for all transects performed in one site is an estimate of the percent cover of that species.

Chain transects - Chain transects measure benthic cover and species composition in a three-dimensional plane as the chain follows the contour of the reef. Chain transects provide details on rugosity (i.e., roughness - Figure 10). In addition, the presence/absence of particular taxa or abiotic substrates can be recorded under every link or a certain percentage of the links (similar to the point intercept method) to provide estimates of cover.

Belt transects - Belt transects (Figure 11) are similar to line transects, but examine a wider area and are used most frequently to:

1) Assess populations when examining whole colonies to obtain information on species composition, size and condition, and spatial distribution of corals or other taxa
2) Quantify the prevalence of bleaching, disease, and other stressors, and
3) Count mobile invertebrates and fishes

The optimal width of a belt transect will depend on the parameter monitored. For example, a narrow belt (e.g., 1 m) may be adequate for a very abundant organism, while wide belt transects (e.g., 3-5 m) may be necessary to accurately estimate abundance of rare taxa.

Quadrats - Quadrats (Figure 12) can provide data on percent cover, frequency of occurrence, and species diversity, abundance, density, and size for small to medium-sized organisms (Matta 1981; Laydoo 1990; Chiappone et al. 2001).

Figure 10. Divers monitoring coral along a chain transect. Photo courtesy of Andrew Bruckner, NOAA National Marine Fisheries Service.

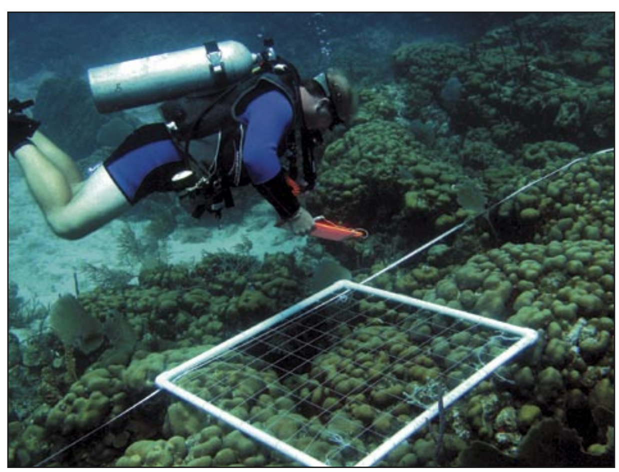

Figure 11. Diver assessing coral reefs along belt transects using quadrats. Photo courtesy of Andrew Bruckner, NOAA National Marine Fisheries Service.

Figure 12. Photoquadrat (70 x 100 cm) and algae quadrat (25 x 25 cm) placed along a transect to monitor benthic communities. Photo courtesy of Andrew Bruckner, NOAA National Marine Fisheries Service.

Quadrats are most often used to assess coral recruitment patterns, coral growth, and algal composition and biomass. Quadrats are typically divided into a number of smaller squares (e.g., a 1 m^2 quadrat may be divided into 100 squares) to increase accuracy of coverage estimates for visual counts. Visual estimates using quadrats may require time intensive counts which limit the number of replicates. It is also possible to bias data by selecting particular areas of interest (e.g., areas of high cover or the presence of a certain taxa, disease, or other feature) instead of randomly placing quadrats throughout the survey area. This can be avoided by placing quadrats along linear transects at set intervals, with the appropriate interval determined on land prior to conducting the survey, and also by increasing the sample size and area evaluated.

Photoquadrats and video transects - Photoquadrats and video transects provide a permanent record of benthic communities, allow rapid data collection, and require minimal taxonomic expertise for field work (Bohnsack 1979; Maney et al. 1990; Meier and Porter 1991; Mumby et al. 1995; Ninio et al. 2000; Motta et al. 2001). Video data collection can be used to monitor and assess macroalgae and coral reef health, growth, abundance, and percent cover before, during, and after restoration efforts (Dartnall and Jones 1986; Maney et al. 1990; Ninio et al. 2000; Jaap and McField 2001; Rogers et al. 2001). In general, photoquadrats provide higher resolution than video transects, although data are collected at a smaller scale. Photographic images can be analyzed using random points (for video, individual frames must be grabbed prior to analysis) or by digitizing the planar area of organisms to provide an accurate percent cover and size estimates. Digitized images can be used to compare fine-scale changes in benthic communities over time. The major disadvantages with underwater photography include equipment costs, time required for image processing and analysis, possible loss of resolution, and inability to detect cryptic organisms (Jaap and McField 2001).

Tagging - Coral tagging[6] allows a comparative evaluation to be performed of the degree of impact on coral health over time. For example, some stressors such as disease, predation, algal overgrowth and bleaching that affect the health of the coral can be monitored via tagging.

Coral Recruitment

Coral recruitment is an important parameter to monitor at reef restoration sites in order to document whether structural modifications, such as the removal of sediments and rubble

[6] This method involves marking and monitoring specific individual corals at designated sites.

or stabilization of the substrate, were adequate to enhance settlement. Dead pieces of coral skeleton may be secured to natural substrate in order to increase the availability of settling surfaces for coral recruits. In addition, artificial surfaces, such as terracotta tiles, can be used to 'collect' crustose coralline algae, a preferred substrate for coral settlers (Mundy 2000; Heyward et al. 2002).

Visual quadrats and photoquadrats - Visual quadrats and photoquadrats are used most frequently to evaluate patterns of survival and growth of juvenile corals on natural substrates, and these types of studies often also assess the quality and availability of substrate, topographic complexity, grazing rates, and variations in light and nutrients (Sammarco 1980; Wittenberg and Hunte 1992). Quadrats are typically smaller (e.g., 0.25 m^2 or less) than those used to examine adult corals, although some researchers have used larger quadrats (e.g., 1 m^2) to survey both juvenile and non-juvenile corals simultaneously (Bak and Engel 1979; Chiappone and Sullivan 1996).

Underwater photography - Underwater photography is also used in recruitment studies, although close-up photographs of small areas are necessary to maximize resolution and obtain sufficient contrast to identify recruits. Patterns of recruitment on denuded coral surfaces, for example, can be examined using a Nikonos V camera fitted with a close-up lens that photographed a 16.5 x 23.5 cm area (Edmunds 2000). This method allows identification and quantification of corals ranging in size from 4 -40 mm. Quadrats may be placed in specific locations or randomly along transects, or be permanently fixed to the substrate. Fixed quadrats can provide information on temporal changes in recruitment, growth, and mortality, while random quadrats provide an indication of spatial distribution of juvenile corals.

Artificial settlement plates - Artificial settlement plates provide data on patterns of early recruitment, including the relative abundance in space and time. Recruitment can be monitored using unglazed, flat terracotta (ceramic) tiles (approximately 10 x 10 cm and 1 cm thick) that are either attached directly to the coral reef substrate or to wire racks secured to the bottom. Multiple tiles (generally 20-50 tiles per site) are positioned at various angles and distances from the substrate and in areas of differing topographic complexity. While brooding species may reproduce on a monthly to seasonal basis, tiles should be placed in the field 4-6 months before the mass spawning event (e.g., July - September in the Caribbean) to detect broadcast spawners by allowing them to acquire a rich fouling community and crustose coralline algae. A portion of the tiles are removed at various intervals (e.g., monthly to quarterly) and replaced with new tiles. In the lab, a microscope is used to count the number of recruits per tile, size and number of polyps per recruit, position of settlement (e.g., top or underside of tile; edge or middle of tile), and relationships between settlement and presence of other invertebrate or algal colonizers (Mundy 2000; Hill and Wilkinson 2004).

Coral Diseases

A variety of approaches have been used to identify the prevalence (i.e., number of affected corals divided by the number of corals examined) and incidence (i.e., number of new colonies with disease occurring in a population over a given time divided by the number of unaffected individuals at the beginning of the time period) of coral diseases, including quantitative, semi-quantitative, and qualitative surveys (Table 2). Many monitoring programs rely on repeated sampling of permanently marked transects, quadrats, or radial study sites. Detailed monitoring of particular reefs, through the establishment of permanent sites, can provide information on disease incidence. In addition,

Table 1. Advantages and Limitations of Methods to Monitor Benthic Coral Reef Communities

Methods	Advantages	Limitations
Linear transect	Useful in continuous reef areas.	Not suitable for patchy environments due to limitations on number of replicates.
Line intercept transect	Measurements taken along entire line instead of random or fixed points.	Focuses on horizontal plane of reef.
Point intercept transect	Rapid determination of species diversity and cover.	Does not allow examination of whole organism.
Chain transect	Enables determination of structural complexity.	Can be used to measures of cover, diversity, and abundance but requires large number of time consuming transects.
Belt transect	Assesses whole colony health and specific impacts such as disease; counts motile invertebrates and fishes.	May be time consuming, especially in areas with high abundance of corals.
Video transect	Permanent archive; does not require user to be able to identify species; rapid, easy to use, and allows survey of large areas.	Limited resolution; cannot distinguish small corals and algae; high relief octocorals may overshadow underlying benthic community; requires user to stay at fixed distance from substrate and repeat photographs must be taken from exactly the same angle; analysis is time consuming and requires considerable expertise and expensive equipment.
Quadrat	Fine-scale monitoring of coral recruits and algae; permanent quadrats offer high precision. Suitable for patch reefs and other discontinuous environments.	Visual estimates may have significant user variation and bias depending on placement.
Photoquadrat	High precision and detail for measures of percent cover. Allows analysis in lab using point count or planar area.	Planar view only; repeat photographs must be taken at the same angle/distance for comparisons.
Tagging coral colonies	Most specific detail on individual corals and impacts of stressors such as disease.	Time consuming. May be difficult to relocate corals. Cause and effect studies require frequent monitoring.
Recruitment tile	Collects information on new recruits. Higher detection than from photoquadrats or visual quadrats. Can be analyzed in the laboratory.	Very small scale. Tile composition and placement may affect recruitment patterns.
Timed swim	User covers larger area than possible with transect or quadrat methods. Useful for detecting rare organisms or large-scale phenomena like bleaching; can estimate species cover and diversity over large areas.	Low precision; limited to areas where divers look.
Manta tow	Best suited for examining widely spaced organisms or providing an overview of large areas; allows determination of appropriate sites for monitoring. Can be combined with video.	Area examined controlled by boat operator and not diver. Can only collect limited data at low precision.

long-term monitoring of individually tagged colonies affected by microbial pathogens can provide detailed information on the duration of infections, frequency of reinfection, and effect at the species level. Because diseases often occur at a low frequency or they exhibit a clumped distribution, a large number of transects may be required within each reef to accurately estimate disease prevalence. To obtain a more realistic measure of disease prevalence overall at a larger (nationwide or regional) scale, and to determine factors responsible for the increase and spread

Table 2. Monitoring and Assessment Techniques for Coral Diseases

Monitoring Approach	Condition Examined and Technique Description	Author(s)
Timed swim	All syndromes. Diver swam for 30 minutes along a single depth gradient and examined all corals in a band approximately 2 m wide, recording the type of disease, species, and number of affected corals. Disease occurrence categorized as rare (1-3 cases), moderate (4-12 cases), frequent (13-25 cases), abundant (26-50 cases), epidemic (51-100 cases), or catastrophic (greater than 100 cases).	Antonius 1995
Radial site	Prevalence and incidence of BBD. Total number of infected and uninfected colonies of each species present was recorded within a circular area (10 m radius; 314 m^2).	Edmunds 1991; Kuta and Richardson 1996; Bruckner et al. 1997a
Radial belt transect	All diseases on stony corals and gorgonians. Total number of affected and unaffected colonies of each species present was recorded within the outer 8-10 m of an arc radius (circular area, 10 m radius; 314 m^2).	Santavy et al. 2001
Linear transect	A. Changes in composition, size, and cover. Twenty 25 m transects on reef from 0.3-21 m depth. Permanent transects were extended parallel to each other to subdivide an area approximately 25 m x 300 m. Mean colony size (length under the transect line) and distance between colonies were recorded; colonies were inspected for signs of mortality (disease, physically damaged areas, sediment covered tissue, or other blemishes). B. Condition of stony corals. Minimum of ten 10 m transects per reef/depth used and surveys at 3 m and 10 m depth conducted; species, size, percent recent, and old mortality of all colonies that touch the transect line were recorded; whole colony examined for diseases or other sources of mortality.	A. Dustan 1985 B. AGGRA 1998
Belt transect	A. Sea fan disease. One or two 4 m x 12.5-50 m transects per country used. B. All diseases - corals and gorgonians. Ten 10 x 2 m belt transects (level 1) and three 20 m x 2 m belt transects per depth used; minimum 9 transects at each site (level 2) used. C. Reef condition. Three 20 m x 5 m transects per reef used; divers noted presence and proposed type of disease and affected species, but did not collect quantitative information.	A. Nagelkerken et al. 1997 B. CARICOMP 2001 C. Hodgson et al. 2004

Table 2. Monitoring and Assessment Techniques for Coral Diseases (cont.)

Monitoring Approach	Condition Examined and Technique Description	Author(s)
Quadrat	A. BBD in gorgonians. Prevalence measured using three 100 m x 250 m quadrats per reef; incidence measured using one 10 m x 10 m quadrat per reef. B. Sources of mortality. Two photostations of 2 m x 2.25 m established per reef; examined two reefs to identify sources and amount of mortality over time, complemented with permanent chain transects extended over 25 m to measure changes in percent coral cover, diversity, and colony size. C. Coral reef monitoring. 160 stations, each 2 m x 22 m, were sampled at 40 sites in the Florida Keys National Marine Sanctuary. 15-minute survey of each quadrat conducted to complete a species inventory, identify species affected by bleaching or disease, and record the type of disease. No data collected on disease prevalence. Also ran video transects. Sites re-examined once per year from 1996-2000.	A. Feingold 1988 B. Porter and Meier 1992 C. Jaap et al. 2000

of diseases, a repeated measures approach consisting of multiple random belt transects positioned throughout each reef environment is necessary (Bruckner 2002).

PHYSICAL

Topography/Bathymetry

Bathymetry is the science of measuring the depths of the oceans and mapping the corresponding topography, or physical features, of those depths. Accurate geo-referenced information on the location of specific natural resources, depths, topography, and corresponding habitat types is important for effectively managing marine habitats. An understanding of the bathymetry can assist in:

1) Creation of accurate baselines for long-term monitoring
2) Characterization of habitats for place-based conservation measures such as marine protected areas
3) Enhancement of scientific understanding of the large-scale oceanographic and ecological processes affecting the health of reef ecosystems, and
4) Identifying changes in topography associated with physical impacts and structural restoration efforts

Comprehensive maps can also be used to illustrate trends in coral reef health over time by providing a geo-referenced tool to track disease and invasive species and documenting loss of habitat and reef-dependent species.

Shallow-water coral reefs are generally restricted to depths of about 160 ft, with distinct depth-related zonation patterns exhibited by corals and other sessile invertebrates. Reef topography and bathymetry also vary among reef types, thereby creating unique zones that support different marine organisms or life history stages by providing shelter, feeding grounds, breeding areas, or substrates for attachment (Holliday 1989). Topographic complexity of a reef can be altered due to natural events such as a severe hurricane that dislodges, shatters, and removes branching corals. Human activities, such as the grounding of a vessel, can crush and detach coral colonies and fracture the reef surface, while dredging, beach nourishment, and shoreline modification projects can bury reefs under a layer of sediment. A number of destructive fishing practices, such as dynamite fishing and the use of bottom trawls, can also reduce the three-dimensional heterogeneity of coral reefs by pulverizing the corals that provide the structural framework. The broken coral has a low potential for survival, and the skeletons become a shifting, unstable rubble field that inhibits new coral colonization (Fox et al. 2001).

One of the primary goals of coral reef restoration is to stabilize the substrate and quickly reestablish the spatial heterogeneity as a first step to restoring ecological function. Topographical information about the site prior to the injury or the surrounding undamaged area can provide information on the extent of structural restoration necessary as well as a reference to gauge recovery within the restored area.

Measuring and Monitoring Methods

Seafloor characteristics, including habitat types, bottom features, bathymetry, substrate type, thickness of deposits, and cover of certain dominant groups of organisms can be assessed and monitored using a variety of remote sensing tools (e.g., satellite and aerial photos), acoustical systems (e.g., side-scan sonar and echosounders) (Dustan et al. 2001; NOAA Center for Coastal Monitoring and Assessment 2002; Mumby et al. 2004), in-water imaging (e.g., video or still photography), and coring.

Remote sensing - Remote sensing involves the measurement of electromagnetic radiation reflected from or emitted by the Earth's surface using satellite or aerial photographs, and then relating these measurements to the spatial extent and distribution of different habitat types, water quality, and in some cases (depending on the sensor and its resolution), the cover, composition, and/or condition of dominant organisms. Satellite imagery and aerial photography are limited by environmental conditions such as water turbidity, sun angle, cloud cover, and surface waves, and are generally useful in clear tropical waters to depths of 60 ft. Acoustical systems towed behind a survey vessel (e.g., multi-beam echosounder) or deployed closer to the bottom (using a side-scan sonar) can be used to characterize the seafloor in deeper or turbid areas.

Satellite imaging, aerial photographs, and acoustic technologies are often used to create detailed maps of the spatial dynamics and distribution of coral reef ecosystems, and are particularly useful for large or remote areas. In addition to documenting baselines for long-term monitoring, accurate geo-referenced information can be used to illustrate community-scale trends in ecosystem condition, characterize habitat types, and understand large-scale oceanographic and ecological processes affecting reef health (Riegl et al. 2001). Maps created using these technologies can also assist restoration practitioners in assessing the severity and spatial extent of impacts and developing restoration strategies. Some of the newer sensors are able to discriminate between common coral reef features when using the proper algorithm, such as live coral versus algae-covered dead coral, bleached corals, and other organisms (Holden and LeDrew 2001). Aerial photographs provide a much finer scale than satellite images, but without the spectral resolution and measure of absolute radiance. Using a digital scanner, aerial photographs can be converted to RGB digital imagery at resolutions of 25 cm and may be comparable to line transects and underwater quadrats. Multispectral cluster analysis then transforms the image into the geographical information system domain, and after appropriate groundtruthing and geo-referencing, the cover of corals and other large organisms can be calculated (Riegl et al. 2001). Sonar uses sound not light and measures distances based on how much time it takes for a sound signal to reflect back to the source and the strength of the returned signal. This indicates what type of material reflected the signal. For example, mud absorbs much of the sound signal, providing a weak echo, while rock reflects most of the sound, providing a strong echo.

While remote sensing and acoustic technologies are an excellent option for consistent, repetitive monitoring of coral reefs on a large scale, there are limitations to each remote sensing method used (see Table 3). These technologies are particularly useful for a general survey of a reef, can assist in selecting study sites for more detailed analysis, and provide a record of large-scale changes. While these approaches can assist in identifying major zones and habitats, they have a limited ability to document changes in the condition or abundance of particular organisms. Other factors that limit the accuracy of remote identification of individual organisms include the effects of water column transparency on optical reflectance characteristics of the organism (Holden and LeDrew 2001). It may also be difficult to estimate depths and structural relief using remote sensing techniques, as certain "dark" areas such as grassbeds may appear much deeper than lighter colored sand flats. These limitations can be overcome using snorkel or scuba diving to groundtruth the images. Detailed bathymetric and topographic information can be collected using underwater photography and video and chain transects to groundtruth remotely-sensed images.

Video monitoring - Video monitoring allows divers to sample larger areas of the reef in less time than non-photographic *in situ* reef monitoring techniques but it covers a smaller area than remote sensing or acoustic technologies (Dartnall and Jones 1986; DeCouet and Green 1989; Jaap and McField 2001; Rogers et al. 2001). Digital video data offer a visual representation of the sampled area that can be archived and shared electronically. It can be used to document the effects of a variety of stressors that cause conspicuous changes in the appearance of coral colonies, such as breakage from hurricanes and boat anchors, diseases, and bleaching. They can also show recovery of reefs following damage. The main disadvantage, in terms of reef structure, is that videos provide a planar view of the reef surface instead of the three-dimensional complexity, thus organisms located on the sides and undersurface of rocks and corals are missed, and the resolution decreases with distance from the substrate.

Chain transects - Chain transects are the most accurate and widely used method to monitor structural complexity at a smaller scale, such as an individual reef or habitat where restoration was conducted. Measures of rugosity (spatial index or the ratio of reef surface contour distance to linear distance), provide a way to quantify changes in topographical complexity of the reef. Other non-photographic techniques such as the visual assessment of quadrats and linear transects generally require more time in the water, and may not provide data on spatial complexity of a habitat.

Sediment

Sediments exert marked biological and geological effects on reefs. High rates of sedimentation can affect coral settlement, growth, and survival as well as the distribution and composition of sessile invertebrate assemblages through burial, smothering, shading, and abrasion. Sediments suspended in the water column also effect light penetration due to absorption and scattering of light. The ability of corals to withstand sedimentation varies considerably among species and is affected by their growth form and the ability of sediment rejection mechanisms (e.g., polyp distension, ciliary action, and mucus production) to remove foreign material from the colony surface (Hubbard and Pocock 1972). Reefs with high sediment loads are characterized

Table 3. Advantages and Limitations in Broad-Scale Remote Sensing Techniques to Map and Characterize Coral Reef Ecosystems

Methods	Advantages	Limitations
Satellite imaging	Measures wavelength and intensity of reflected radiation to differentiate habitat types like sand, seagrass, and coral-dominated areas. High resolution satellites can distinguish objects as small as 1 m, but these are costly and may be unavailable.	Difficult to differentiate shoreline features from shallow-water areas because reflection through water produces similar signatures; sun glare causes interference; cloud cover blocks reflected light; inappropriate for turbid areas
Airborne hyperspectral imaging	Visible and infrared light spectrum split into many narrow bands allows finer resolution than satellite images. Can be used to monitor oil spills, schools of fishes, and effluent, and can provide a detailed view of benthic habitats and habitat features. Can gather information from depths approximately three times greater than standard aerial photography.	Only works in shallow, non-turbid water. Limited by environmental conditions including water turbidity, sun angle, cloud cover, haze, and surface waves.
Aerial photography	Allows for broad-scale habitat mapping, delineation of habitats over wide areas, and detection of features smaller than 1 m.	Accurate spatial data requires geo-referencing. Limited by environmental conditions including water turbidity, sun angle, cloud cover, haze, and surface waves.
Hydrographic Light Detection and Ranging (LIDAR)	Used for detection and mapping of bottom topography in inshore areas. Can be used to determine depth (by recording the time it takes for the reflected signals from the surface and seafloor to return to the aircraft). Can be used to about 50 m depth in clear water.	Provides a good compliment to acoustic techniques, which cannot be used in shallow water, but is limited by water clarity.
Acoustic in situ methods	Unlike remote sensing, these tools are not limited by water turbidity.	They provide information on sediment surface, but must be combined with sub-bottom profiling systems to characterize sub-surface sediments.
Single-beam echosounder	Collects discrete data points along survey track lines.	Very portable and inexpensive, but lower resolution than multi-beam.
Multi-beam echosounder	Collects continuous high resolution bathymetry data throughout the survey areas and may measure strength of reflected sound (backscatter), allowing differentiation of soft and hard bottom substrates.	Can accurately detect features as small as 1 m.
Side scan sonar	Can identify different substrate types, such as mud, sand, and rock. Provides for continuous characterization of seafloor at all depths.	Because the sonar emitting and receiving device is towed underwater, closer to the surface of the ocean bottom, there is less signal attenuation and a lower angle of viewing differences in topography.

by lower diversity, lower percent coral cover, reduced rates of reef accretion, small colony sizes, compressed reef zonation patterns, and a predominance of sediment-resistant species. For example, the large star coral (*Montastrea cavernosa)* in Puerto Rico was found to be the dominant scleractinian coral in turbid water, primarily due to its efficient sediment rejection capabilities, while *Montastraea annularis* dominates in clear water (Loya 1976).

Grain size, composition[7], and depositional environment

Most coral reef sediments can be grouped into terrigenous sediments and biogenic sediments. Terrigenous sediments have been eroded from land and carried into the marine environment by rivers, wind, and runoff. Terrigenous sediments generally travel large distances from places where they are eroded before being deposited. During this transport, the composition, sorting, shape, and size of original grains may be significantly altered. Biogenic sediments are derived principally from precipitated skeletal material (calcium carbonate and silica) and usually have been broken down by physical and biological erosion. Sources of biogenic sediments on reefs include fragments of corals, coralline algae, green calcareous algae (*Halimeda*), foraminifera tests, mollusk fragments, echinoderm spines, sponge spicules, and other skeletal remains (Mckee et al. 1959).

The deposition of carbonate sediments is affected by hydrodynamics (currents, waves, and tides), gravitational deposition, and biological processes (death and bioerosion). Much of the reef carbonate is deposited very near its point of origin, thus the distribution of sediment-producing organisms has an impact on the distribution of sediments. Carbonate sediments, however, have variable grain shapes that are determined by the skeletal architecture of the organisms from which they are derived (e.g., spherical and disc-shaped forminiferans versus elongate sponge spicules) and have a high porosity (e.g., *Halimeda* consists of thin plates with pores and chambers), making them more susceptible to transport than terrigenous grains of a similar size. Once deposited, these sediments may be further modified through bioturbation by deposit-feeding sea cucumbers and burrowing shrimp (*Calianassa*). While normal wave and tidal conditions are responsible for resuspension of small or buoyant carbonate particles, the efficiency of wave and tidal transport is related to the water depth and size of the waves. Most large pieces of reef debris, such as reef blocks, boulders, and large coral fragments are moved only by high energy storm waves. Storms may also remove enormous volumes of sediment from reef ecosystems and keep this sediment in suspension for extended periods.

In spite of the complexity of reef sediments, sedimentary assemblages are characteristic of particular zones in a reef. The sediment produced by physical and biological destruction of calcium carbonate skeletons accumulates as aprons around the base of the reef or on lagoonal floors, filters into the reef framework, and fills in holes and crevices. In reef flat environments, course sediments consisting of coral fragments, mollusk shells and foraminiferan tests accumulate in shallow grooves on the pavement, while coral areas typically contain smaller fragments of coral and coralline algae, *Halimeda* plates, and echinoid spines. Sediments in the backreef may be a mixture of skeletal sand produced by the disarticulation of organisms that live there under normal conditions, gravel or cobbles washed in from the adjacent reef crest during storms, and carbonate mud produced through biological breakdown. In deeper, low energy lagoonal environments, accumulations of fine sediments contain high concentrations of organic matter, and grain size progressively decreases with depth. Patch reefs further modify sediment composition of adjacent lagoons by affecting water circulation patterns and introducing coarse reef debris.

[7] Sediment grain size and composition is associated with the reef's geomorphology.

Sediment composition varies geographically and across large spatial scales due to differences in physical and biological processes and the availability of various sediments. Oceanic reefs are almost entirely composed of calcium carbonate of local origin, while reefs near continents may have a significant terrigenous component. Furthermore, *Halimeda* and coral fragments are the most important sediment constituents of Caribbean reefs, while sediments of Indo-Pacific reefs are often dominated by encrusting coralline algae fragments and benthic foraminiferans.

Sedimentation rates and quality

Levels of sediment runoff from many high islands and continental areas have increased in recent decades due to human-induced changes in adjacent watersheds and increased soil exposure associated with forest clearing, agriculture, coastal development, and dredging. By understanding rates of sedimentation and sediment composition it may be possible to differentiate impacts of natural processes from human activities, such as the effects of dredging operations, coastal runoff, and land erosion (Babcock and Davies 1991; Philipp and Fabricius 2003; Torres et al. 2001). Terrigenous sediments create an unsuitable environment for corals in at least three ways:

- Unconsolidated sediments provide an unstable substrate for coral settlement
- Acute sediment stress associated with a storm event or runoff during unusual rainfall events may smother corals through rapid deposition or resuspension, and
- Chronic sediment stress resulting from elevated suspended sediment loads reduces water clarity and light levels, and may raise a coral's energetic cost of cleaning its living surfaces (McLaughlin et al. 2003).

Sediment constituents may be a useful indicator of the general condition of reef ecosystems, on a scale of years to decades (Lidz and Hallock 2000). Sediments dominated by identifiable skeletal fragments of mixotrophic organisms indicate low nutrients, while calcareous algae and gastropods are important constituents of sediments in higher nutrient environments. Sediments consisting of coated grains and difficult to identify debris are indicative of high rates of bioerosion. Findings from Florida suggest that sands dominated by coral grains reflect areas with poor coral health, while sediments consisting primarily of *Halimeda* and mollusk fragments occur in areas with better coral health (Lidz 1997). A greater volume of coral sands may be produced when corals are weakened by disease, turbidity, contaminants, mechanical damage, or other environmental and physical factors, and their injured skeletons are increasingly eroded by parrotfish, *Diadema*, boring algae and sponges, and other bioeroders.

Knowledge of the sediment load being transported from coastal areas, the spatial impact of terrigenous sediments as you move further away from the point source, and the relative proportion of terrigenous versus carbonate sediments can help determine the suitability of particular sites for coral transplantation and selection of particular species for transplant based on their sediment rejection capabilities. In addition, areas dominated by unstable coral rubble may need to be stabilized to increase survivorship of transplanted corals and new recruits.

Sampling and Monitoring Methods

Monitoring methods for sediments include measures of sediment composition within reef environments; sediment discharge, loading, and settling rates; and various water quality parameters including turbidity, water transparency, and temperature.

Light

The intensity and quality of incident light[8] is the most ecologically-limiting, physical environmental parameter in coral reef ecosystems, due to the critical role that incident light plays in rates of zooxanthellae photosynthesis and coral calcification. Reef-building corals are able to grow under a wide range of different light regimes, although the greatest densities of zooxanthellate corals are found in shallow, illuminated waters less than 30 m deep. Corals that are restricted to shallower depths in coastal areas, particularly near urban areas may be exposed to increased levels of sediments transported in from upland sources, resulting in higher sedimentation rates as well as reduced light transmission (Sheppard 1982). Reduced light levels have a profound affect on shallow water reef community structure and zonation patterns, with deeper water corals adapting to diminished light through changes in morphology (e.g., plating growth forms) or hosting a different genetic clade of zooxanthellae. Zooxanthellae also adapt to lower light by increasing the concentration of chlorophyll a and/or the relative composition of other pigments (e.g., beta-carotene, perdinin, and diadinoxanthin) (Hoegh-Guldberg 1999). Additionally, other factors can reduce light transmission reaching corals such as algal overgrowth (see section titled water sources). While turbidity may not be a critical characteristic to be monitored in many coral restoration projects, projects located near urban or agricultural areas may need to consider adding the characteristic as a monitoring variable based on local conditions or causes of decline.

Sediment composition - Spatial variability in the composition of sediments can be determined through the analysis of replicate cores collected in various locations within a particular coral reef and its associated habitats (USEPA 1985; Radtke 1997). The samples are subdivided into fractions based on their position within the core and analyzed in the lab to determine the relative proportion of carbonates and terrigenous components, specific constituents of the carbonates (e.g., amount of coral versus algal fragments), and the size of the grains (Sheldrick 1984; Pope and Ward 1998). For grain size analysis, sediment is dry sieved on a shaker through a standard sieve set, separating components into the following size fractions according to the Wentworth scale:

Sediment Type	Size Fractions
Pebbles	4-16 mm
Granules	2<4 mm
Very coarse sand	1<2 mm
Coarse sand	0.5<1 mm
Medium sand	0.25<0.5 mm
Fine sand	0.125<0.25 mm
Very fine sand	0.0625 <0.125 mm
Silt and clay	<0.0625 mm

The distribution of sediment types throughout the survey area is compared using a cluster analysis and dendrograms.

Sedimentation rates - The collection of samples at and above the substrate can provide an estimate of the amount of sediment being transported along the bottom as well as the sediment that is settling out of the water column (Rogers et al. 2001). Sediment traps (Figure 13) passively collect sediment that drops out of suspension over time (Baker et al. 1988; Rogers et al. 2001). These can be left in place for extended time periods to determine total sediment input, or more importantly over shorter, predetermined intervals to allow differentiation of acute sedimentation rates (e.g., sediment input associated with an unusual rainfall event) from chronic or seasonal patterns of sedimentation. Important considerations in the design of sediment traps include the distance that collection bottles are placed above the substrate, type of collection bottle (and size of opening), and duration between sampling events. Most sediment traps are constructed of multiple PVC pipes or jars attached to a steel rod and positioned at varying distances above the substrate. Each of the collection jars has a lid to seal it before removal and baffles at the top of

[8] Light that falls on a surface.

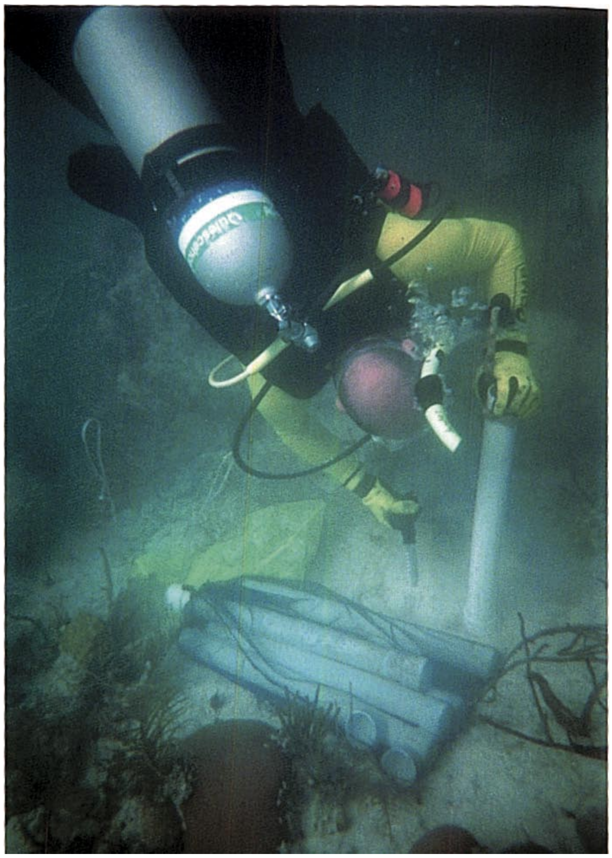

Figure 13. Diver installing a sediment trap. Photo courtesy of Kathy Price, NOAA Center for Coastal Environmental Health& Biomolecular Research (CCEHBR).

the jar to prevent entry of unwanted organisms. These are placed in replicate at various depths and collected typically on a weekly to monthly basis. Samples are filtered, dried, weighed, and analyzed in a laboratory.

In addition to the collection of sediment samples at the study or restoration site, discharge rates of sediments from streams and catchments can be measured using cutthroat flumes or open-channel stream gauging stations using automatic samplers or hand-held depth integrated samplers.

Suspended sediments - The amount and type of sediment and organic matter in the water column can be measured through the collection of water samples, followed by filtration and quantification in a laboratory. In many oligotrophic coral reef locations, the amount of suspended particles is very low and analysis requires the collection and filtration of large volumes of water.

HYDROLOGICAL

Currents and Wave Energy

Currents, wave action, and tidal changes have profound influences on reef distribution and also define coral zonation and distributional patterns within a reef. Water movement affects all aspects of the life history of coral reef organisms, including fertilization success, settlement, growth and mortality, and feeding success. Water motion also affects the supply of plankton and particulate matter, availability of dissolved nutrients, metabolic gas exchange, and removal of wastes, sediment, and excess mucus. In general, calcification rates are higher in areas of high water flow, although linear extension rates may be lower than in areas of reduced water flow.

Individual coral colonies display different and often distinctive growth forms, such as a branching, plating, crustose, or massive morphology, that are determined partially by their physiological and structural tolerances to water movement. Flow rates also influence the orientation, shape, and size of branches, with corals exhibiting reduced spacing and more robust, shorter, and thicker branches in areas of high wave exposure (Graus et al. 1977). Corals found on the windward side of islands, which are routinely exposed to strong waves, winds, and the full brunt of storms, tend to be stronger and hardier, but they may be less abundant and consist of fewer hardier species. Leeward reefs are protected from storm waves and the pounding surf, and tend to have higher diversity communities dominated by fragile, branching, and plating species. Distinct zones within a reef are defined by water motion in combination with other limiting factors such as temperature, salinity, food availability, depth of light penetration, and other factors. The reef crest, for example, is nearest to the water's surface and is constantly subjected to pounding waves, strong currents, and high light levels. As a result, reef crest environments are often dominated by small polyp-encrusting and robust branching corals and certain massive corals that can withstand extreme wave forces.

Water motion also plays a major role in the production, transportation, deposition, and resuspension of sediments, as well as the formation and stability of coral islands (i.e., cays). High water flow and turbulence is responsible for the transport of nutrients in sediments and detrital material out to sea or into back reef and seagrass environments. Reefs in embayments with restricted circulation are likely to experience nutrient build-up and may become eutrophic if they are adjacent to human population centers or agricultural areas. Storm waves are also important in preventing the burial of reefs by sediments, although the movement of sand and rubble can negatively impact sessile organisms through abrasion, dislodgement, and fragmentation, and may result in increased turbidity.

Hurricanes and tropical storms can have catastrophic impacts to coral reefs, though the extent and type of damage varies on small spatial scales. The amount and type of destruction are generally more severe in shallow, exposed habitats, but they also depend on the severity and duration of the storm, benthic community composition (e.g., fragile branching corals are likely to sustain greater injuries than robust, massive corals), and amount of time since a previous storm (Lirman 2001). Damage and mortality may result solely from the physical forces of hurricane-generated waves or from a combination of factors such as:

1) Abrasion and burial from transported sediments and coral fragments
2) Turbidity associated with resuspension of sediments and increases in plankton standing stocks
3) Decline in salinity with high sediment and nutrient loads associated with heavy rainfall and runoff from land, and
4) Rapid drop in temperature

Recovery of affected reefs following the passage of a hurricane may be rapid in communities dominated by branching corals, provided that detached and fragmented corals are deposited within the surrounding area and that they exhibit high rates of survival, reattachment, and regrowth (Highsmith 1982). Compounding factors such as additional storms, outbreaks of coral disease, intense predation on surviving corals, algal overgrowth, and a variety of human impacts may, however, delay natural recovery (Knowlton et al. 1990; Rogers et al. 1991).

The degree of wave exposure and frequency of storms has major implications for all aspects of coral reef restoration including restoration planning, implementation, and monitoring. In Florida, several restoration projects in response to major ship groundings required substantial structural reconstruction and stabilization to prevent expansion of the injury due to erosion during periods of high wave energy (Bruckner and Bruckner 2001).

Sampling and Monitoring Methods

There are several methods available to assess current patterns, wave exposure, surge, tides, and upwelling.

Current meters - Commercially available current meters (e.g., InterOcean S4 recording current meter) can be placed near the bottom or suspended in the water column to continuously sample water flow and record flow speed, direction, and pressure.

Clod cards or plaster blocks - Low cost methods that may be used to quantify water motion include clod cards or plaster blocks. Such methods provide a measure of overall water motion (mass flux) by monitoring the dissolution (e.g., loss of mass) over time. Clod cards or plaster blocks are appropriate for use in the evaluation of biological processes relevant to bulk water motion such as filter feeding rates, larval settlement rates, fertilization success and passive dispersal. One limitation is that the loss of mass is affected by bulk movement of water past the object as well as turbulence, making it difficult to quantify water movement (Bell and Denny 1994).

Recording spring scale or dynamometer - A recording spring scale or dynamometer may be used to estimate the direction and maximum magnitude of wave-induced forces. These instruments typically consist of a small ball attached to a spring that is secured to the substrate. With each passing wave, the motion of water generates drag on the ball, causing the spring to extend. By recording the maximum extension of the spring, an estimate of the maximum hydrodynamic force can be made (Bell and Denny 1994). Knowledge of the maximum velocity to which organisms are exposed allows predictions of the degree of hydrodynamic disturbance (e.g., likelihood of dislodgement of sessile organisms) and could help develop possible restoration alternatives, such as the appropriate organisms to transplant at the site.

Wave characteristics, including wavelength (length between successive crests), height (vertical difference between trough and crest), steepness (ratio of height to length), amplitude (half of the wave height), period (time between successive waves passing a fixed point), and frequency (the number of occurrences within a given time period) are measured using a variety of methods. These include pressure gauges placed on the sea floor, accelerometers attached to buoys on the sea surface, and remote sensing from satellites. Other methods for measuring wave energy, direction, height, and periods are discussed in Draper et al. (1974); Middleton et al. (1978); Fu et al. (1987); Brumley et al. (1983); AshokKumar and Diwan (1996); Tortell and Awosika (1996); Terray and Brumley (1999); and Yang et al. (2004).

Temperature

Most coral reefs occur in areas where temperatures rarely drop below 16°C or exceed 30°C, with an optimal range of 26-29°C. Although there are regional differences in the minimum temperature tolerance of some species, very few zooxanthellate corals tolerate temperatures below 11°C over prolonged time periods (Veron 1995). Water temperature limits the occurrence of reefs and reef-building corals through interactive ecological processes where the energy demands of reef construction become progressively less competitive against macroalgae-dominated ecosystems as temperatures decline (Veron 1995). Low temperature is one of the main environmental factors responsible for the absence of coral reefs in areas of intense upwelling along the western margin of continents, and growth rates of corals are correlated with temperature. Growth rates of corals in the Caribbean are greater than their members of the same species or genus further north, with declines observed during cold water periods and on high latitude reefs subject to greater temperature and light variations (Lewis et al. 1968; Gladfelter 1984). Estimates of mean growth of *M. annularis* in Barbados and Jamaica surpassed estimates from Florida by 1.8-2.4 times, and growth rates for *A. cervicornis* in these countries also exceeded Florida by factors of 1.3 and 2.3, respectively (Shinn 1966; Lewis et al. 1968). Furthermore, the occurrence of periodic cold fronts has limited the distribution of certain species, has been associated with partial to total colony mortality and bleaching, and has significantly altered large-scale features of reefs in locations like southern Florida (Saxby 2001). For instance, a cold water event in 1977 in the Dry Tortugas led to the sudden demise of prominent *A. cervicornis* thickets (Davis 1982). Walker and Ormond (1982) proposed that the growth rates and distribution of *Montastraea annularis* in the northern Florida Keys were in large part controlled by the periodic influx of cold water pushed out from Florida Bay during the passage of major cold fronts.

Most corals exist near their upper thermal limits. Heat stress associated with reduced tidal flushing, abnormally low tides, inter-annual climatic fluctuations (e.g., El Niño Southern Oscillation events), and the discharge of heated water from electrical and nuclear power plants has been demonstrated to affect rates of growth and calcification, metabolic functions, reproductive activity, and resistance to pathogens and disease (Neudecker 1981; Hung et al. 1992; Wilson et al. 2002). Warming of 1-2°C above the mean summer maximum temperatures for one to two weeks may also trigger the loss of zooxanthellae through bleaching (Figure 14). Localized coral bleaching was first reported at least 90 years ago (Vaughan 1914; Boschma 1924). Regional bleaching events were first observed in 1979-1980, with bleaching events of increasing extent and severity occurring in 1982-1983 and 1986-1988 (Williams and Bunkley-Williams 1990). Since the 1990s, regional scale bleaching has become a pervasive and frequent phenomenon, with the most intensive and extensive coral bleaching event on record occurring during the unusually strong El Niño/La Niña event of 1998-1999 (Wilkinson et al. 1999). Variation in temperature thresholds for bleaching and mortality may be related to the physiology of the coral or clade of zooxanthellae, the degree of adaptation of a species to a particular habitat or zone, as well as physical and environmental factors that may enhance susceptibility or resilience of the habitat (e.g., upwelling, turbidity, current patterns) to stressors (Williams and Bunkley-Williams 1990; Edmunds 1994; Fitt and Warner 1995; Kramer and Kramer 2000).

Sampling and Monitoring Methods

It is important to monitor water temperature fluctuations to help understand and characterize differences in coral growth, survival and recruitment, patterns of coral bleaching, and relationships between temperature and mortality or recovery.

Coral Reef Early Warning System (CREWS) stations - NOAA established CREWS stations (Figure 15) in a number of locations in the Caribbean and Pacific to record basic

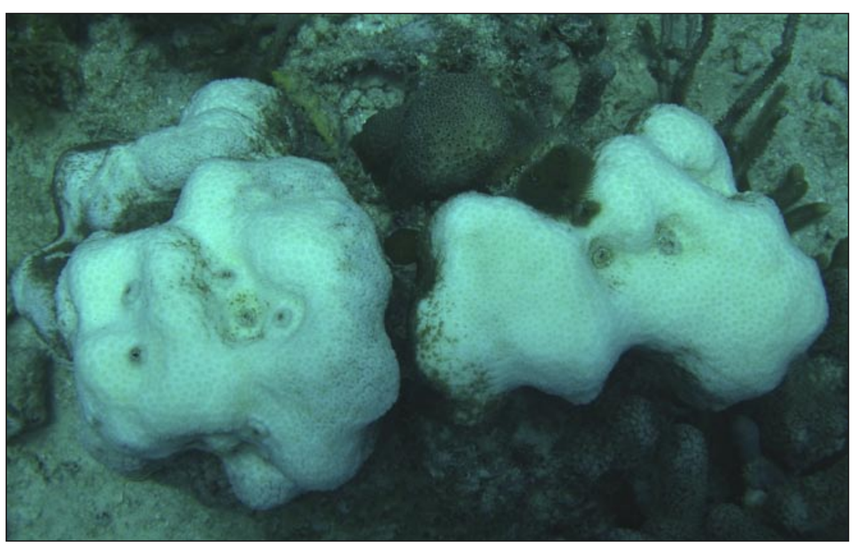

Figure 14. Bleached coral in the Caribbean waters. Photo courtesy of Andrew Bruckner, NOAA National Marine Fisheries Service.

Figure 15. A CREWS station at Lee Stocking Island, Bahamas. Photo courtesy of Andrew Bruckner, NOAA National Marine Fisheries Service.

meteorological and oceanographic parameters such as water temperature on an hourly basis. Data from CREWS stations assist in the prediction and interpretation of patterns and trajectories of coral bleaching, coral mortality, growth, and other parameters. While CREWS stations provide valuable comparative regional data, local water temperatures may vary, and should be monitored within study sites to obtain accurate information on temperature-related impacts. Temperature should be measured just below the water surface (approximately 30 cm) as often as possible using a mercury thermometer enclosed in a protective casing.

***In situ* Data loggers -** Data loggers (e.g., Hobos temperature meters) can be deployed on the reef to instantaneously record sea temperatures at intervals ranging from every few minutes to daily or weekly, and can provide average, minimum or maximum temperatures over a specific duration. Information from data loggers can be downloaded as frequently as necessary, and depending on the unit and the frequency of measurement, the instruments can be left in place for months to years. Data loggers should be calibrated against a certified reference thermometer after each deployment (Colin 2000; Fitt et al. 2000).

Water Sources

Upwelling[9]

Coral reefs thrive in waters that contain low levels of inorganic nutrients (i.e., oligotrophic waters). Nutrient concentrations are generally much lower than those of temperate coastal systems (e.g., 0.1-0.5 μM nitrate, 0.2-0.5 ammonium, and <0.3 phosphorus; Furnas 1991). At higher latitudes, as well as areas prone to intense upwelling, increased nutrient concentrations and high influxes of nutrients may limit reef development. In many locations, terrestrial discharges of nutrients and other pollutants to coastal waters have increased considerably from pre-industrial levels, reflecting increases in human activities in the surrounding watershed. Persistently high concentrations and fluxes of nutrients are major factors contributing to the decline of reefs. This has become especially problematic in coral reefs located close to shore, especially within embayments and lagoons and in reefs associated with large land masses and significant human populations.

Although excess nutrients are generally problematic, a continuous supply of inorganic nutrients is essential for the maintenance of metabolic processes, proper functioning of reef ecosystems, and persistence of coral and coralline algae-dominated communities. Many flourishing coral reefs occur in regions subjected to seasonal upwelling or other natural events such as volcanic eruptions that contribute temporary pulses of nutrients. Nutrient fluxes associated with upwelling events, currents, tides, and other sources can play an important role in the overall productivity of coral reefs. Furthermore, reefs will persist in areas affected by nutrient loading, provided that herbivores are sufficiently abundant and diverse and are able to control proliferation of macroalgae. Even under

[9] Transport of subsurface water to the surface.

low nutrient conditions, coral reefs are seldom subject to nutrient limitations due to the efficient recycling by the reef community and nitrogen fixation by cyanobacteria and other organisms.

Coral reef ecosystems can persist in areas affected by elevated nutrients and plankton productivity as long as water circulation removes excess production off the reefs and maintains water clarity. Once productivity increases to such an extent that water clarity and light penetration is reduced, normal functioning of the reef may be affected (Tomascik and Sander 1985). Chronic nutrient over-enrichment can introduce an inbalance in the exchange of nutrients between zooxanthellae and the host coral, and reefs may exhibit a progressive shift from high coral cover and low algal cover/biomass to high cover and biomass of fleshy algae. As algae decompose, dissolved oxygen concentrations may be greatly reduced, especially in coastal areas with limited flushing. Nutrients can also indirectly affect the reef structure through proliferation of fleshy and filamentous macroalgae that can rapidly overwhelm coral populations, and through an increased abundance of filter feeders such as boring sponges which are responsible for the bioerosion of reefs (Szmant 2002). The combined effects of reduced herbivory (resulting from overfishing and/or die-off of herbivorous sea urchins) and anthropogenic nutrient enrichment has been implicated in phase-shifts from coral-dominated systems to macroalgal-dominated communities throughout the Caribbean during the last two decades (Hughes et al. 1999; Stambler 1999; Szmant 2002).

Coral reefs prone to the effects of high nutrient concentrations are usually exposed to other anthropogenic stressors, such as:

- Increased sedimentation,
- Organic carbon enrichment, and
- Metals and organic pollutants originating from agriculture, industry, and stormwater runoff

Degraded water quality has direct physiological effects on corals, can affect growth and reproductive rates, may destabilize the functioning of the coral-zooxanthellae symbiosis, and may increase coral susceptibility to diseases or bleaching (Kim and Harvell 2002). By evaluating coral reef water sources, and the potential impacts resulting from them, restoration practitioners can design an effective restoration plan to include parameters to monitor water quality. Discussed below are examples of how upland and groundwater sources of water and freshwater inputs can affect coral reefs.

Upland source

The effects and degree of nutrient enrichment (i.e., eutrophication) vary greatly depending on the source (and type and extent of pre-disposal treatment), accompanying contaminants (e.g., organic matter, sediment loads, pesticides and herbicides, oil, heavy metals, and pharmaceuticals and/or pathogenic microorganisms), as well as interactions between gross production and total community composition. The most common causes of eutrophication of coral reefs are:

- Discharge of sewage and agricultural wastewater, with localized impacts from power-generating plants and other industrial discharge
- Forest clear-cutting
- Coastal development and dredging
- Oil drilling, production, and transport
- Beach renourishment, and
- Metal mining (Dubinsky and Stambler 1996)

Groundwater source

Because coral reefs are frequently surrounded by highly porous, limestone drainage areas, groundwater discharges from adjacent industrialized and urbanized terrestrial areas may be considerable, and in many cases have high nutrient content associated with sewage discharge and fertilizer runoff from agricultural areas, hotel gardens, and golf courses. The submarine groundwater discharge flux and associated input of nutrients, dissolved organic carbon, trace elements, and other contaminants could be quantified using naturally occurring radium (Ra) isotopes. Radium isotopes have been shown to be excellent tracers for groundwater inputs into estuaries and coastal areas (Moore 1996; Hussain et al. 1999; Krest et al. 2000). There are four radium isotopes (^{224}Ra, ^{223}Ra, ^{228}Ra, and ^{226}Ra) with a wide range of half-lives (3 days to 1600 years) that are produced by the decay of uranium and thorium in aquifer rocks. The presence of brackish or saline water along the coast causes the Ra to desorb, greatly increasing the concentration of dissolved Ra in saline coastal groundwater (Moore 1996). Through such analysis, the effect of groundwater sources on the delicate carbon and nutrient balance of coral reef ecosystems can be evaluated.

An understanding of the effects of nutrients on coral reef communities as well as how and when nutrient enrichment has contributed to coral reef decline or recovery requires consideration of all mechanisms involved in nutrient dynamics of coral reef ecosystems. These include:

- Patterns of upwelling versus coastal input of nutrients, sediments, and pollutants
- Degree of physical and biological transport and exchange of nutrients and other materials within reef zones and surrounding habitats
- Patterns of productivity and fates of primary production
- Composition, abundance, and biomass of fish and invertebrate grazers, and
- Grazing pressure and preferences, and effects of reduced herbivory on algal diversity and palatability

Freshwater inputs and salinity increase

The salinity of coastal and offshore environments is influenced by a number of environmental factors such as runoff, precipitation, evaporation, surface current patterns, and upwelling. Coral reefs are normally found in areas with salinities of 32 to 40 parts per thousand (ppt), with higher salinities (up to 45 ppt) reported for certain parts of the northern Red Sea and the Arabian Gulf. There is a general absence of corals reefs adjacent to major rivers (e.g., reefs do not occur adjacent to the Amazon and Orinoco River basins) primarily due to low salinity. As salinity declines, carbonate reefs are progressively dominated by vermetids, oysters, serpulids, and blue-green algae.

Salinity fluctuations are a key factor determining local zonation patterns of corals, with reefs in close proximity to major freshwater sources dominated by a few hardy species (e.g., certain species of *Porites, Montipora, Siderastrea,* and *Goniopora*). Certain species of corals found in tidepools, shallow nearshore lagoons, and near rivers are adapted to hypersaline and hyposaline waters, and can survive temporary salinity changes during periods of rainfall or drought. In a shallow lagoon within Biscayne Bay, Florida, which is periodically affected by reduced salinity levels during the rainy season, only a limited number of coral species, including *S. radians* (lesser starlet coral) and *P. furcata* (finger coral) can survive (Lirman et al. 2003). Rapid decreases in salinity after monsoon rains or flood events, as well as chronic stress due to flood rains or rates of evaporation that are outside the normal range experienced in a particular environment, can create conditions that fail to sustain corals. In addition to the effects of heavy rainfall, upwelling, natural fluctuations in salinity, and discharges from freshwater point sources and wastewater and power plants have caused coral mortality events (Jokiel and Coles 1974).

Experimental studies have found that most corals will not tolerate salinities at 110% of normal levels for more than two weeks, while salinities of 150% of normal levels will kill a coral within 24 hours (Borneman 2001). Four reef-building corals found in the Pacific - *Porites lutea*, *P. australiensis, Galaxea fascicularis*, and *Goniastrea pectinata* - died in less than 24 hours when exposed to 53 ppt, died in less than a week at 48 ppt, and experienced partial mortality when exposed to 44 ppt (Nakano et al. 1997). In addition to the potential for increased coral mortality associated with higher than normal salinities, a 20% reduction in salinity resulted in up to an 84% decrease in reproductive success (Richmond 1993). Since wide salinity fluctuations and factors that increase or decrease salinity levels can have detrimental impacts on benthic reef-building corals, salinity levels should be monitored within reef restoration sites to verify the role of salinity perturbations in the success of the project.

Sampling and Monitoring Methods

Water quality - A variety of methods are available to assess water quality parameters. Although inexpensive field kits exist, accurate estimates require sensitive detection methods due to the low nutrient fluxes observed in many oligotrophic reefs. It is recommended that nutrient sampling include analysis of both the water column and bottom sediments. Sampling should be undertaken at a minimum of four times per year, while weekly or bimonthly monitoring may be necessary to account for seasonal differences as well as sporadic major rainfall events. It may be difficult to detect nutrient influxes in areas affected by phytoplankton blooms because phytoplankton rapidly remove nutrients from the water. Thus, nutrient measures should be supplemented with measurements of chlorophyll under these conditions. Water samples are usually collected in acid-washed syringes or bottles, stored on ice, and frozen for later analysis in the lab. Water samples can be analyzed for dissolved inorganic and organic nutrients (nitrates, nitrites, ammonia, phosphates, and silicates) and sediment core samples analyzed for total carbon, nitrogen, and phosphorus. In addition, analysis of trace metals and other contaminants may be particularly useful for reefs adjacent to industrialized and urbanized watersheds.

Some methods to assess nutrients and related literature include:

- Seepage cylinder to estimate nutrient discharge in groundwater in nearshore areas (Corbett et al. 1999)
- Fluorometric analysis (e.g., ammonium and dissolved organic matter analysis, see Holmes et al. 1999)
- Persulfate method (total nitrogen and phosphorus in water samples, see D’Elia 1977)
- Cadmium reduction method (Parsons et al. 1984), and
- Flow autoanalyzer (Ryle et al. 1981)

There are numerous general water chemistry method manuals that provide detailed explanations on the necessary equipment and methods for conducting water quality analysis. These include: Strickland and Parsons (1972), USEPA (1983), Parsons et al. (1984), and APHA, AWWA, and WEF (1995). Additional resources can be found in the second appendix of this chapter.

Salinity

Salinity can be measured using a hydrometer, refractometer, or salinity meter. Water samples should be collected in small plastic vials from the surface and just above the substrate of the study site. For sites located near a freshwater discharge, a series of salinity measurements should be made to determine the extent of any gradient in salinity caused by the freshwater input.

Hydrometer - A hydrometer is placed into a tall flask with the sample water and salinity is determined by taking a reading of the position of the water surface at the bottom of the meniscus (Rogers et al. 2001). Hydrometers are typically calibrated for use at a specific temperature and a conversion chart must be consulted to estimate salinity of a sample taken at a different temperature (Rogers et al. 2001).

Refractometer - A refractometer is a hand-held instrument that measures the bending of light between dissolved salts as it passes through seawater (Strickland and Parsons 1972; Parsons et al. 1984; Rogers et al. 2001). To measure salinity, one or two drops of the sample are placed on the prism. The observer holds the cover down, faces the instrument toward the light, and looks at the scale through the eye piece to determine the salinity (Rogers et al. 2001). A refractometer must be frequently recalibrated with distilled water and may give incorrect readings in turbid waters.

Salinity meter - The most expensive and accurate measure of the salt content of water is an electronic salinity meter comprised of a probe connected by a cable to meter or a computer.

CHEMICAL

The chemical characteristics associated with coral reefs include nutrient concentrations from various water sources (discussed in the previous section, “Water Sources”) and, nutrients provided by epiphytes and algae that support corals. In the Functional Characteristics section of this chapter, under the segment titled “Supports Nutrient and Carbon Cycling,” is a discussion on the role epiphytes and algae play in supporting coral reefs.

FUNCTIONAL CHARACTERISTICS OF CORAL REEFS

Coral reefs and associated mangrove forests and seagrass beds perform important biological, ecological, and physical functions. Two of the main outputs of reefs are organic and inorganic carbon production. Carbon, available as bicarbonate ions dissolve in seawater, is fixed by reef organisms for the production of their skeletons at an annual rate of 1-10 kg per m^2 (Kinsey 1991). The resulting skeletal structure provides a substrate for the settlement and attachment of other sessile organisms, as well as topographical relief that serves as habitat for motile fishes and invertebrates. Coral and algal skeletal materials are also broken down into sediments that form beaches and soft bottom habitats, are incorporated into the reef structure, and form an important part of the inorganic carbon pathway.

Primary production of organic carbon by symbiotic zooxanthellae, turf algae, macroalgae, and coralline algae ranges from 3.5-32.2 kg per m^2 annually (Crossland et al. 1991). This production supports the diverse organisms and complex food webs found on coral reefs. In addition to sunlight as an energy source fueling photosynthesis and water motion for transporting resources and removing wastes, high rates of primary production are maintained through rapid removal of primary producers. Through grazing and dislodgement, turf algae and frondose algae are maintained in an early stage of ecological succession where rates of photosynthesis and growth are highest (Choat 1991). Secondary consumers (predators of herbivorous fishes and invertebrates) further enhance reef productivity by maintaining their prey in high growth phases and by supplying concentrated nutrients to their prey (Williams and Carpenter 1988). Furthermore, gradients of water temperature, light, nutrients, and organic matter affect the functions of coral reef ecosystems. Along gradients from offshore oligotrophic waters to nearshore eutrophic conditions, the symbioses between zooxanthellae and corals decrease, abundance of heterotrophic suspension feeders increases, and ratio of organic carbon to inorganic carbon production increases (McClanahan et al. 2002).

Of tremendous importance to the function of coral reefs is their proximity to other associated communities such as seagrass beds and mangroves. Mangroves (Figure 16) are highly productive habitats found on cays associated with leeward reefs and along the shoreline in areas protected from the full force of waves. They act as a buffer between the land and sea, trapping much of the soil and nutrients that runoff from land. Most of the production in mangroves is associated with the microbial community in the sediments, which is responsible for breaking down the organic matter from land and leaves that fall off trees, which is largely exported

Figure 16. Mangroves in Florida. Photo courtesy of Andrew Bruckner, NOAA National Marine Fisheries Service.

to reef communities where it is utilized as a nutrient source.

Mangrove roots also act as nurseries and shelter for a number of coral reef species including juvenile fishes, mollusks, and lobsters. Seagrass beds provide food, shelter, and nurseries for reef-associated fishes and invertebrates, and also play an important role in trapping sediments and excess nutrients from reef communities and land.

Some of the functional roles of coral reefs and associated habitats include:

Biological

- Contributes to primary production
- Provides habitat and shelter/refuge for motile fish and invertebrates and cryptic fauna and flora
- Provides breeding, feeding, and nursery habitats for a wide range of marine species
- Provides hard substrate for settlement and growth of sessile organisms

Physical

- Protects shorelines from strong wave action and full impacts of storms

Chemical

- Supports nutrient and carbon cycling

BIOLOGICAL

Contributes to Primary Production

Coral reefs have high rates of gross production but generally little net excess production due to consumption of primary productivity by reef heterotrophs and highly efficient nutrient recycling between producers and consumers. Benthic and endolithic algae, cyanophytes, seagrasses, and zooxanthellate corals contribute significantly to primary production and enter the food web in varying ways. Algal turfs trap organic debris and provide sites for bacterial growth, and are a major accessible source of food for grazing benthic herbivores and detritivores. Reef-building corals gain much of their nutritional requirements from zooxanthellae. Corals also utilize other food sources to varying degrees, including zooplankton, suspended bacteria, detritus particles, and dissolved and particulate organic substances, and their waste products are translocated to the zooxanthellae. Algal mats, especially those within damselfish territories, often support blue-green algae populations that contribute significantly to reef nitrogen fixation.

Provides Habitat

Coral reefs show considerable structural diversity through a wide variety of ecological zones and numerous microhabitats. These habitats are created through both accretionary processes of reef-building organisms (e.g., corals and algae) and destructive forces that mechanically erode, dissolve, or bioerode their skeletons. Coral reefs are also often associated with other habitats such as mangroves and seagrass beds, many of which support unique sets of characteristic invertebrate and fish fauna or particular life stages of reef-dwelling species. Environmental conditions (e.g., wave exposure, currents, storm frequency, light levels, temperature) and biological factors (e.g., rates of bioerosion, type and amount of available food, competition, etc.) affect the distribution, abundance, and growth forms of the corals and other framework builders, as well as the occurrence of mangroves and seagrasses. Coral reefs vary enormously in size, shape, physical exposure, geological history, and vertical depth contours. Even within similar ecological zones, the spatial distribution of structure-forming organisms, algae, and sessile and mobile animals vary widely among reefs, partially due to differing morphologies of corals of different species and also the intermixing of coral assemblages with rubble, sand, and hard ground substrata.

The high diversity of species found on coral reefs is a direct reflection of the high number of niches afforded by this environment. In addition to macroinvertebrates and fishes found on the surface of the reef and in the water column, diverse species assemblages inhabit crevices and fissures in the reef. Many species occur in association with living and dead coral heads, and symbiotic relationships are plentiful. In addition, a specialized community of macroscopic and microscopic animals and plants live below the surface of the sand and rubble and within the skeletons of living and dead corals. Each species found on a coral reef has a specialized role in the ecosystem and contributes to the complex trophic food webs found there. Many species restrict their range to a particular section of the reef to suit particular needs such as refuge; substrate for attachment; or feeding, resting, nursery, and/or breeding grounds (*all of which are discussed in the following sections*). Other species may utilize multiple habitats during different stages of their life or different times of day. The organisms found among coral reefs can be grouped into the following categories:

- Ecologically, commercially, and recreationally important fish such as grouper *Epinephelus* spp., snapper *Lutjanus spp.,* grunts (Figure 17)
- Mobile macroinvertebrates (lobsters, crabs, mollusks, and echinoderms)
- Sessile and sedentary invertebrates (sponges, tunicates, gorgonians, and bryozoans)
- Infaunal organisms and meiofauna (diatoms, foraminifera, and microinvertebrates)
- Endolithic algae and cyanboacteria
- Epilithic and benthic algae (turf algae, macroalgae, crustose and erect coralline algae, and cyanobacteria) (Figure 18)
- Flowering plants (seagrasses and mangroves)
- Zooplankton and phytoplankton

Provides Shelter/Refuge from Predation

The structure of fish and invertebrate communities is influenced by the physical complexity of the substrate and amount of coral cover, with increases in substrate complexity providing a greater diversity of shelter and feeding sites. Coral reefs contain numerous crevices, fissures, and convolutions that increase spatial heterogeneity and microhabitat variety.

In general, small sessile invertebrates are most abundant on internal reef surfaces where they are protected from most predators, while

Figure 17. Grunts (Haemulidae) in staghorn coral (*A. cervicornis)*. Photo courtesy of Andrew Bruckner, NOAA National Marine Fisheries Service.

Figure 18. Coral reef covered with brown algae (*Lobophora*). Photo courtesy of Andrew Bruckner, NOAA National Marine Fisheries Service.

algae, zooxanthellate corals, sponges, and other large sessile invertebrates are found on open reef surfaces, often in areas with high rates of herbivory. Certain corals that are extremely vulnerable to predation, especially those with a branching morphology (i.e., *Acropora*), often proliferate in turbulent reef zones and shallow reef-flat habitats where they escape predation by sea stars and other corallivores due to high wave exposure that limits the occurrence of these predators.

Interstices formed by coral skeletons trap plankton and provide shelter for small invertebrates. Some macroalgae and sessile animal taxa such as bryozoans, polychaetes, mollusks, barnacles, and tunicates occur in these crevices. Filamentous green algae, cyanobacteria, and crustose coralline algae are often abundant in cryptic habitats such as the underside of foliaceous corals. In both microhabitats, the intensity of feeding by other herbivores and carnivores is reduced. Many of the algal species found on coral reefs also have defensive strategies that protect them from grazing. A number of red coralline algae (e.g., *Porolithon* spp.) are hard and plate-like. Many brown algae are leathery and contain spines (e.g., *Turbinaria* spp.) and some green algae are calcified (e.g., *Halimeda*) or produce toxins (e.g., *Caulerpa)* to deter herbivory.

The potential risk of predation within exposed coral reef environments limits grazing activities of smaller reef fishes to areas with considerable structural relief. The distribution of herbivorous fish varies inversely with tidal exposure and wave action as well as with the availability of shelter for the herbivores from predatory fishes. Herbivorous fishes may be low in abundance in the very shallowest sites due to limited accessibility, abundant at intermediate depths due to high accessibility and shelter, and rare in deep reefs where the abundance of shelter declines (Hixon 1991). In areas where overfishing has reduced the abundance of piscivores, herbivorous fishes may be active over greater depths and algal standing stocks will be lower (Hay 1984). Furthermore, where large shelters are nearby, large herbivorous fishes will be locally abundant, while areas with few large shelters and numerous small shelters will have a dominance of small herbivores.

Diurnal[10] species such as most herbivorous fishes (e.g., surgeonfishes, damselfishes, and parrotfishes (Figure 19)) and small predatory fishes (e.g., goatfishes) rely on vision to feed. At night, most diurnal animals seek shelter within crevices in the reef (e.g., surgeonfish), bury themselves within the sand (e.g., wrasse), or construct mucus cocoons (e.g., some parrotfish) to block detection. If they are too large to shelter within protected spaces, many fishes go through a nightly color change, typically becoming darker. Many nocturnal predators (e.g., grunts, soldierfish) are highly gregarious during the day, and often shelter in dense, resting schools under coral heads in reef caves and crevices.

In addition to structural refuge offered by coral reefs, fish and invertebrate prey minimize the risk of predation through their morphology,

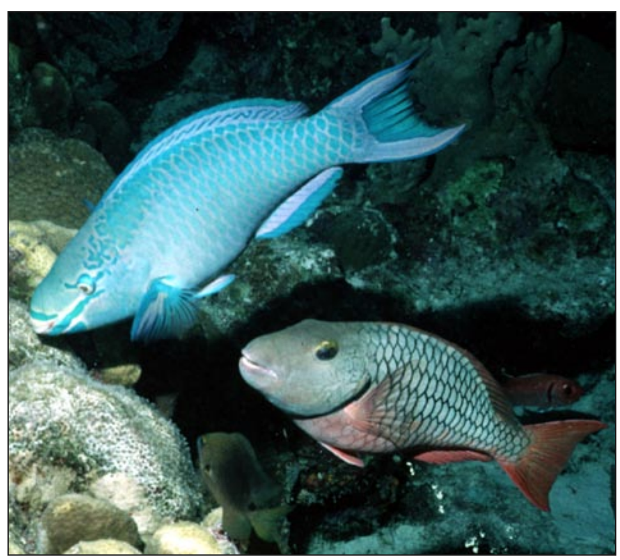

Figure 19. A terminal phase (male) princess parrotfish and an initial phase stoplight parrotfish. Photo courtesy of Andrew Bruckner, NOAA National Marine Fisheries Service.

[10] Organisms active during the daytime.

color, toxins, and behavioral modifications such as schooling. Reef fishes exhibit a variety of body shapes and structures that discourage predation, such as tough skin, spines, ability to inflate, and deep bodies. Cryptic coloration, including mimicry[11], eyespots, and aposematic warning coloration is widespread among benthic reef fishes. Many nocturnal fish are red, which makes them invisible to predators.

Provides Breeding Grounds

Coral reef species have an extraordinary diversity of reproductive patterns defined by life history traits of the organism. The majority of coral reef species exhibit complex life cycles that include separate planktonic larval stages and bottom-dwelling juvenile and adult phases. Reproductively mature adults may spawn larvae (or gametes) into the water column, deposit eggs on the substrate, or incubate the eggs and release offspring in various stages of development, depending on the extent of parental care. To understand and predict changes in spatial and temporal distribution, abundance, population structure, and patterns of recovery following disturbance, it is necessary to understand the life history of the species of concern, environmental factors affecting the site, ecological interactions among associated species, and processes that affect survival of both planktonic and benthic phases of the organism.

Invertebrate reproductive patterns

Invertebrates exhibit both sexual and asexual reproduction and provide varying degrees of parental care to their offspring. Reproductive activities show annual, seasonal, monthly, lunar, and daily patterns. Environmental parameters such as seawater temperature, day length, salinity, food, moonlight, and tidal cycles regulate reproductive cycles through interactions with endogenous biorhythms.

The most common strategy for sessile invertebrates, including many of the coelenterates, sponges (Figure 20), bivalves, mollusks, tunicates, tube worms, and bryozoans, is to release eggs and sperm into the water column for external fertilization. Organisms using this strategy are referred to as broadcast spawners. Reproduction is usually seasonal and concentrated during brief annual periods. Most stony and soft corals, sponges, and several other sessile invertebrates participate in predictable mass spawning events, reproducing within several days of the full moon or new moon during summer. This strategy may maximize fertilization success and saturate planktonic predators such that a high proportion of the eggs survive.

A number of stony corals also brood their larvae. Eggs are fertilized internally by sperm picked up from the water column and well-developed planulae are released into the water. Some brooded planulae are produced asexually. Corals that brood larvae often reproduce on a lunar cycle for a number of months per year, and the large larvae that are released settle within hours to days after release, often recruiting close to the parental stock. About three quarters of all corals are simultaneous hermaphrodites and produce both male and female gametes, while the remainder has separate male and female individuals (Richmond and Hunter 1990).

In asexual reproduction, new clonal polyps are formed through budding of the "parent" polyp as

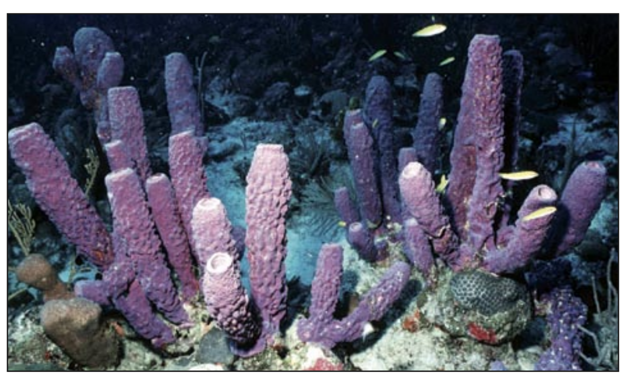

Figure 20. Sponges (Porifera). Photo courtesy of Andrew Bruckner, NOAA National Marine Fisheries Service.

[11] Resembling another organism or structure to avoid being seen.

the colony continues to expand in size. Budding, fission, polyp bail-out, and fragmentation of adult colonies are also employed by corals and other anthozoans to form new colonies.

A number of motile invertebrates including most echinoderms, polychaetes, and certain mollusks (chitons and scaphopods) also release gametes into the water column for external fertilization. Most other motile invertebrates also have a planktonic larval phase, although reproduction may involve internal fertilization following copulation.

Gastropods and cephalopods may encase eggs in gelatinous strings or masses or in hardened capsules, and attach them to the substrate, although some gastropods brood their eggs. Most mollusks have separate sexes, with the exception of many limpets, the coral-eating snail *Coralliophila,* and other prosobranches that are protandrous hermaphrodites (i.e., change from male to female). Large numbers of reef squid come together to copulate and spawn at the same time, depositing a community pile of egg strings. Octopods care for the eggs after they are deposited and the females of some species die after the eggs hatch.

Almost all crustaceans have separate sexes, with the exception of a few shrimp that are protandrous hermaphrodites. Crustaceans typically copulate seasonally, shortly after the female molts. The female will brood eggs on her abdomen for several months before releasing larvae into the water column.

Reproductive patterns of fishes

Spawning patterns of reef fishes vary on daily, lunar, and seasonal time scales, with most fishes having long reproductive seasons characterized by one or more annual peaks. Species that spawn on a daily periodicity may have fixed, short spawning periods based on the timing of the tides or other factors, while others spawn throughout the day (e.g., parrotfishes and wrasses). For species that spawn on a lunar cycle, seasonally, or annually, reproduction of an entire local population may by synchronized or acyclic and unsynchronized. In addition to temporal variations, there is considerable variation in where and how species spawn, the types of eggs they produce, and the amount of parental care. Most fishes release a cloud of gametes into the water column for external fertilization, while others deposit their eggs on the benthos, either indiscriminately (e.g., chromis and sergeant major) or in discrete clutches that are intensively guarded (e.g., damselfishes). Some species spawn within a small home range or territory, either close to the reef (primarily small fishes) or in the water column. Several pelagic spawners migrate to traditional spawning grounds. Small grazers, planktivores, and mobile invertebrate feeders (bluehead wrasse, certain parrotfish, goatfish, and surgeonfish) typically travel short distances to local spawning areas, while large predatory groupers and snappers may migrate tens of kilometers to form transient spawning aggregations. Seahorses, jawfishes, and several species of cardinal fishes incubate eggs inside their mouths or within an abdominal pouch until hatching. Internal fertilization and live-bearing young is the least common reproductive strategy of reef fishes, but typical of sharks (Figure 21) and rays (Sale 1991).

Fishes that are characterized as broadcast spawners often exhibit polygamy (multiple mates), while many small site-attached pelagic spawners have small harems consisting of a single territorial male and multiple females (e.g., parrotfish and wrasses). In addition, a number of species, including most wrasse, parrotfish, and sea bass families are sequential hermaphrodites that change sex from female (initial phase) to terminal males (protgynous hermaphrodites). Less common are protandrous hermaphrodites (e.g., snook) and simultaneous hermaphrodites with both functioning ovaries and testes (small sea basses like hamlets - Figure 22). While most species will mate with multiple partners, several

Figure 21. Nurse shark (*Ginglymostoma cirratum*) among coral reefs. Photo courtesy of Andrew Bruckner, NOAA National Marine Fisheries Service.

Figure 22. Hamlet (*Hypoplectrus* spp.) near Colpophyllia (brain coral). Photo courtesy of Andrew Bruckner, NOAA National Marine Fisheries Service.

angelfish, butterfly fish, seahorses, pipefishes, jawfish, and other species establish stable relationships that last several breeding cycles.

The timing, location, and behavior of spawning in reef fishes are affected by risk of predation on adults and generally occur where and when the eggs and larvae have a high probability of drifting safely away from the reef (Sale 1991; Deloach 1999).

Provides Feeding Grounds

Coral reefs are characterized by complex trophic food webs consisting of diverse assemblage of primary producers, filter feeders, grazers, predators, and scavengers. The primary producers include symbionts associated with corals, giant clams, sponges, and other organisms, as well as algae, seagrasses, and cyanobacteria. Algae, cyanobacteria, and coelenterates dominate the community structure and production of new organic materials. Invertebrates and fishes transform this plant material into animal material and also utilize external sources of organic material, particulate organic carbon, and zooplankton. Herbivores include surgeonfish, parrotfish, and other fishes as well as a number of invertebrates (e.g., urchins and some mollusks and crustaceans) that feed primarily on benthic algae; a number of fishes and invertebrates also consume plankton. Herbivores are represented by browsers with cutting teeth that feed primarily on algae and grasses above the substrate and grazers that crop very close to the substrate, ingesting plant tissue and a portion of the associated substrate. They feed primarily on unicellular algae (e.g., diatoms), filamentous and fleshy algae on benthic substrates, and algae and seagrasses consumed incidentally with other prey items (e.g., epiphytes). A high diversity of secondary consumers are also found in the interstices of coral colonies and include filter and suspension feeders such as sponges, sipunculids, polychaetes, mollusks, and crustaceans. Macroinvertebrate feeding strategies are varied and include suspension or filter feeders that consume phytoplankton and zooplankton (e.g., sessile invertebrates), detritivores that ingest sediment and organic matter (e.g., sea cucumbers), corallivores that prey on reef-building corals, gorgonians and other cnidarians (certain gastropods, polychaetes, and echinoderms), invertebrate predators (certain polychaetes, gastropods, and crustaceans), and a few piscivores. The diets of reef fishes are quite varied and often change as they grow. Most reef fishes are planktivores during their larval stage, transforming into carnivores after settling into shallow-water habitats, and later switching to their adult diets.

Herbivores

Nearly all phyla of coral reef organisms contain one or more species that feed on plants to various degrees. While small mollusks (chitons and conch) and crustaceans may be locally important herbivores, larger, more abundant herbivores, such as sea urchins, surgeonfish, and parrotfish may alter the standing crop, productivity, and community structure of algae on coral reefs, and consequently affect the array of species with which sessile organisms must compete for space. Herbivory can increase community diversity by removing the dominant competitors and clearing substrate for new colonization, or decrease species richness by selectively removing preferred alga and altering rates of succession. For example, low intensities of parrotfish grazing lead to reef communities dominated by fleshy algae. At intermediate densities, a greater diversity of corals and algae occur, while high densities have low biomass of algae and low diversity of coral (Brock 1979). Intensive grazing by herbivores in some systems enhances local productivity by maintaining algal communities at an early successional stage.

The effects of herbivorous fishes on algae and seagrass community structure also depends on interactions between specific types of fishes and any morphological, structural, or chemical characteristics of the algae, as well as the degree of competition with invertebrate herbivores. For instance, long-spined sea urchin (*Diadema antillarum*) shows a strong preference for algal turf. When algal turf is plentiful, they avoid macroalgae and crustose algae. When algal turf is sparse, alternate food sources are consumed. The preference hierarchy among algal species is similar between *Diadema* (Figure 23) and herbivorous fishes (Hay 1984), although *Diadema* forages over a much smaller range in comparison with schooling herbivorous fishes. In addition, *Diadema* will occupy coral reefs, grassbeds, mangrove roots, and sand flats, and are able to survive on a wide variety of food sources, including circumstances under which herbivorous fishes cannot exist (Birkeland 1988). Territorial damselfishes also have strong local effects on shallow reef algae. The defensive and grazing activities of damselfish result in visually distinct mats of macroalgae that are of greater productivity than comparable areas outside of territories. Damselfish often maintain algal communities at a mid-successional stage that are a superior food source for the fishes and consist of a higher diversity.

Approximately 25% of all reef fishes eat algae. Many of these, such as parrotfishes, surgeonfishes, and rabbitfishes, occur in large

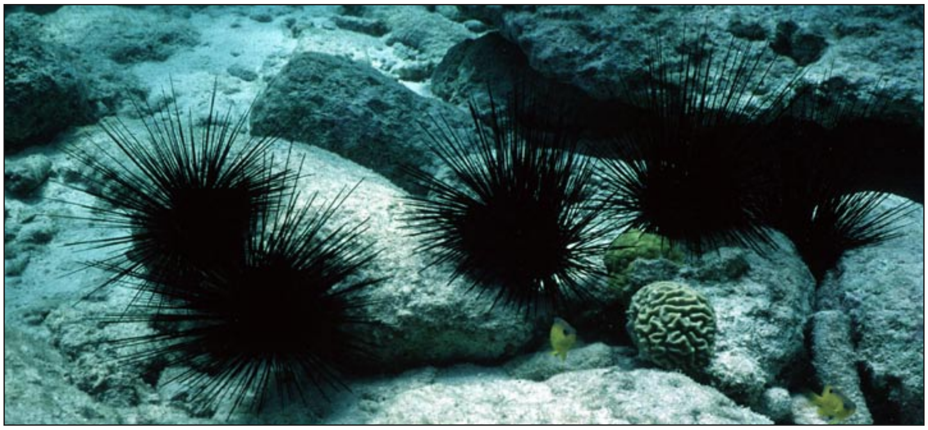

Figure 23. Sea urchins (*Diadema bonaire*). Photo courtesy of Andrew Bruckner, NOAA National Marine Fisheries Service.

Figure 24. Triggerfish (*Balistes* spp.) near Mountainous star coral (*Montastraea faveolata*). Photo courtesy of Andrew Bruckner, NOAA National Marine Fisheries Service.

schools with densities that may exceed 10,000 herbivorous fishes per ha, and secondary productivity that may approach 3 metric tons per km^2 per year (Hixon 1991). These fishes may substantially modify the standing crop of algae on reefs through intensive feeding, removing most of the algal biomass except for encrusting corallines, basal portions of filamentous algae, and chemically or structurally defended macroalgae. Herbivorous fishes are generally more selective than echinoids because they move over large areas and are visually discriminating. Several herbivores (e.g., parrotfish and large wrasse) often erode calcareous structures, producing sediment as a byproduct of feeding.

Corallivores

Adult fishes (e.g., certain butterflyfish, parrotfish, damselfish, blennies, and other species) and certain invertebrates (*Drupella* and *Coralliophila* gastropods, *Acanthaster* crown-of-thorns sea stars, *Hermodice* polychaetes, as well as some nudibranchs and crustaceans) are obligate or facultative corallivores that feed on coral tissues and associated symbionts or on coral mucus. These corallivores can affect the local distribution, abundance, and diversity of corals through selective predation on certain taxa, and have been observed to prevent recovery of coral populations after major disturbances such as hurricanes. Other carnivores (e.g., triggerfish (Figure 24), pufferfish, filefish) may affect abundances of reef-building corals indirectly by preying upon their corallivore predators or by controlling populations of sponges, ascidians, alcyoneans, and gorgonians that compete with corals for space.

Planktivores

Many species of soft corals, sponges, clams, feather-duster worms, and other filter feeders as well as small zooplankton utilize phytoplankton directly as a food source. In particular, coral reef communities with rich terrestrial nutrient input often support a rich phytoplankton-based food web characterized by an abundance of suspension feeding invertebrates and planktivorous fishes. Zooplankton is also an important food source for fishes and invertebrates, with planktonic eggs, larvae, and newly settled juveniles often subject to more intense predation than adults. Planktivorous fishes that feed in the day tend to occur in schools in the water column on reef slopes adjacent to deep water and in areas affected by currents. They feed primarily on transient zooplankton from open water, consuming primarily crustacean and fish eggs. Zooplankton increases in abundance and size after dark in many reef environments due to vertical migration upward within the water column, and include transient species as well as various polychaetes, ostracods, mysids, amphipods, and crustacean larvae that spend a relatively short period of time in the water column prior to settlement on benthic substrates. Nocturnal planktivores include fishes, echinoderms (e.g., brittle stars, crinoids, and basket stars) as well as a number of sessile invertebrates such as coelenterates that wait for passing food sources.

Some planktivorous fishes may affect recruitment success of invertebrate corallivores, herbivores, and other species of invertebrates and fishes by consuming early developmental stages of these organisms. For instance, a Red Sea damselfish is known to feed on larval urchins and sea stars *(Acanthaster)* (Figure 25). Intense predation by triggerfishes, pufferfishes, large wrasses, and porcupine fishes may also affect adult populations of urchins and sea stars. Intense predation is thought to limit population explosions of *Acanthaster* (Ormond et al. 1973) and prevent the formation of discrete barren zones due to overgrazing of algae by urchins (Hay 1984). Many of these planktivores dominate in abundance and biomass within mangrove forests, tidal channels, and outer edges of reef slopes, where they consume a variety

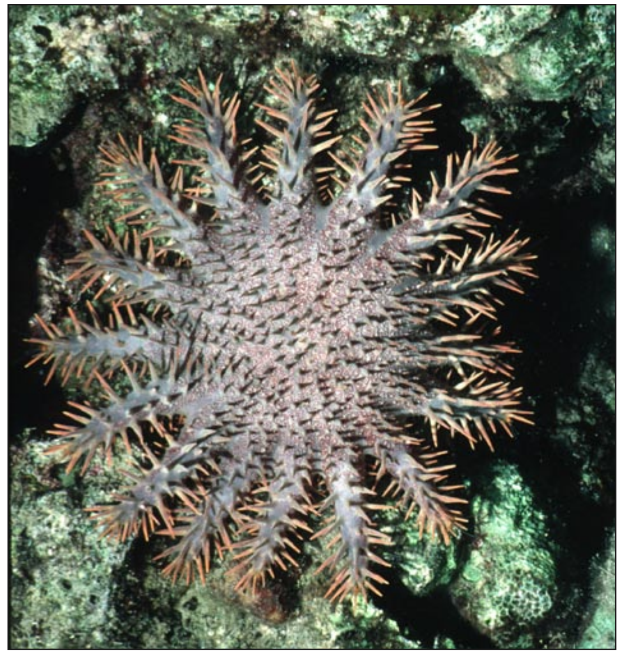

Figure 25. Sea stars (*Acanthaster*). Photo courtesy of Andrew Bruckner, NOAA National Marine Fisheries Service.

of organisms such as copepod, crab, mollusk, and echinoderm larval stages and post-larval fishes, depending on the season (Robertson et al. 1988).

Carnivores

Many of the large carnivores found on reefs are generalists and highly opportunistic in their feeding habitats. Predators have many different methods of food capture and ingestion, and predation pressure may influence prey populations and substrata composition. An increase in abundance of a species of prey often causes predators to switch their attention to the more abundant prey item. Several fishes are specialized feeders, but will alter their diet when their preferred prey becomes rare. Certain triggerfish and toadfish prefer *Diadema*, but began feeding on a broad range of mobile benthic invertebrates following the mass mortality of this urchin in the Caribbean. The population densities of the predators and prey, condition of the prey, its preference as a food source, and extent of defense by structural or chemical attributes and symbionts (e.g., crustacean guards) also affect predation pressure. Furthermore, changes in the physical or biotic environment can suddenly cause a prey species to become more vulnerable to predation.

Fishes that feed on mobile invertebrates are more common than those consuming corals and other sessile invertebrates. Crabs, shrimps, stomatopods, and amphipods are the major food source of many species, with selected predators targeting mollusks within reefs and in soft bottom communities. Some species of wrasse, angelfish, butterflyfish, filefish, and triggerfish feed to varying degrees on sessile invertebrates such as sponges, tunicates, and coelenterates, as well as large mobile epifauna. Most bottom-feeding fishes that consume small crustaceans, polychaetes, and other invertebrates within coral heads (e.g., trunkfish) and in the sediment (e.g., goatfish) are active in the day. Nocturnal fishes, such as squirrelfishes, bigeyes, and grunts, locate crabs and shrimps with their large eyes.

A number of motile invertebrates are also important predators. Errant polychaetes (e.g., *Hermodice*) feed on colonial cnidarians,

Figure 26. A green moray (*Gymnothorax* spp.) among corals. Photo courtesy of Andrew Bruckner, NOAA National Marine Fisheries Service.

sponges, and other sessile invertebrates. Certain mollusks (e.g., *Charonia*) prefer echinoderms, while the octopus will feed primarily on crustaceans and mollusks. Decapods (lobsters, crabs, and shrimp) couple predacious feeding with scavenging, although some are filter feeders (e.g., burrowing shrimp, pea crabs, mole crabs, and porcelin crabs).

A small number of invertebrates feed on fishes, including a few coral species, squid, and some crustaceans. Piscivorous fishes are represented by roving predators such as certain sea basses, sharks, jacks, morays (Figure 26), ambush predators such as frogfishes, lizardfishes, and scorpionfishes), and stalkers (e.g., trumpetfish and barracudas). Roving predators often have peak of feeding activity at dusk and dawn, concentrated during the time when diurnal schooling fish return to their nocturnal refuges and reduced light levels render anti-predator schooling mechanisms less effective.

Detritivores and scavengers

The dominant detritus feeders on coral reefs are sea cucumbers (Holothuridae and Stcihopodidae) that feed by shoveling sediments into their mouth and digesting the organic and inorganic detritus and associated microorganisms, protozoans, and other micro-fauna. Nearly all hermit crabs as well as many lobsters (Figure 27), crabs, and shrimp are also scavengers, feeding on almost any dead organic material. Bacteria and associated flora and fauna facilitate breakdown of detritus and waste products in sediments and the water column, providing nutrients that are channeled back to various primary producers.

Provides Nursery Grounds

Nearshore habitats associated with coral reefs, including the back reef, lagoonal seagrass and patch reef habitats, mangrove forests, algal flats, and rock, mud, and rubble habitats often contain high abundances of juvenile fishes and invertebrates. The habitats used by the juveniles

Figure 27. A lobster (Panuliridae) on a reef off Mona Island, Puerto Rico. Photo courtesy of Andrew Bruckner, NOAA National Marine Fisheries Service.

are often different from those used by adults. These juvenile habitats are often characterized by a high degree of structural complexity that supports production of juveniles to sub-adult or adult populations during a particularly vulnerable stage in their life cycle. The nursery value of different coral reef habitats is often species-specific, and will depend on their life history traits, environmental factors, seascape features and ecological processes affecting the distribution, abundance, and population dynamics of juveniles (Beck et al. 2001). Environmental factors that influence juvenile settlement and survival include water depth, salinity, temperature, turbidity, tidal regime, wave exposure, extent of disturbance, and other parameters. Seascape features such as size, shape, complexity, and quality of the habitats as well as the relative location of the habitat to sources of larvae, other juvenile habitats, and adult habitats also affect settlement patterns.

Most coral reef fishes and invertebrates have a two-phase life cycle characterized by planktonic larvae, demersal or benthic juveniles, and adults. Some site-attached benthic organisms such as territorial damselfishes use the same habitat as juveniles and adults, and settle, reproduce, and mature in a single location. As the juvenile fish grow and change their dietary requirements, they shift to intermediate habitats or their adult home range. Many parrotfish are adapted to a wide variety of habitats, but may remain in the same habitat from settlement through adult life stages. Economically important fishes such as snappers, groupers, grunts, and lobsters exhibit complex habitat, diet, and behavioral shifts during transition from settlement through late juvenile phases, with larvae settling in habitats that are distinct from adult habitats.

Seagrass communities harbor a wide range of benthic, demersal, and pelagic organisms. This includes permanent residents which spawn and spend most of their lives in seagrass beds and transient species. Transient species spend their lives in seagrass beds during their juvenile through adult life cycles but spawn outside the seagrass beds or move between habitats on a daily basis, using seagrass beds for food or shelter. Other transients seek food and shelter in seagrass beds during their juvenile stage, and move to other habitats as sub-adults or adults. Seagrass beds are considered the major nursery ground for commercial pink shrimp, spiny lobster, gray snapper, sea trout, barracuda, and grunts. See Chapter 9, “Restoration Monitoring of Submerged Aquatic Vegetation” for more details.

Mangrove forests offer habitats of different complexity and quality and are often vertically zoned in response to tidal changes, degree of inundation by seawater, and degree of association with other habitats. The prop roots provide a substrate for attachment of sessile organisms such as sponges, tunicates, bryozoans, bivalve mollusks, and coelenterates that settle as juveniles. A number of motile invertebrates including gastropods, echinoderms, and crustaceans use mangrove roots as nursery areas and/or adult habitats. In Florida, mangrove prop roots support juvenile populations of snook, gray snapper, spotted sea trout, red drum, barracuda, and mullets (Thayer and Sheridan 1999). In Curacao, 17 different fish species which inhabit coral reefs as adults were found to use mangroves, seagrass beds, and other shallow-water nearshore environments, including grunts, snappers, parrotfish, barracuda, butterfly, and goatfish (Nagelkerken et al. 2001). See Chapter 11, "Restoration Monitoring of Mangroves" for more details.

Research and monitoring efforts to assess the density, growth, survival, and movement patterns of ecologically and economically important species, and characterize linkages between juvenile and adult habitats may facilitate restoration decisions. A comparative sampling approach that examines habitat utilization patterns and production, and places these habitats within a spatial context of the overall habitat mosaic, will help determine how a species is affected by habitat loss or fragmentation and the likelihood of its recovery. This information may help identify the best suite of actions to restore function and connectivity among these habitats.

Provides Substrate Attachment

Most sessile invertebrates and algae require some form of hard substrate for attachment. This can include coral reef and hard ground substrates, mollusk shells, rubble, seagrass blades and calcified algae, mangrove prop roots, and various cryptic habitats such as the underside of plating corals and cavities within the reef framework. In many locations, suitable substrata becomes limiting and sessile organisms compete for available settlement sites. The structure and diversity of these communities is largely controlled by complex interactions between benthic inhabitants that compete for space, grazing activities of motile fishes and invertebrates, and physical and environmental factors. Local space limitations can create conditions involving contact between neighboring individuals that may ultimately result in overgrowth and death of a part or all of one organism by the superior competitor (Jackson 1979). Other biological factors such as herbivory and predation can also alter spatial relationships among species. At intermediate densities, urchin grazing may decrease competition between algae and corals and provide additional free space for settlement, while the absence of echinoids can result in massive coral mortality due to monopolization of space and overgrowth by fleshy macroalgae (Sammarco 1982). Physical disturbance also slows space monopolization, and can have a major influence on species diversity and zonation.

Sampling and Monitoring Methods

Macroinvertebrates

Many researchers monitor large mobile invertebrates that are fished for food or curios such as lobsters, conch, and sea cucumbers to determine the effect that fishing is having on the ecosystem. Another group of macroinvertebrates included in most monitoring programs are species that prey on corals such as crown-of-thorns sea stars (*Acanthaster*) and *Drupella* and *Coralliophila* gastropods and key herbivores (e.g., *Diadema* and other urchins). Non-invasive monitoring methods used to quantify populations of mobile macroinvertebrates include:

- Manta tows to identify populations of abundant, large species and assess the impacts of outbreaks of predators (e.g., *Acanthaster*) over large areas
- Roving diver (timed swim) surveys to estimate abundance of multiple species within relatively large uniform areas (conch within grassbeds), in topographically complex and cryptic habitats (e.g., lobsters within crevices, caves, or coral thickets) that may be missed by other methods, and for rare species that may be missed with other methods

- Belt transects to obtain information on abundance and size structure of larger target and keystone species (e.g., urchins) within specific zones or depths
- Point intercept methods for sessile invertebrates such as sponges and gorgonians
- Quadrats (or individual corals) to get precise estimates of smaller invertebrates such as *Drupella* and *Coralliophilla* and evaluate rates of coral tissue consumption, and
- Portable and stationary drop samplers and trap studies for lobsters and crabs, population surveys, and capture and release studies to quantify nocturnal invertebrates and assess mobile organisms in deeper or turbid environments where scuba diving is impractical (Negrete-Soto et al. 2002)

Fish

Fish monitoring methods include both fisheries monitoring (e.g., catch, effort, catch per unit effort, biological characteristics of key fisheries species) and biological monitoring of fish assemblages and/or target species. Biological monitoring approaches are discussed briefly below. The four most commonly used visual census techniques to quantify coral reef fish assemblages are broad-scale towed diver (manta tow) surveys, plotless methods (roving diver techniques), belt transects (Brock 1954), and stationary plots. In addition to visual censuses, sampling may be carried out using portable and stationary drop samplers, traps, block nets, trawls, and fish poisons (e.g., rotone or quinaldine). The most appropriate method depends on a number of factors including:

- Size of the survey area and desired scale of surveys
- Structural complexity of the survey area
- Species of interest (all species or target species such as food fishes, aquarium fishes, indicator species, or herbivores) and their behavior, and
- Life stage of interest (recruits, juveniles, adults, spawning aggregations)

Manta tow - Towed diver surveys involve towing one or two divers or snorkelers behind a boat at a constant speed. The diver maneuvers a towboard that can be outfitted with video and still cameras, slates, and other survey equipment. Compared to traditional dive surveys, which have limited spatial coverage, towed diver surveys provide rapid estimates of large areas and observers are able to differentiate fish assemblages within multiple habitats (e.g., patch reefs, rubble zones, algal flats, seagrass beds) in a single tow. This method allows for the detection of rare pelagic fishes that are infrequently encountered during traditional surveys, and is most effective at estimating abundance and density of large, mobile predators. It is not appropriate for estimating size or for use with cryptic species or small (<20 cm), bottom-dwelling animals.

Belt transect surveys - Belt transect surveys can be used to census the abundance and size of a defined list of reef fishes within specific habitats or zones. The approach involves deploying a transect of a predetermined length and then counting and recording the number of individuals (and other parameters as desired, such as size) within a fixed distance (e.g., a window of fixed width and height above the substrate) of the transect path. Divers may deploy the line prior to the assessment. However, it is preferable to release the line as you slowly swim in a straight line, as this minimizes disturbance to the fish prior to being counted. One example of a belt transect approach is the Atlantic and Gulf Rapid Reef Assessment (AGRRA) protocol, for which divers extend a 30 m transect along depth gradients and census economically and ecologically fishes within a 2 m window (AGGRA 1998).

There are a number of factors that should be considered when conducting belt transect surveys:

- The precision and accuracy of transect surveys are affected by the length of the transect and size of area surveyed
- The width of the belt should be suitable to the type and behavior of fish that will be examined and the number of species to be counted
- It may be necessary to examine the reef within a 1 m belt for small, cryptic species and recruits, while 2-5 m belts can be used for larger, more mobile species
- Visibility also affects the width of belt
- Transects should cover a significant portion of the sampled habitat in order for the results to be representative of the fauna in the transect area, and
- A stratified design will provide greater information in sampling areas that have a high microhabitat diversity and high species diversity
- The optimal transect area is determined by the diversity and abundance of fishes; most researchers use 30-50 m long transects

Solitary species that are wary of a diver's presence may stay away from the transect line, while other species may be attracted to divers. Some of this can be avoided by laying the transect line behind the diver. Species present in relatively low numbers are less likely to be sampled by the transect method. To avoid bias, it is important to exclude species seen outside the transect area from the results. One of the major limitations of transect surveys is the absence or presence in large numbers of roving fishes that form large schools.

Roving Diver Technique (RDT) -The RDT assesses species presence, frequency of occurrence, and abundance of all fish species within a particular site or zone (Bohnsack 1995). Divers swim a compass direction, a depth contour, along some identifiable habitat feature, or in an area of a known size and record the number (and size) of each species observed during a predetermined period. The main advantage of the method is that it does not require the observer to deploy a transect line. This allows a diver to census a greater area, increasing the likelihood of observing inconspicuous fishes. The method does not provide a precise estimate of density per unit area, but rather the species observed per unit time.

Underwater visual surveys - The stationary underwater visual census method involves counting all target fishes within an imaginary cylinder of fixed diameter extending from the reef to the water's surface (Bohnsack and Bannerot 1986). The diver stands at the center point of the cylinder and makes several slow 360º turns, counting and identifying each observed species (and estimating their length) within a specific time. Using the size data, biomass estimates can be obtained using published mass-length relationships (Bohnsack and Harper 1988). This method works best for patch reefs and total fish counts, and avoids problems associated with moving divers and transect tapes.

Capture techniques - Under turbid conditions and when assessing juveniles, nocturnal, or cryptic species, block sampling, drop sampling, and trap sampling may be preferred over traditional visual census techniques. The fish poisons rotenone and quinaldine has been used to evaluate total fish composition within a defined area (e.g., small patch reefs) and may be particularly useful to evaluate early settlement juveniles in turbid locations. Poisons are not appropriate for large areas, deep habitats, or high flow environments and their use should be limited to avoid injuring other reef organisms. Traps may be an effective approach to characterize larval settlement patterns, and also are useful for assessing species composition within deeper areas. Traps may target certain species over others (depending on the bait and trap design) and it is difficult to quantify the area fished by a trap. Bottom trawls are most effective in shallow, soft-bottom habitats such as seagrass beds and algal flats, and can be used to quantify the diversity, abundance, life stage, and size of species within a certain area. Nets that are set in one location and allowed to stand for an extended period (e.g., overnight) can be used to survey movement patterns of species between habitats and in areas with high tidal flow or currents.

PHYSICAL

Protects Shorelines

Coral reefs form a physical barrier that protects coastal areas from the full force of waves, currents, and storms, thereby preventing erosion, property damage, and loss of life. Reefs also protect highly productive coastal wetlands such as mangroves and seagrass beds, as well as ports and harbors. In some cases, associated ecosystems are interdependent; mangroves may both protect coral reefs from silt and be protected by the coral reefs from strong wave action, thus protecting nurseries of commercially important reef fishes and invertebrates. During typhoons and hurricanes, damage from wave action to coastal communities is generally much less where there are reefs. In Guam, for example, losses to coastal communities during typhoons have been much less in areas protected by extensive reef flats, while villages located off narrow fringing reefs have suffered much greater damage (Birkeland 1997 a and b). Unlike human-constructed breakwaters which require considerable investment of resources to build and maintain, coral reefs are natural, self-repairing breakwaters. As coral reefs buffer the wave's energy, lagoons and other sedimentary environments that are suitable for mangroves and seagrasses develop over time (Ogden 1988).

CHEMICAL

Supports Nutrient and Carbon Cycling

Coral reefs are generally found in waters with lower dissolved nutrient concentrations than those of temperate coastal ecosystems. Despite this, coral reefs sustain a high gross primary productivity and biotic growth due to:

1) Tight nutrient cycling among individual organisms, and
2) Localized diurnal and seasonal nutrient inputs as water masses pass across reef communities

Dissolved nutrients on coral reefs can originate from a range of sources including *in situ* fixation by bacteria and cyanobacteria, fluxes out of reef matrices, terrestrial runoff, groundwater discharge and outflow of coastal water, onshore transport of oceanic water masses, and localized upwelling of nutrient-rich subsurface waters (D'Elia and Wiebe 1990). Nutrients are lost from reefs as salts, and as organic detritus which are fed upon by plankton, and larger pelagics (e.g., jacks) in coral reef areas. Nitrogen and other nutrients may also be advected out of coral reefs in dissolved or particulate form.

Inorganic and organic nutrients of oceanic waters are assimilated by phytoplankton and bacteria, and enter the reef food web through the activity of filter feeders, with a secondary mechanism of uptake involving direct assimilation of dissolved organic matter by corals and other benthic filter-feeding invertebrates (Sorokin 1993). Inorganic nutrients in the water column are also utilized by benthic algal communities, while seagrasses obtain nutrients primarily from the sediment through their roots. Nutrients contained in the biomass of zooplankton enter the nutrient pool of reef ecosystems through their consumption by planktonic and benthic predators. Fish and larvae of benthic invertebrates excrete feces containing the bulk of nutrients consumed, which are then mineralized by animals that feed on feces.

Nitrogen fixation is a key feature of the nitrogen cycle of most coral reefs. The assimilation of atmospheric nitrogen by nitrogen-fixing microbes and cyanobacteria occurs in sediments and reef substrates, epiphytes on macroalgae, endolithic organisms in coral skeletons, and cyanobacteria within sponges and corals (D'Elia and Wiebe 1990; Lesser et al. 2004). The fixed nitrogen is transferred to the rest of the trophic system through excretion of ammonium by nitrogen fixers, decomposition of nitrogen fixers, and grazing on nitrogen fixers by herbivores (Szmant-Froelich 1983). While microorganisms are responsible for many of the processes of nitrogen cycling, large organisms conserve and translocate significant quantities of fixed nitrogen and phosphorus, with much of the recycling and nutrient regeneration occurring within the sediments (Smith et al. 1981).

The symbiotic dinoflagellates of reef-building corals play an enormous role in the overall production of the reef, using sunlight, carbon dioxide (CO_2), water, and nutrients to produce sugars and cellular material and supply the coral with energy-rich products of photosynthesis, providing up to 95% of corals' carbon requirements, as well as essential compounds such as amino acids, complex carbohydrates, and small peptides (Hoegh-Guldberg 1989; Muscatine 1990). In addition to providing a protected microhabitat for zooxanthellae, the coral host supplies essential compounds such as ammonia and phosphate derived from the food caught by the coral (Trench 1979). Corals are able to consume inorganic nutrients (e.g., ammonia and inorganic phosphate); phosphate is accumulated in the zooxanthellae, where it is incorporated into adenosine triphosphate (ATP) and nucleotides, and translocated to the animal's cells. The phosphorous is mineralized by the coral, and again consumed by the zooxanthellae, drastically decreasing loss to the surrounding waters. A portion of the primary productivity is, however, indirectly cycled throughout the reef community via coral predators, coral mucus, and coral detritus. For instance, corals exude up to half of the carbon assimilated by their zooxanthellae as mucus. The released coral mucus efficiently traps organic matter from the water column and rapidly carries energy and nutrients to other reef zones, and may be deposited in associated sediments where it is consumed by the heterotrophic reef community (Sorokin 1993).

Understanding the complex interactions between biogeochemical and physical processes within reef ecosystems is important for determining the contribution of coral reefs to the global carbon cycle and the air-sea flux of CO_2. Coral reefs contribute to the ocean carbon cycle through the processes of photosynthesis, respiration, calcium carbonate ($CaCO_3$) production, and dissolution. One of the most significant benefits that reef-building corals derive from zooxanthellae is the enhancement of the calcification process, which is essential to coral skeletal growth (Muscatine et al. 1984). Photosynthesis by zooxanthellae increases $CaCO_3$ production by providing the energy needed by the host for the uptake of calcium from seawater and the transport to sites of calcification, and by creating an internal environment favoring calcification through the uptake of respiratory CO_2 (Porter 1976). The fate of CO_2 in coral reefs is dependent on many factors, including the ratio of organic carbon production to $CaCO_3$ production, irradiance levels, and the dominant type of calcifying organism (Buddemier 1996; Gattuso et al. 2000). Recent evidence suggests that reefs dominated by hard corals are sources of CO_2 to the atmosphere, whereas reefs dominated by macroalgae are oceanic sinks of CO_2. The precipitation of $CaCO_3$ by corals results in the release of CO_2 from seawater to the atmosphere, and respiration and calcification may increase acidification of water, which favors release of

CO_2 back into the water column (Ware et al. 1992).

Calcification, photosynthesis, and respiration are the three major metabolic processes dominating the community metabolism of coral reefs. By following changes in dissolved oxygen and total alkalinity of reef water, it is possible to evaluate these processes at a community level. Gross production is the rate of photosynthetic carbon and nutrient fixation into organic matter, resulting in oxygen evolution. Community respiration is the rate of aerobic decomposition of organic matter, which supplies energy to reef heterotrophs, causing inorganic carbon to increase and oxygen to decrease. Calcification is a measure of the rate of $CaCO_3$ deposition, which is higher in the day than at night for most organisms. Net fluxes of nutrients within reef environments have been estimated using a flowing water respirometry method and measurements of chemical changes (oxygen and pH) in the water as it flows over the reef; this involves taking samples of water flowing across reefs and estimating the elemental exchange between the reef and the water. Factors that affect nutrient fluxes and must be considered when using this method include the depth and velocity of the water, length of the transect, and oxygen concentration in the samples. Flow respirometry and other approaches used to estimate net fluxes of nutrients are described in more detail in D'Elia (1988). Investigations of the processes controlling seawater CO_2 and the air-sea exchange of CO_2 in coral reef ecosystems have generally been based on measurements of pH, total alkalinity (TA), and dissolved oxygen (Smith 1973; Suzuki et al. 1995; Kraines et al. 1997; Chisholm and Barnes 1999).

PARAMETERS FOR MONITORING STRUCTURAL/FUNCTIONAL CHARACTERISTICS OF CORAL REEFS

The following matrices present parameters for restoration monitoring of the structural and functional characteristics of coral reefs. These matrices are not exhaustive, but represent those elements most commonly monitored. These parameters have been recommended by experts in coral reef restoration and are described in detail in the literature on coral reef restoration and ecological monitoring. The closed circle (●) denotes a parameter that should be considered in monitoring restoration performance. Parameters with an open circle (❍) are of secondary importance, depending on specific restoration goals.

Parameters to Monitor the Structural Characteristics of Coral Reefs

Parameters to Monitor	Biological	Physical	Hydrological		Chemical
	Habitat created by animals	Topography/Bathymetry	Currents/Wave energy	Water sources	Nutrient s
Geographical					
Acreage of habitat types	●				
Biological					
Plants					
Species, composition, and % cover of:					
Algae					❍
Epiphytes					●
Animals					
Vertical relief	●	●			
Hydrological					
Physical					
Shear force at sediment surface				❍	
Temperature			●		
Upstream land use			❍		
Chemical					
Nitrogen and phosphorus (N and P)					❍
Toxics			❍		
Soil/Sediment					
Physical					
Basin elevations		❍			
Geomorphology (slope, basin cross section)		●			
Sedimentation rate and quality		●			●

Parameters to Monitor the Functional Characteristics of Coral Reefs

Parameters to Monitor	Biological: Exhibits symbiotic species interactions	Provides breeding grounds	Provides feeding grounds	Provides nursery areas	Provides refuge from predation	Provides substrate for attachment	Supports a complex trophic structure	Supports biomass production	Supports biodiversity	Physical: Affects transport of suspended/dissolved material	Alters turbidity	Reduces erosion potential	Reduces wave energy	Chemical: Supports nutrient cycling
Geographical														
Acreage of habitat types	●	●	●	●	●	●	●	●	●			●	●	●
Biological														
Plants														
Species, composition, and % cover of:														
Algae	❍	❍	❍	❍	❍	❍	❍	❍	❍			❍	❍	❍
Epiphytes	●		●				●	●	●					●
Interspersion of habitat types		❍	❍	❍	❍		❍	❍	❍			❍	❍	❍
Nutrient levels in algal tissues (N and P)														❍
Biological														
Animals														
Species, composition, and abundance of:														
Fish		❍	❍	❍	❍		❍	❍	❍					
Invasive species			●	●	●			●	●					
Invertebrates		❍	❍	❍	❍		❍	❍	❍					
Coral growth rate	❍	❍	❍	❍	❍	❍	❍	❍	❍					
Coral recruitment and survivorship	❍	❍	❍	❍	❍	❍	❍							

Parameters to Monitor the Functional Characteristics of Coral Reefs (cont.)

Parameters to Monitor	Biological: Exhibits symbiotic species interactions	Provides breeding grounds	Provides feeding grounds	Provides nursery areas	Provides refuge from predation	Provides substrate for attachment	Supports a complex trophic structure	Supports biomass production	Supports biodiversity	Physical: Affects transport of suspended/dissolved material	Alters turbidity	Reduces erosion potential	Reduces wave energy	Chemical: Supports nutrient and carbon cycling
Grazer density				○	○									
Vertical relief of reef		●	●	●	●	●	●					●	●	
Trash			○											
Upstream land use										○	○			
Water column current velocity												○		
Chemical														
Toxics		○	○	○										
Soil/Sediment														
Physical														
Basin elevations		○	○	○	○	○			○					
Geomorphology (slope, basin cross section)		●	●	●	●	●			●			●		
Sediment grain size (OM[12]/sand/silt/clay/gravel/cobble)						○		○				○	○	○
Sedimentation rate and quality									○			○		

[12]Organic matter

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Williams, S. L. and R. C. Carpenter. 1988. Nitrogen-limited primary productivity of coral reef algal turfs: potential contribution of ammonium excreted by *Diadema antillarum*. *Marine Ecology Progress Series* 47:145-152.

Williams, E. H. and L. Bunkley-Williams. 1990. The world-wide coral bleaching cycle and related sources of coral mortality. *Atoll Research Bulletin* 335:1-71.

Wilson, S., S. M. R. Fatemi, M. R. Shokri and M. Claereboudt. 2002. Status of coral reefs of the Persian/Arabian Gulf and Arabian Sea region. Status of coral reefs of the World: 2002. pp. 53-62. AIMS, Townsville, Australia.

Wittenberg, M. and W. Hunte. 1992. Effects of eutrophication and sedimentation on juvenile corals. *Marine Biology* 112:131-138.

Yang, J., W. Huang, C. Zhou and Q. Xiao. 2004. Wave Height Estimation from SAR Imagery. *Chinese Journal of Oceanology and Limnology* 22:157-161.

Zann, V. P. and L. Bolton. 1985. Zone distribution, abundance, and ecology of the blue coral *Heliopora coerulea* (Pallas) in the Pacific. *Coral Reefs* 4:125-34.

APPENDIX I: CORAL REEFS ANNOTATED BIBLIOGRAPHY

This annotated bibliography contains summaries of restoration case studies and basic ecological literature. It is designed to provide restoration practitioners with examples of previous restoration projects as well as overviews of papers from the ecological literature that offer more detail than that covered in the associated chapter. Entries are presented from both peer reviewed and grey literature. They were selected through extensive literature and Internet searches as well as input from reviewers. They are not, however, a complete listing of all of the available literature. Entries are arranged alphabetically. Wherever possible, web addresses or other contact information has been included in the reference to assist readers in easily obtaining the original resource. Summaries preceded by the terms '*Author Abstract*' or *'Publisher Introduction*' or similar descriptors were taken directly from their original source. Summaries without such descriptors were written by the author of the associated chapter.

Arceo, H. O., M. C. Quibilan, P. M. Alino, G. Lim and W.Y. Licuanan. 2001. Coral bleaching in Philippine reefs: Coincident evidences with mesoscale thermal anomalies. Marine Science Institute, University of the Philippines, Diliman, Quezon City 1101 Philippines. *Bulletin of Marine Science* 69: 579-593.

Author Abstract. Massive bleaching was observed in various reefs throughout the Philippines (5-21^{o} N, 116-128^{o} E), beginning early June until late November 1998. Satellite-derived SST data from NOAA/NESDIS was used to examine thermal anomalies ('hotspots') observed in the country during this same period. Anecdotal reports from the Coral Reef Information Network of the Philippines partners revealed the extent of bleaching in other parts of the country. The observations coincided with the occurrence of a hotspot over the region. Coral community studies detected significant decrease in live coral cover (up to 46%) and increase in dead coral cover (up to 49%). The results support the hypothesis that elevated sea temperatures was the major cause of the bleaching event. Some patterns of susceptibility within and across reefs, possibly due to influences of factors such as wave energy, tidal fluctuations and reef morphology, were also observed. The extent and scale of the 1998 bleaching events in the Philippines could not be fully attributed to small-scale anthropogenic disturbances directly affecting reefs since severe bleaching was also observed in offshore reefs. Its coincidence with the El Nino-related temperature anomalies suggests that the interaction between human-induced and natural factors behind bleaching remains to be investigated further. This interaction is critical for reef recovery, and the discrimination between both impacts can be useful for policy and decision-making processes in management.

Bohnsack, J. A. 1995. Two visually based methods for monitoring coral reef fishes. In Crosby, M. P., G. R. Gibson and K.W. Potts (eds.), A Coral Reef Symposium on Practical, Reliable, Low-cost Monitoring Methods for Assessing the Biota and Habitat Conditions of Coral Reefs. Miami Laboratory, Southeast Fisheries Science Center, National Marine Fisheries Service, Miami, FL. EPA 904/R-95/016. Annapolis, Maryland. http://www.epa.gov/owow/oceans/coral/symposium/bohnsack.html

Author Abstract. Two visual methods are described to monitor coral reef fishes. The Roving Diver Technique (RDT) developed by the Reef Environmental Education Foundation

(REEF) uses volunteers to collect reef fish species presence, frequency of occurrence, and abundance data. The more quantitative Stationary Sampling Technique (SST) requires more highly trained divers to collect quantitative data on sizes, frequency of occurrence, and abundance for all visually observable species. From these data in index of biomass and importance value can be calculated. Both methods can be used to answer a wide variety of monitoring and scientific questions although each has advantages and disadvantages. Additional information methods used for monitoring reef fishes are described in this document.

Caribbean Coastal Marine Productivity Program (CARICOMP). 1997. CARICOMP Monitoring of Caribbean Coral Reefs. Proceedings of the 8th International Coral Reef Symposium 1: 651-656, Panama. Contact information: CARICOMP Data Management Center, Center for Marine Sciences, University of the West Indies, Mona, Kingston, Jamaica. Phone # (876) 927-1609 and Fax # (876) 977-1033. http://www.ccdc.org.jm/abstracts.html

CARICOMP Abstract. Permanent chain transects since 1993 at 15 sites around the Caribbean, using the CARICOMP Level One protocol, at 10 $\pm$ 3m depth, to assess benthic community composition and, later, productivity. Each of the sites differed in geographical situation and recent history. Though their locations were away from obvious point sources of pollution, some were known to have changed significantly previously to initiation of the survey. In 1995, studies showed that the main species present were algae (13-59% total cover, 16-74% live cover) and hard corals (6-42% total cover, 9-63% live cover). Minor components were soft corals (0.2-26% total cover, 0.5-50% live cover) and sponges (0-10% total cover, 0-16% live cover). *Diadema antillarum* was present at four sites located in the Bahamas, Barbados, Belize, Puerto Rico but were absent from the others. In 1993-94, researchers indicated that there were no major changes in coral cover based on observations, except in Jamaica (17.7% to 9.5%). Within the limitations of the method, the data will serve as a baseline reference for monitoring further change in benthic community composition.

Carriquiry, J. D., A. L. Cupul-Magana, F. Rodriguez-Zaragoza and P. Medina-Rosas. 2001. Coral bleaching and mortality in the Mexican Pacific during the 1997-98 El Niño and prediction from a remote sensing approach. *Bulletin of Marine Science* 69:237-249.

Author Abstract. A coral reef monitoring program was initiated at Bahia Banderas (21^{o} N, 105^{o} W), on the Pacific coast of Mexico, on January 1997, several months before the onset of the El Nino-Southern Oscillation (ENSO) event of 1997-98. Live coral cover, sea surface temperature (SST) and salinity were monitored during 1997-98, in conjunction with 'hot spot' satellite bleaching predictions of NOAA's NESDIS. Coral reef bleaching during the 1997-98 El Nino at Bahia Banderas coincided closely with satellite bleaching predictions and with experimental observations on coral tolerance to thermal stress. The initial bleaching event rapidly evolved into an unprecedented massive coral mortality (96%), equivalent to the catastrophic coral mortalities observed in the Galapagos Islands during the 1982-83 ENSO. The sudden mass bleaching and mortality of corals at Bahia Banderas was most likely caused by the marked accelerated warming rate (+3.5 degree C mo^{-1}), an order of magnitude higher than that observed during the 1982-83 El Nino in the Galapagos Islands (+0.35 degree C mo^{-1}). Also, the SST anomaly observed during the 1997-98 ENSO at Bahia Banderas (+6.1^{o} C) was 30% higher than in 1982-83 in the Galapagos area (+4.5^{o}C). The recovery of the Bahia Banderas coral reefs is uncertain since the dead coral substrate has already been covered with filamentous fleshy algae. In contrast to the long-lasting existence of corals and coral reefs in the region, reef frameworks are typically very thin. This situation may indicate the frequent recurrence of mortality events due to environmental extremes, such as ENSO, that have limited reef development in the northeastern tropical Pacific Ocean.

Chiappone, M., K.Sullivan-Sealey, G. Bustamante and J. Tschirky. 2001. A rapid assessment of coral reef community structure and diversity patterns at naval station Guantanamo Bay, Cuba. *Bulletin of Marine Science* 69:373-394.

Author Abstract. Ten shallow (<20 m) reefs at Naval Station Guantanamo Bay, southeastern Cuba, were surveyed during July-August 1996 to evaluate topographic complexity and community structure with respect to depth-related zonation and potential sedimentation impacts from the Guantanamo River. While the methods employed were not novel, coral reefs in the study area had not been previously studied and, because of low human population density, may provide useful comparisons to more disturbed reefs in the Caribbean. On leeward and windward sides of the Bay, four shallow (5 m) and four deeper (10 m) spur-and-groove reefs were surveyed, along with two reefs within the mouth of the Bay. On each reef, four 25-m transects were oriented perpendicular to shore on four haphazardly selected spurs and used to randomly select 1 m x 1 m quadrat locations. Benthic coverage using point-intercept counts and topographic complexity using the chain-length method were quantified within quadrats. All sampled reefs were dominated by algae, especially algal turfs, and stony corals. Mean percent algal cover among reefs ranged from 50 to 78%, while coral cover ranged from 11 to 49%. Analysis of variance showed that depth was more important than location in explaining the variability in mean coral cover. Cluster analysis using percent coverage of all bottom types and relative coral cover confirmed that reefs at the same depth were more similar in benthic composition. Several species considered to be less tolerant of sedimentation, however, were more abundant on windward reefs, suggesting that differences in sedimentation between windward and leeward areas may affect relative species abundance, but not total coral cover. Percent coral cover estimates from 9 of the surveyed reefs were well above recent values reported for other wider Caribbean reefs. The predominance of corals on these reefs is surprising, given the low abundance of herbivores (due to mass mortality and overfishing) and possible disease outbreaks affecting acroporid corals. These disturbances appear to have had less severe consequences than for other wider Caribbean reefs such as those in Jamaica and the Lesser Antilles, potentially due to the relative rarity of destructive storm events.

Cochran. S. 2000. Biologic Monitoring Sites Enhance Hawaii Coral Reef Studies. United States Department of Interior, United States Geographical Survey (USGS), Fieldwork Studies. Contact information: scochran@usgs.gov, Phone # (831) 459-3431. http://soundwaves.usgs.gov/2000/04/fieldwork.html

The USGS and scientists from the Hawaii Institute of Marine Biology, at the University of Hawaii, Manoa have collaborated to map coral reefs along the south shore of Moloka'i and to detect changes in reef health due to various environmental and anthropogenic factors. The coral reef mapping project includes the protocol established by the University's Coral Reef Assessment and Monitoring Program (CRAMP) which detects changes in coral cover over time with statistical confidence (P>0.8). The data obtained through this program are placed into a Hawaii-wide database for use by managers and reef scientists. Methods used for mapping reefs include permanent transects and photoquadrats located at 3-m and 10-m depths along the outer forereef and at a depth of 1 m in the inner reef flat. Algae, fish, coral, and other invertebrates were quantified at selected study sites. Re-sampling was performed at the sites over time. Digital video footage was collected along transects for percent coral cover analysis using twenty randomly selected video frames per transect with fifty randomly selected points per frame. Images taken from fixed photoquadrants allowed researchers to examine a single colony's recruitment, growth, and mortality trends. Ground-truthing of aerial photographs and LIDAR (Light Detection And Ranging) images were sampled using Digital video and photo recordings. Study sites were re-sampled once a year. Additional information on techniques used can be obtained from the source listed above.

English. S., C. Wilkinson and V. Baker. 1997. Survey Manual for Tropical Marine Resources, 2nd edition. Published by Australian Institute of Marine Science Townsville ISBN 333.952072013 or Protocols for Coral Reef Monitoring.

This publication discusses techniques used for coral reef monitoring. The first method described is broad scale monitoring such as Manta tow or time swim. This method allows researchers to observe a broad photo of the reef; observe changes in the physical structure of the reef (e.g., structural damage and diseases); and ensure that monitoring sites are descriptive of the whole reef. Researcher's record percent cover of live and dead corals, soft coral, and regional specific parameters (e.g., crown-of-thorns starfish, giant clams, and large patches of damage to corals). The tow method is used to select transect monitoring sites. Line intercept or other transect methods are used to assess coral health. Parameters are recorded as lifeforms or as species. Several lifeforms or species can be grouped into larger groups (e.g. branching and digitate *Acropora* and branching non-*Acropora* can be merged into branching coral). Transects are placed where coral density is highest and then used for fish census counts. Researchers advised that transects be marked from beginning to end with steel stakes. Live fish visual censusing can also be used and are based on line transects, but with the use of 3 X 50 m transects, allowing fish to be assessed in a column 5 m wide and 5 m high above the line. This method is designed particularly for counting fish, especially those targeted by fishers. The fish and lifeform transects can be performed on the same transect lines. Fish surveys must also be completed before benthos assessment, to circumvent fish deterrence. See publication for additional information on methods that can be used for coral reef monitoring.

Epstein, N., R. P. M. Bak and B. Rinkevich. Applying forest restoration principles to coral reef rehabilitation. 2003. Israel Oceanographic and Limnological Research, National Institute of Oceanography, Tel Shikmona, Israel. *Aquatic Conservation* 13:387-396.

Author Abstract. Forest restoration through silviculture (gardening) programs revives productivity, biodiversity, and stability. As in silviculture approaches, the coral 'gardening' strategy is based on a two-step protocol. The first step deals with the establishment of *in situ* and/or *ex situ* coral nurseries in which corals are farmed (originating from two types of source material: asexual [ramets, nubbins], and sexual [planula larvae, spat] recruits). The second is the reef rehabilitation step, where maricultured colonies are transplanted into degraded sites. We compare here the rationale of forest restoration to coral reef ecosystem restoration by evaluating major key criteria. As in silviculture programs, a sustainable mariculture operation that focuses on the prime structural component of the reef ('gardening' with corals) may promote the persistence of threatened coral populations, as well as that of other reef taxa, thus maintaining genetic diversity. In chronically degrading reef sites this may facilitate a halt in biodiversity depletion. Within the current theoretical framework of ecosystem restoration, the recovery of biodiversity indices is considered a core element since a rich species diversity provides higher ecosystem resilience to disturbances. The gardening measure may also be implemented worldwide, eliminating the need to extract existing colonies for transplantation operations. At degraded reef sites, the coral gardening strategy can assist in managing human and non-human stakeholders' requirements as is done in forest management.

Epstein, N., R. P. Bak and B. Rinkevich. 2001. Strategies for gardening denuded coral reef areas: The applicability of using different types of coral material for reef restoration. *Restoration Ecology* 9:432-442.

Author Abstract. Recreational and other human activities degrade coral reefs worldwide to a point where efficient restoration techniques are needed. Researchers tested several strategies for gardening denuded reefs. The gardening concept included *in situ* or *ex situ* mariculture of coral recruits, followed by transplantation into degraded reef sites. In situ nurseries were established in Eilat's (Northern Red Sea) shallow waters, sheltering three types of coral materials taken from the branching species *Stylophora pistillata* (small colonies, branch fragments, and spat) and monitored for two years. See publication for additional information on method used. Researchers stated that pruning more than 10% of donor colonies' branches increased mortality, and surviving colonies displayed reduced reproductive activity. However maricultured isolated branches surpassed donor colony life span and reproductive activity and added 0.5-45% skeletal mass per year. Results showed that forty-four percent of the small colonies survived after 1.5-year mariculture, revealing average yearly growth of 75 ± 32%. Three months ex situ maintenance of coral spat (sexual recruits) prior to the in situ nursery phase increased survivorship. Within the next 1.5 years, their colonies developed 3-4 cm diameter. Nursery periods of 2 years, 4-5 years, and more than> 5 years have been estimated for small colonies, spat, and isolated branches, respectively. Researchers suggest that reef gardening may be used as a key management tool in conservation and restoration of denuded reef areas.

Gleason. D. F., D. A. Brazeau and D. Munfus. 2001. Can self-fertilizing coral species be used to enhance restoration of Caribbean reefs? *Bulletin of Marine Science* 69:933-943.

Author Abstract. Reef restoration programs involving transplantation should be most successful when using coral species exhibiting high reproductive potential, local recruitment, and the ability to tolerate stresses induced by transplantation. One mode of enhancing reproduction, especially when population densities are low, is through self-fertilization. To determine if the high reproductive output observed in many hermaphroditic brooders is the product of self fertilization, randomly amplified polymorphic DNA was used to quantify selfing rates in three brooding, hermaphroditic Caribbean corals, *Favia fragum*, *Porites astreoides*, and *Agaricia agaricites.* See publication for additional information on methods used. Self-fertilization rates in the field were high (49% for *F. fragum*, 34% for *P. astreoides* and 38% for *A. agaricites*). Given these high selfing rates, we tested the resiliency of hermaphroditic brooders by transplanting intact and divided colonies of *P. astreoides* within and between 9 and 24 m depth. Survivorship was high in all transplant groups after 21 mo. Growth rates and larval production of transplanted colonies fell below those of colonies remaining at their depth of origin only at 24 m depth. Even so, colonies transplanted from 9 to 24 m depth appeared healthy throughout the experiment. These results suggest that hermaphroditic brooders meet at least two of the criteria needed for successful coral transplantation programs.

Hendee, J. C., E. Mueller, C. Humphrey and T. Moore. 2001. A data-driven expert system for producing coral bleaching alerts at Sombrero Reef in the Florida Keys, USA, pp. 139-147. In Pepper, D. W., C. A. Brebbia and P. Zannetti (eds.), Proceedings of the 7th International Conference on Development and Application of Computer Techniques to Environmental Studies. Computational Mechanics, Publications/WIT Press, Southampton.

Author Abstract. A computer expert system shell was employed to provide interpretations of near real-time acquired combinations of meteorological and oceanographic parameters from a SEAKEYS (Sustained Ecological Research Related to Management of the Florida Keys Seascape) station at Sombrero Reef. When environmental conditions were conducive to coral bleaching, according to different models, 'alerts' were automatically posted to the World-Wide Web and emailed to researchers so they could verify and study bleaching events as they might happen. The models were refined using feedback from field data on bleaching recorded after alerts from the expert system. The expert system was programmed to produce alerts when sea temperatures over 30˚C occurred, or when temperatures of 30˚C occurred concomitant with low winds. Alerts were produced in June 1998 when these conditions were met, but bleaching did not occur. Reconfiguration of the system, which included a point system for three models (high sea temperature only, high sea temperature plus low winds, high sea temperature plus low winds plus low tide), resulted in the transmittal of alerts which coincided with bleaching during early August, 1998. Bleaching occurred after sea temperature reached an average of 31.5˚C over a period of 3 d, with excursions over 31.8˚C occurring over fifteen times during those 3 d. High sea temperatures, low wind speeds and a very low tide occurred coincident to the time of bleaching, but it was not possible to tell if these were factors acting synergistically.

Jan, R-Q., J-P. Chen, C-Y. Lin and K-T. Shao. 2001. Long-term monitoring of the coral reef fish communities around a nuclear power plant. *Aquatic Ecology* 35:233-243.

Author Abstract. Over the past 21 years (1979-1999) we have observed temporal changes in the fish communities on a coral reef around a nuclear power plant in southern Taiwan. Data used for analyses were collected bimonthly by scuba-diving ichthyologists at four sub-tidal stations (Stations A, B, D, E). The commercial operation of the nuclear power plant was launched in the summer of 1984. During the study period the number of fish species varies, with the coefficient of variation (CV) ranging from 19.0% (Station A) to 25.2% (Station D). Nevertheless, the sequential data on number of species follow a random trend in terms of runs up and down at all four stations. This characteristic persists both before and after the initiation of power plant operation. Dendrograms drawn using UPGMA (unweighted pair-group method using arithmetic averages) on the dissimilarity coefficients between yearly fish occurrences show that the years 1980-1984 are more closely grouped than any other years. This phenomenon prevails at all stations, indicating that wide-scale change occurred between 1984 and 1985. After the power plant began operation, changes in water temperature were minute at these sub-tidal stations. Impacts from other sources such as chlorine release and fish impingement seem remote. We believe temporal variations in the studied fish communities can be better explained as arising from natural fluctuations of environmental factors as well as physical disturbance caused by typhoons. The latter factor is also thought to account for the major faunal change between 1984 and 1985.

Jordan, I. E. and M. J. Samways. 2001. Recent changes in coral assemblages of a South African coral reef, with recommendations for long-term monitoring. *Biodiversity and Conservation* 10:1027-1037.

Author Abstract. Two-mile reef, Sodwana, South Africa is an unusual coral reef, being situated on a submerged fossilized sand dune and being very southerly (27º 54'). It is a popular Scuba diving venue receiving about 100,000 dives year^{-1}. The line-intercept transect method, as recommended by the Global Coral Reef Monitoring Network (GCRMN), was used to determine soft coral, hard cora,l and other benthos percentage cover. Physical coral damage, disease, and bleaching were also recorded. Results were compared with those of B. Riegl (1993 - unpublished Ph.D. thesis) 5 to 7 years earlier. The reef appears to be ecologically and highly dynamic. In the interim, there has been an increase in living benthos cover of 22.3% but also an increase in coral bleaching from 0% in 1993 to 1% in 1998. Physical damage, despite the large number of dives on the reef, was minimal (1.52%), although it appears as if coral diseases may be increasing. The 20-m transects recommended by GCRMN are too long for this highly rugose reef with its distinct ridges and gullies. It is recommended that benthos cover, coral damage, bleaching and disease should be monitored annually using 40 5-m transects on the reef ridges and 40 5-m transects on the reef slopes

LeGore, S., D. S. Marszalek, L. J. Danek, M. S. Tomlinson, J. E. Hofmann and J. E. Cuddeback. 1989. Effect of chemically dispersed oil on Arabian Gulf corals: A field experiment, pp. 375-381. In Proceedings of the 1989 International Oil Spill Conference, API Publication Number 4479, American Petroleum Institute, Washington DC.

A large-scale experiment was conducted on Jurayd Island, off the coast of Saudia Arabia on coral responses to oil spills by setting realistic conditions. The corals were exposed to crude oil only at 24 hours and 120 hours. Coral reefs consisting primarily of *Acropora* with distributed colonies of *Porites sp., Platygyra* sp. and *Goniopora sp.* were studied. Plots were measured 2 X 2 m and situated over about a depth of 1-m at low tide and anchored in place. Oil was then added to the test plots using 14 liters within the 24-hour oil only treatment and, 5.63 liters within the 120-hour experiment. Hydrocarbons in the water concentration were measured using infrared. In oil only plots, visual inspections were done to assess corals that were exposed at the end of the 24-hour and 120-hour periods. Monitoring was conducted for one year with no changes occurring relative to the un-oiled plots. See publication for additional information on techniques used for monitoring. While the dispersed oil appeared to slow down coral reef recovery from seasonal bleaching, researchers did not observe this occurring in the oil-only plots. No correlation to treatment in the 24-hour exposure for the growth rates was observed. Authors concluded that healthy reef corals can tolerate short oil exposures without any noticeable effect but corals susceptibility to exposures may vary during winter season.

Lirman, D. and M. W. Miller. 2003. Modeling and monitoring tools to assess recovery status and convergence rates between restored and undisturbed coral reef habitats. *Restoration Ecology* 11:448-456.

Author Abstract. Boating activities are an increasing source of physical damage to coral reefs worldwide. The damage caused by ship groundings can be significant and may result in a shift in reef structure and function. In this study we evaluate the status of two restoration projects established in 1995, six years after two freighters, the M/V Maitland and the M/V Elpis, ran aground on reefs of the Florida Keys National Marine Sanctuary. Our approach includes field monitoring in support of simulation model development to assess the effectiveness of the restoration efforts. A population model was developed for the coral *Porites astreoides* to project the convergence rates of coral abundance and population size structure between the restored and surrounding reference habitats. Coral communities are developing rapidly on the restoration structures. Species richness and abundance of the dominant coral, *P. astreoides*, were nearly indistinguishable between the restoration structures and reference habitats after only 6 years. However, although abundance and size structure of *P. astreoides* populations are rapidly approaching those of the reference habitats (a convergence in size structure within 10 years was simulated), maximum coral size will take twice as long to converge for this species. The sensitivity of the model to maximum recruitment rates highlights the importance of recruitment on the recovery rates of restored habitats, suggesting that special attention should be afforded to provide coral recruits with appropriate recruitment substrate at the time of restoration. Finally, the rates of convergence and, hence, the level of success of a restoration effort were shown to be influenced not only by the recruitment and survivorship rates of corals on the restoration structures but by the characteristics of the reference population as well. Accordingly, reference populations ought to be considered a "moving target" against which restoration success has to be measured dynamically. The simple, cost-effective, monitoring-modeling approach presented here can provide the necessary tools to assess the current status of a restoration effort and to project the time required for coral populations to resemble those found on undamaged reference habitats.

Motta, H., M-A. Rodrigues and M. H. Schleyer. 2001. Coral reef monitoring and management in Mozambique, pp. 43-48. In Souter, D., D. Obura and O. Linden, (eds.), Coral Reef Degradation in the Indian Ocean: Status Reports and Project Presentations 2000. CORDIO, Stockholm, Sweden.

A survey was conducted at the end of summer 1999 on coral bleaching in relation to ENSO on Mozambican coastline. Bleaching was observed on seventeen reefs. Visual assessments were made of reef type, faunal cover, and the extent of reef damage that may have resulted from bleaching and crown-of-thorns starfish (COTS). Based on the results, the effects of El Niño bleaching in Mozambique were most widespread on exposed reefs in the north and declined south except at Inhaca Island where detrimental bleaching was recently observed. Widespreade COTS damage was seen at Bazaruto and Inhambane. Monitoring was conducted between August and September. During the first year of monitoring, 9 "core" reefs were selected for annual survey. See publication for additional information on methods used. The reefs condition varied between healthy to severely impacted due to natural and anthropogenic stresses. However, the main factors responsible for reef deterioration were bleaching and the crown-of-thorns starfish infestation. On the reefs of northern Mozambique and in marine protected areas coral cover was greatest. Recovery was observed on few reefs with soft corals as the primary colonizers.

National Oceanic and Atmospheric Administration. 2002. A National Coral Reef Action Strategy, Report to Congress. NOAA Coral Reef Conservation Program,

Office of Response and Restoration, National Ocean Services, Silver Spring, MD. Contact information: Phone # (301) 713-2989, roger.b.griffis@noaa.gov. http://coris.noaa.gov/activities/actionstrategy/01_exec_summ.pdf.

The National Coral Reef Action Strategy document was developed to comply with the requirements of the Coral Reef Conservation Act of 2000 (CRCA) and aid in tracking implementation of the National Action Plan to conserve coral reefs. Information provided in this document was obtained from government and non-government organizations, scientists, resource managers, stakeholders, and the public. The major goals of the National Coral Reef Action Strategy are to increase the understanding of coral reef structure and functions, identify threats to coral reef habitats, establish effective monitoring and assessment techniques used, conduct surveys that track changes in reef habitats, enhance the understanding of social and economic factors of conserving coral reefs, improve education and outreach, and reduce coastal pollution and physical impacts to the reef. To ensure that these goals are accomplished, NOAA and the U.S. Coral Reef Task Force encourage (1) working with partners and stakeholders, developing and implementing a long term program that will inventory, assess and monitor U.S. coral reef habitats; (2) developing a web-enabled data management and information system for U.S. reef monitoring and mapping data that will provide user-friendly GIS based mapping; and (3) developing and creating a biennial report on the status of U.S. coral reef habitats.

Nemeth, R. S. and J. S. Nowlis. 2001. Monitoring the effects of land development on the near-shore reef environment of St. Thomas, USVI. *Bulletin of Marine Science* 69:759-775.

Author Abstract. This study evaluated the impacts of shoreline development on the coral reef at Caret Bay, St. Thomas, USVI. Studies in rates of sedimentation, changes in water quality and changes in the abundance and diversity of corals and other reef organisms were conducted along five permanent transects from July 1997 and March 1999. Monitoring was conducted monthly. See publication for additional information on methods used. The results from monthly monitoring before, during and after construction indicated that sedimentation and total suspended solids increased during large rainfall events, and that sediment load onto Caret Bay reef was greatest directly below ravine outlets and in locations where the shoreline was sheltered. Sedimentation rates decreased relative to average monthly rainfall after buildings, landscaping and road paving were completed Based on visual assessment of coral condition researchers indicated that coral pigment loss was associated with both influx of terrigenous sediments and with natural seasonal phenomena. Bleaching of coral colonies showed a positive relationship with sedimentation ($r^2 = 0.92$). Reef sites exposed to sedimentation rates between 10 to 14 mg cm^{-2} d^{-1} showed a 38% increase in the number of coral colonies experiencing pigment loss than reef sites exposed to sedimentation rates between 4 to 8 mg cm^{-2} d^{-1}. Coral cover along the entire reef tract declined about 14% (range: -3.92% to -31.34%). This decline in coral cover from pre- to post-construction surveys showed weak negative associations with sedimentation ($r^2 = 0.52$) and bleaching ($r^2 = 0.48$). Patterns of abundance of macro algae, sponges and encrusting gorgonians were mainly to natural seasonal changes rather than to rates of sedimentation. Overall monthly monitoring was good at detecting and differentiating changes in the reef environment that were associated with human activity and natural causes.

Petersen, D. and R. Tollrian. 2001. Methods to enhance sexual recruitment for restoration of damaged reefs. *Bulletin of Marine Science* 69:989-1000.

Author Abstract. Natural recruitment of scleractinian corals is highly influenced by various environmental effects. Predation, sedimentation, algal growth and grazing may cause high mortality rates in larvae and settlers. In the past, methods have been developed to produce large quantities of planulae. Under laboratory conditions the survival of *ex situ* produced propagules can be optimized to obtain large amounts of sexual recruits. Sexual recruitment plays an important role in conservation management, especially for the preservation of genetic diversity in natural and *ex situ* populations. We carried out pilot studies which indicate the possibility to transport, settle and recruit scleractinian corals, here *Acropora florida* Dana 1846, in closed-system aquaria using artificial seawater. After further development, this method promises to be an economical and effective way to mariculture corals for restoration of damaged reefs. To fulfill this aim, collaboration with commercial coral farms and public aquaria should be envisaged. Coral farms that provide work for coastal populations can play an important role in mariculturing sexual settlers. Such farms could produce thousands of propagules for reef conservation and even more for the aquarium trade thus reducing natural collection of corals and providing financial support by resulting incomes. Public aquaria may help to optimize this method.

Riegl, Bernhard. 2001. Degradation of reef structure, coral and fish communities in the Red Sea by ship groundings and dynamite fisheries. *Bulletin of Marine Science* 69:595-611.

Reef degradation was investigated on 66 Egyptian Red Sea reefs--60 reefs for dynamite damage (using line transects) and six ship grounding sites (using 1 m sample squares). Ship groundings and dynamite fishing caused similar damage, reduction of the reef to rubble (65% of reefs were dynamited mostly leeward, 58%). Changes in coral (line transect study) and fish communities (point count study) in impacted sites were documented. On impacted reefs, coral cover decreased, bare substratum and rubble increased, and fish dominance shifted away from Pomacentridae. Oceanographic conditions result in a stable pattern of coral communities (windward Acropora, leeward Porites). Most dynamite damage was on leeward, near-climax Porites reef slopes or Porites carpets. Most ship groundings were on windward Acropora reefs with regeneration periods calculated to be between 100 and 160 yrs. Regeneration time of dynamite damage is expected to be similar because of similar damage. Rehabilitation could speed up recovery but has to be consistent with natural community patterns. Coral transplants should mimic previously existing community structure in order to avoid space preemption by introduced superior competitors. Particularly if Acropora were introduced on a large scale into normally Porites dominated reef areas, re-establishment of the original community within the desired time-frame could be delayed.

Riegl, B., J. L. Korrubel and C. Martin. 2001. Mapping and monitoring of coral communities and their spatial patterns using a surface-based video method from a vessel. *Bulletin of Marine Science* 69:869-880.

Author Abstract. Maps are useful tools for understanding spatial dynamics and the general distribution of ecosystems, which is of high value to resource managers and scientists, and many management plans rely heavily on maps. Restoration ecologists are aided by maps to be able to assess the severity of impacts and to be able to produce restoration strategies. A variety of approaches exist to mapping the spatial distribution of benthic biota and bedforms, like remote sensing from satellites or planes, or geophysical methods like side-scan sonar surveys. Most of these methods were developed for specific reasons other than coral reef research and coral-specific applications have only fairly recently been developed. The method described in this paper is an application that was specifically designed for coral research. In order to establish the value and spatial distribution of coral areas that were almost accidentally discovered during a dredging pre-survey in the southern Arabian Gulf (Dubai, United Arab Emirates), a concise method was called for that not only allowed the description of the coral covered area, but also allowed coral species to be differentiated as well as the healthy coral distinguished from the diseased. This called for a visual survey, since other frequently used methods, like airborne imagery or side-scan sonar, allow delineation of coral covered area but give no information on species or health status. Due to the large area involved (37.7 km^2), the time-frame available and the desired level of accuracy (100% visual cover of the area), a diver-based mapping approach was not possible. Therefore, rather than have divers undertake large numbers of video transects, we decided to make 'mega-video transects' from a boat that covered the entire coral area. This had the advantage of significantly reducing diver time, speeding up overall survey time, and increasing accuracy by providing 100% recorded visual cover of the coral area. The desired output was a map that specified spatial patterns of coral communities that could be used for management planning. Furthermore, over 1996 a thermal anomaly led to widespread coral mortality in the study area and it was of interest to map the spatial extent of coral growth lost in this event. This paper describes (1) the technical details of the vessel-based video survey, (2) shows the product (the maps), and (3) discusses management and monitoring implications of the product.

Rinkevich, B. 1994. Restoration strategies for coral reefs damaged by recreational activities: The use of sexual and asexual recruits. *Restoration Ecology* 3:241-251.

Author Abstract. The unique marine ecosystems of coral reefs express varying levels of degradation as a result of increasing anthropogenic pressures. This is the main reason why more than 200 coral reef localities were proclaimed as natural reserves or marine parks under varying legislation, rules, and monitoring and management programs. Ironically, the conventional management plans increased accessibility to many reef localities and enhanced dramatically the impact of tourism on reef habitats. Recreational activities including SCUBA and skin diving, fishing, human trampling, sediment resuspension, and other damage caused by "innocent" visitors are causing a rapid deterioration of many reefs. Their destruction requires years and decades for full recovery. Rinkevich proposed to rehabilitate such damaged habitats by the alternate strategy of "gardening coral reefs" with asexual and sexual recruits. Coral branches, colony fragments, and whole small colonies (asexual recruits) and laboratory or *in situ* settled planula-larvae (sexual recruits) are designed to be transplanted into denuded reefs for restoration. This approach is further improved when the sexual and asexual recruits are maricultured *in situ* within special protected areas, before being transplanted. The use of sexual recruits ensures an increase in genetic diversity. Rinkevich discussed several methodologies and results already accumulated showing the applicability of this gardening strategy for rehabilitation of denuded coral reefs. This restoration strategy should be integrated with proper management similar to that of already established reforestation in terrestrial habitats. The best candidates for employing this strategy are the fast-growing coral species, usually branching forms and species that brood their planulae larvae.

Rinkevich, B. 2000. Steps towards the evaluation of coral reef restoration by using small branch fragments. *Marine Biology* 136:807-812.

Author Abstract. Gardening of denuded coral reef habitats is a novel restoration approach in which sexual and asexual recruits are used. The present study aimed at the evaluation of the potentiality for restoration use of different types of small fragments subcloned from the Red Sea coral species *Stylophora pistillata*. *In situ* short-term (24 h, ^{45}Ca method) and long-term (1 year, alizarin Red S vital staining) experiments revealed high variation (up to 70%) in growth rates between up-growing branches of a specific genet, and that tip ratios in dichotomous branches (n = 880) differ significantly between newly formed and older branches, further emphasizing the within-colony genetic background for spatial configuration. Small, isolated branches (<4 cm) revealed high survivorship (up to 90%, 1 year) and up to 20-30% (1 year, single- vs. dichotomous-tip branches, respectively) growth, showing that small-sized branches are suitable for restoration purposes. Results differed significantly between genets. Total length added for dichotomous-tip branches was in general at least twice that recorded for single tips of a specific genet. Restoration protocols may be applied either by sacrificing whole large colonies via pruning high numbers of small fragments or, by pruning only a few small branches from each one of many genets. An *in situ* "nursery period" of approximately 8 years is predicted for *S. pistillata* small fragments.

Risk, M. J., J. M. Heikoop, E. N. Edinger and M. V. Erdmann. 2001. The assessment 'toolbox': Community-based reef evaluation methods coupled with geochemical techniques to identify sources of stress. *Bulletin of Marine Science* 69:443-458.

Author Abstract. There have been few seminal advances in techniques of health evaluation of coral reefs since line transects and visual fish counting were first proposed in 1972, yet the rate of resource destruction increases rapidly. Especially in Third World settings, coastal communities need access to simple techniques that have been shown to identify stress on reefs: (1) Coral mortality indices, (2) Benthic bioindicators (stomatopods, forams, amphipods), (3) Coral associate counts, and (4) Bioerosion amounts in coral rubble. Coral growth rates are an undependable measure of reef health: corals on dying reefs with low coral cover often exhibit higher than normal growth rates. Transect data may be cast into other forms, such as triangular diagrams, to be more effective in reef management. All of these rapid assessment techniques have been shown to be effective in the hands of persons with limited technical training. Each is rapid and cost-effective. Once one of the 'tools' in the assessment 'toolbox' has detected stress, the precise nature of the source can be identified via geochemical techniques: (1) Sewage: stable isotope ratios of nitrogen (delta ^{15}N) in a number of organisms (stomatopods, corals) are enriched at sites subject to sewage discharge. (2) Siltation: in areas subject to siliciclastic input, insoluble residues in coral skeletons are a measure of exogenous sediment input. (3) Thermal/Light stress: as has been shown in studies of El Niño events and the Indonesian 'haze' of 1997, the delta ^{13}C signal in coral skeletons is a measure of metabolic stress caused by changes in light and temperature.

Rogers, C. S. and V. H. Garrison. 2001. Ten years after the crime: Lasting effects of damage from a cruise ship anchor on a coral reef in St. John, United States Virgin Islands. *Bulletin of Marine Science* 69:793-803.

Author Abstract. In October 1988, a cruise ship dropped its anchor on a coral reef in Virgin Islands National Park, St. John, creating a distinct scar roughly 128 m long and 3 m wide from a depth of 22 m to a depth of 6 m. The anchor pulverized coral colonies and smashed part of the reef framework. In April 1991, nine permanent quadrats (1 m^2) were established inside the scar over a depth range of 9 m to 12.5 m. At that time, average coral cover inside the scar was less than 1%. These quadrats were surveyed again in 1992, 1993, 1994, 1995 and 1998. Recruits of nineteen coral species have been observed, with *Agaricia agaricites* and *Porites* spp. the most abundant. Quadrats surveyed outside the scar in June 1994 over the same depth range had a higher percent coral cover (mean = 7.4%, SD = 4.5) and greater average size (maximum length) of coral colonies than in quadrats inside the damaged area. Although coral recruits settle into the scar in high densities, live coral cover has not increased significantly in the last 10 yrs, reflecting poor survival and growth of newly settled corals. The relatively planar aspect of the scar may increase the vulnerability of the recruits to abrasion and mortality from shifting sediments. Ten years after the anchor damage occurred, live coral cover in the still-visible scar (mean = 2.6%, SD = 2.7) remains well below the cover found in the adjacent, undamaged reef.

Rogers, C. S. and J. Miller. 2001. Coral bleaching, hurricane damage, and benthic cover on coral reefs in St. John, U.S. Virgin Islands: A comparison of surveys with the chain transect method and videography. *Bulletin of Marine Science* 69:459-470.

Author Abstract. The linear chain transect method and videography were used to quantify the percent cover by corals, macroalgae, gorgonians, other living organisms, and substrate along permanent transects on two fringing reefs off St. John. Both methods were used simultaneously on Lameshur Reef in November 1998 and on Newfound Reef in March and October 1998. Hurricane Georges passed over St. John in September 1998 and a severe coral bleaching episode began the same month. Both methods gave remarkably similar values for coral cover, while the video method gave consistently higher values for gorgonians and macroalgae. The most dramatic difference was in the quantification of bleaching. At Newfound, the chain method indicated 13.4% (SD = 14.1) of the coral tissues were bleached and the video method, 43.4% (SD = 13.0). Corresponding values at Lameshur were 18.1% (SD = 22.3) and 46.5% (SD = 13.3). Although hurricane damage was conspicuous at Newfound Reef, neither method showed significant changes in coral cover or other categories as a result of the storm.

Syms, C. and G. P. Jones. 2001. Soft corals exert no direct effects on coral reef fish assemblages. *Oecologia* 127:560-571.

Author Abstract. Correlations between abundance of organisms and their habitat have often been used as a measure of the importance of particular habitat features. However, experimental manipulation of the habitat provides a more unequivocal estimate of its importance. In this study we quantified how fish communities on small patch reefs covaried with changes in benthic cover habitat features. A random sample of small patch reefs was selected and both fish abundance and habitat measures recorded. Naturally occurring patch reefs could be classed into three habitat types based on their benthic cover. Reefs dominated by massive soft corals were the most abundant (50%), followed by those dominated by rock and soft corals in equal proportions (36%), then reefs dominated by branching corals (14%). Fish assemblages differed between the reef types. Communities on soft-coral-dominated and rock/soft-coral-dominated patch reefs formed a continuum of species responses correlated with degree of soft coral cover. In contrast, branching-coral-dominated reefs were occupied by a more discrete set of species. We tested the role of soft corals in contributing to this pattern by experimentally reducing soft coral cover on patch reefs from a baseline level of ~67% to ~33% and ~6%, and monitoring the experiment over two years. Contrary to expectations derived from the correlative data, and in contrast with previous manipulations of hard corals, soft-coral disturbance did not generate any corresponding changes in the fish assemblage. This negative result indicated that the quality and heterogeneity of habitat generated by soft corals on patch reefs was indistinguishable from equivalent-sized habitat patches formed by bare rock alone. Nevertheless, because soft corals are living organisms they have the potential to generate indirect effects by interacting with other organisms such as hard corals. In the long-term, we hypothesize that biotic interactions between habitat forming organisms might affect composition of fish assemblages on patch reefs.

Torres, J. L. 2001. Impacts of sedimentation on the growth rates of *Montastraea annularis* in southwest Puerto Rico. *Bulletin of Marine Science* 69:631-637.

Author Abstract. Growth rates of the massive reef-builder coral *Montastraea annularis* (morphotype II) were obtained at three heavily disturbed reefs near the Guanica, Guayanilla, and Ponce Bays on the south coast of Puerto Rico. These were compared with growth rates from a virtually undisturbed reef located at La Parguera reef platform on the southwest coast. Sediment plumes have affected the disturbed sites for more than 10 yrs. Resuspended sediment rates (g cm^{-2} d^{-1}) were measured for a year period, and correlated with growth rates. Sediment composition from the samples was also taken into consideration. Average growth rates of *M. annularis* were in the order of 5.4 ± 0.98 mm yr^{-1} at Guanica, 6.68 ± 1.35 mm yr^{-1} at Guayanilla and 7.01 ± 0.63 mm yr^{-1}) at Ponce. These were significantly lower ($P < .05$) than those obtained at Parguera (10.76 ± 1.43 mm yr^{-1}), and negatively related with sediment rates and percentages of terrigenous sediments reaching the sites. Calcium carbonate percentages were significantly higher ($P < .001$) at Parguera and were related positively with coral growth rates suggesting that sediment produced within the reef did not affect the corals as sediments coming from external sources (i.e., inland). The species *M. annularis* had suffered a decline in its growth rates across the reefs of the southwest coast of Puerto Rico. It was determined that linear extension rates of this species correlate negatively with increased sedimentation rates and percent of terrigenous sediments. Carbonate percentages correlate positively with linear extension rates of *M. annularis* and, hence, do not interfere in the growth rates of this species, instead they may be incorporated into the skeleton and used as an alternative source.

United States Coral Reef Task Force Working Group on Ecosystem Science and Conservation. 2000. Coral Reef Protected Areas: A Guide for Management. 17 pp. NPS publication D-1449. U.S. Coral Reef Task Force, Department of the Interior, Washington, D.C. http://www.coralreef.gov/blueprnt.pdf

This report presents information that managers of coral reef protected areas should be familiar with before monitoring. This includes (1) location of the reefs using aerial photography and other remote techniques. Photography may also be use to record baseline reef conditions and provide permanent record of reef exterior at a specific time; (2) the condition of the reefs (whether diseased or healthy); (3) whether the reefs have changed and the cause. For example, changes that occur in reef condition and species abundance due to pollution, storms, or direct impact from boats; (4) whether the present measures are sufficient to prevent coral reef deterioration and in some cases reef recovery.

The monitoring methods and parameters selected will depend on the objectives, threats predicted, and management course of action. Authors also state that measuring coral abundance variations over time and other species that reside on healthy reefs can provide foundation for evaluating changes on nearby reefs that may be stressed by anthropogenic sources. Therefore when monitoring is performed, one should record the number of persons using the reef areas, concentrated zones, and types of activities occurring around or nearby the reef. See publication for additional information that should be taken into consideration for monitoring of reefs.

United States Environmental Protection Agency (EPA) Science Advisory Panel. 2000. Coastal Reef Monitoring Executive Summary, EPA Advisory Panel, Key Colony Beach, December 5-6, 2000. Contact information: Reef Relief Environmental Center, Phone # (305) 294-3100 and Fax # (305) 293-9515. http://www.reefrelief.org/coral_reef_monitoring_project1.html

Coral reef monitoring was conducted at forty reef sites located within five of the nine EPA Water Quality Segments in the Florida Keys National Marine Sanctuary during 1994. Permanent station markers were installed at these sites in 1995. Sampling began in 1996. There were 160 stations among forty sites sampled up to 2000. Three additional sites were installed and sampled in the Dry Tortugas in1999. Sampling was performed using a Sony CCD-VX3 with full automatic settings and artificial lights (two 50 watt) at 40 cm above the benthos. In 2000, sampling was performed using digital video filming all sites with a Sony TRV 900. Video frames were used to predict percent cover analysis with minimal overlap between images. A custom software application Point-Count was used to analyze coral reefs images. Using this method, the analyst opens each image and the software adds ten random points over the image. Selected benthic taxa (stony coral, octocoral, zooanthid, sponge, seagrass, and macroalgae) and substrate would then be identified under each point. After images are analyzed, the data is converted to an ASCII file for Quality Assurance. In addition, hypothesis testing was also used to analyze the percent cover, species richness, and disease/condition data.

Wagner, G. M., Y. D. Mgaya, F. D. Akwilapo, R. G. Ngowo, B. C. Sekadende, A. Allen, N. Price, E. A. Zollet and N. Mackentley. 2001. Restoration of coral reef and mangrove ecosystems at Kunduchi and Mbweni, Dar es Salaam, with community participation, pp. 467-488. In Richmond, M. D. and J. Francis (eds.), Marine Science Development in Tanzania and Eastern Africa 1. WIOMSA Book Series.

Author Abstract. A baseline study was conducted on the fringing coral reef around Mbudya Island. The snorkeling visual census technique was used to estimate percentage of bio-cover. There were substantial areas of no bio-cover (15-40%), which was attributed to dynamite fishing and wave action. Of the hard coral cover, which was 47% on the landward side of Mbudya and 12% on the seaward side, 40-60% was dead, probably largely due to coral bleaching. The live coral included twenty-nine genera representing eleven families. Fish were generally more abundant on the landward side. Preliminary trials were conducted on ecosystem restoration with community involvement. Fishermen were involved in transplanting corals on the fringing reef at Mbudya Island. Approximately, 500 fragments of *Galaxea*, *Acropora, Porites* species, and *Montipora* species were transplanted in seven dynamited sites, using cement filled, and disposable plastic plates. Monitoring was subsequently carried out in the restored sites. Approximately 3 months after transplanting the corals, *Galaxea* species showed very significantly greater survival (100% complete survival) than *Porites* species (55.7%) complete survival, 13.9% partial survival), but there was no significant difference between *Acropora* species and *Montipora* species survival. Over a period of 5 months, increase in height was significant for *Galaxea* species and *Porites* species, but not for *Acropora* species. Likewise, a baseline study was conducted in Mbweni Mangrove Forest using the transect line plots method. One site near the village, which had formerly been dominated by *Rhizophora mucronata*, has been severely cut for firewood and building poles in recent years. It now consists mostly of saplings, dominated by *Ceriops tagal* (0.20 individuals/m super(2)), followed by *R. mucronata* (0.10 individuals/ m^2). In another site, which was clear-cut about two years ago, *C. tagal, Avicennia marina* and *R. mucronata* (mostly seedlings) are now found at densities of 0.23, 0.10 and 0.01 individuals/ m^2, respectively. Women at Mbweni village assisted with the transplanting of more than 3000 seedlings of *Rhizophora mucronata* in Mbweni Mangrove Forest. This mangrove replanting activity resulted in the spontaneous formation of a new community-based organization (CBO) known as Mbweni Environment and Women's Group. The monitoring of mangrove seedlings showed that after 8 months, 35-38% were in perfect condition. The site that had been clear-cut showed very poor seedling survival.

Walter, D. J., D. N. Lambert and D. C. Young. 2001. Sediment facies determination using acoustic techniques in a shallow-water carbonate environment, Dry Tortugas. *Marine Geology* 182:161-177.

Author Abstract. Two high-frequency acoustic seafloor classification systems (12- and 15-kHz) were used in conjunction with sediment core analysis to characterize sediment facies at a study site near Garden Key in Dry Tortugas, Florida. The acoustic system uses echo return amplitude to compute acoustic impedance that is then correlated with sampled sediment impedance values calculated from wet bulk density and compressional wave velocity. Several bottom provinces were identified using the 15-kHz data to construct a real-time map of ship tracks in colors that represent the surficial sediment facies type. Sediment facies over the entire study site (36 km^2) range from sandy silts to exposed limestone rock and coral reef structures. Color contour maps using the 12-kHz data, created after correlating acoustic impedance predictions with core measured sediment properties, validates the initial facies pattern predictions made in real-time. The sediment facies patterns indicate a long-term pattern of deposition of fine-grained, silt-sized, surficial sediments in an area adjacent to the emergent carbonate embankment. Two-dimensional acoustic profiles along survey tracklines also provide cross-sectional views of seafloor and subbottom stratigraphy that confirm the buildup of these fine sediments in the northwest corner of the study site. A generous supply of sediment resulting from an abundance of benthic green algae (*Halimeda* spp.) on adjacent shallow platforms form a thick sequence of fine sandy silt at the base of the southeastern edge of the embankment and fringing reef. Sediment cover over the limestone bedrock thins and becomes coarse southeast of Garden and Bush Keys, suggesting the likely existence of a dominant flow around the shallow carbonate embankment that restricts export of fine sediments out of the area.

Wulff, J. 2001. Assessing and monitoring coral reef sponges: Why and how. *Bulletin of Marine Science* 69:831-846.

Author Abstract. Functional roles of sponges in coral reef ecosystems include: increasing coral survival by binding live corals to the reef frame and preventing access to their skeletons by excavating organisms; mediating regeneration of physically damaged reefs by temporary stabilization of carbonate rubble; reworking of solid carbonate through bio-erosion; recycling nutrients and adding to primary production through microbial symbionts with special biochemical capabilities; clearing the water column of procaryotic plankton; serving as food for a variety of megafauna; and attracting support for responsible human stewardship of coral reefs with aesthetically appealing colors and morphologies. Nevertheless, sponges tend to be avoided in assessment and monitoring of coral reefs because they are not easy to quantify or identify, and because we have only recently begun to understand the importance of their many functional roles. As we gain more understanding of these roles of sponges in coral reefs, the need to carefully assess and monitor changes in sponges is becoming clearer. Focus on functional roles dictates choice of methods for assessing and monitoring sponges, as follows: (1) volume will generally be the most useful way to quantify sponge populations; (2) accurate identification to genus, family, or even order, combined with a brief description and reference to voucher specimens, is preferable to guesses on species names, in cases for which identification can't be verified by specialists; (3) permanently marked sites must be monitored over time in order to be able to detect community changes and to distinguish beneficial from detrimental effects of sponges on corals.

Yamano, H., M. Tamura, Y. Kunii and M. Hidaka. 2002. Hyperspectral remote sensing and radiative transfer simulation as a tool for monitoring coral reef health. *Marine Technology Society Journal* 36:4-13.

Author Abstract. Recent advances in the remote sensing of coral reefs include hyperspectral remote sensing and radiative transfer modeling. Hyperspectral data can be regarded as continuous and the derivative spectroscopy is effective for extracting coral reef components, including sand, macroalgae, and healthy, bleached, recently dead, and old dead coral. Radiative transfer models are effective for feasibility studies of satellite or airborne remote sensing. Using these techniques, we simulate and analyze the apparent reflectance of coral reef benthic features associated with bleaching events, obtained by hyperspectral sensors on various platforms (ROV, boat, airplane, and satellite), and suggest that the coral reef health on reef flats can be discriminated precisely. Remote sensing using hyperspectral sensors should significantly contribute to mapping and monitoring coral reef health.

APPENDIX II: CORAL REEFS
REVIEW OF TECHNICAL METHODS MANUALS

This Review of Technical Methods Manuals includes a variety of sampling manuals, Quality Assurance/Quality Control (QA/QC) documents, standardized protocols, or other technical resources that may provide practitioners with the level of detail needed when developing a monitoring plan for a coastal restoration project. Examples from both peer reviewed and grey literature are presented. Entries were selected through extensive literature and Internet searches as well as input from reviewers. As with the Annotated Bibliographies, these entries are not, however, a complete list. Entries are arranged alphabetically by author. Wherever possible, web addresses or other contact information is included in the reference to assist readers in easily obtaining the original resource. Summaries preceded by the terms '*Author Abstract'* or *'Publisher Introduction*' or similar descriptors were taken directly from their original source. Summaries without such descriptors were written by the authors of the associated chapters.

Caribbean Coastal Marine Productivity Program (CARICOMP). 2001. CARICOMP Methods Manual: Manual of Methods for Mapping and Monitoring Physical and Biological Parameters in the Coastal Zone of the Caribbean. 93 pp. CARICOMP Data Management Center, Centre for Marine Sciences, University of the West Indies. Mona, Kingston, Jamaica. Florida Institute of Oceanography, University of South Florida, St. Petersburg, FL, USA. http://www.ccdc.org.jm/caricomp_manual_2001.pdf.

The CARICOMP program focuses on understanding productivity, structure, and function of coral reefs, mangroves, and seagrass ecosystems. Members of this program designed a methods manual that provides standards for monitoring and assessing the condition of these marine habitats. Some physical measurements that should be taken when monitoring the habitats condition include a detailed site description and selection, site mapping, and time series measurements. A description of coral reefs physical characteristics, parameters that are to be measured, and methods used to monitor and assess the habitat's condition are also provided. Methods and procedures that are commonly used on coral reefs and described in this document include: line transects, recording timing and frequency, sample strategy and collection, data management, survey of habitat structures and grazers. Additional information on methods and procedures used to assess and evaluate the health of each of the habitats mentioned in this abstract are described in this manual.

This Manual provides Cook Inlet Keeper volunteers with information needed to monitor water quality in the Cook Inlet watershed.

Crosby, M. P. and E. S. Reese. 1996. A Manual for Monitoring Coral Reefs with Indicator Species: Butterfly Fishes as Indicators on Indo Pacific Reefs. 45 pp. Office of Ocean and Coastal Resource Management, National Oceanic and Atmospheric Administration.

This manual discusses the use of an indicator species, coral feeding butterfly fishes (family Chaetodontidae) to assess the health of corals reefs in the Indo Pacific regions. Researchers determined the correlations of fish feeding preference, abundance, and behavior with coral abundance and health. Butterfly fishes are monitored along 1 to 30m transects near areas with high coral cover. The number of each species of butterfly fish on either side of the transect line is counted. Also evaluated were the fishes feeding behavior on the coral. Coral cover is also assessed under the transect for 0.5 m or 1.0 m intervals. Line transect methods are also used to determine coral diversity and abundance. The coral species type is identified along the transect line as well as at a specific point in the study area and then recorded. Coral percent cover is established by dividing the number of observations of a specific coral species by the number of data points along the transect. The methods mentioned is this manual for assessing coral health are relatively simple, less expensive and yet effective compared to some other monitoring methods used.

English, S., C. Wilkinson and V. Baker. 1997. Survey Manual for Tropical Marine Resources, 2nd edition. Australian Institute of Marine Science Townsville ISBN 333.952072013 or Protocols for Coral Reef Monitoring. http://www.coral.noaa.gov/gcrmn/protocol.html

This publication discusses techniques used for coral reef monitoring. One method used is Manta tow or time swim. This provides a broad scope of the reef; observes any change in reef structure (like blast damage, plagues); and ensure that more detailed monitoring sites are representative of the whole reef. The Manta tow consists of two minute snorkel tows (minimum of nine) behind a boat at slow speed with stops to record percent cover of live and dead corals, soft coral, and regional specific parameters, e.g., crown-of-thorns starfish, giant clams, large patches of damage to corals. These tows are used to select transect monitoring sites to ensure adequate representation of the entire reef.

Another method used to assess coral reef health is Line Intercept or Transect. Five line transects each 20 m long are commonly used with the parameters recorded as lifeforms, or as species. Lifeforms or species can be grouped into larger groups; however, larger groups cannot be sub-divided back into more detailed groups after data have been collected. Belt and video transects can be inter-calibrated with the lifeform transects. Transects are placed where coral density is highest. Researchers advised that transects be marked from start and finish with steel stakes. Live fish visual censusing can also be used and are based on line transects. The primary focus for this method is counting all fish, especially those targeted by fishers and some indicator species like the Chaetodonts. The fish and lifeform transects can be conducted on the same transect lines, with fish surveys completed before benthos assessment, to avoid deterring fish. See publication for additional information on methods used for coral reef monitoring.

Environmental Protection Agency (EPA) Science Advisory Panel. 2000. Coastal Reef Monitoring Executive Summary, EPA Advisory Panel, Key Colony Beach, December 5-6, 2000. Contact information: Reef Relief Environmental Center, Phone # (305) 294-3100 and Fax # (305) 293-9515. http://www.reefrelief.org/coral_reef_monitoring_project1.html

EPA, Florida Keys National Marine Sanctuary (FKNMS) and National Oceanic and Atmospheric Administration (NOAA) have addressed the importance of monitoring. The sampling site locations were chosen using stratified random procedures. The study was performed at forty reef sites located within five of the nine EPA Water Quality Segments in the Florida Keys National Marine Sanctuary during 1994. Permanent station markers were installed at these sites in 1995. From 1996 to 2000, 160 stations among 40 sites were sampled. Three additional sites were installed and sampled in the Dry Tortugas beginning in 1999. The project's 43 sampling sites include: 7 hard bottom, 11 patch, 12 offshore shallow, and 13 offshore deep reef sites. Sampling performed through 1999 was conducted using a Sony CCD-VX3 with full automatic settings and artificial lights (two 50 watt) at 40 cm above the benthos. By 2000, digital video filming was used at all sites with a Sony TRV 900. The videographer films a clapperboard prior to beginning each transect. The date and location of each film segment is recorded. Percent cover analysis was predicted on selecting video frames that abut, with minimal overlap between images. Image analyses were conducted using a custom software application Point-Count for coral reefs. Selected benthic taxa (stony coral, octocoral, zoanthid, sponge, seagrass, and macroalgae) and substrate are identified under each point. After images are analyzed, the data is converted to an ASCII file for Quality Assurance and entry into the master ACCESS data set. Additional information techniques used are described in this report.

Jaap, W. C. 1995. Monitoring methods for assessing coral reef biota and habitat condition. 80 pp. In Crosby, M. P., G. R. Gibson and K.W. Potts (eds.), A Coral Reef Symposium on Practical, Reliable, Low-cost Monitoring Methods for Assessing the Biota and Habitat Conditions of Coral Reefs. EPA 904/R-95/016.

Researchers used various techniques to evaluate and assess injured or damage to reef resources. Aerial photogrammetry, ground truth surveys, and Global Information System (GIS) mapping were used for larger scale assessments. Techniques commonly used for *in situ* evaluations include: transect, quadrat, 35 mm photography, and video. Sediment and organism samples are collected to assess pollutants (e.g., trace metals) that may be present in the sediment. Disease and bleaching of the reef organisms were evaluated using histopathology and electron microscope analysis. Coral reefs were monitored in the Florida Keys in 1978. Methods used for monitoring include quadrats, line transects, and photography. Quadrat sampling methods involved counting and identifying the organisms under an X, Y coordinate grid (planar point intercept), estimating the cover using a grid of squares, and mapping the distribution of the taxa of interest within the quadrat (*in situ* mapping). Line transects are used in data collection by estimating species abundance. Photography was used to capture spatial patterns and changes occurring over time of a habitat. Additional information on methods used for assessing coral reef conditions is described in this document.

McCobb, T. D. and P. K. Wieskel. 2003. Long-Term Hydrologic Monitoring Protocol for Coastal Ecosystems, 94 pp. United States Geological Survey Open-File Report 02-497. http://water.usgs.gov/pubs/of/2002/ofr02497/

The United States Geological Survey (USGS) and the National Park Service have designed and tested monitoring protocols implemented at Cape Cod National Seashore. The monitoring protocols are divided into two parts. Part one of the protocol discusses the objectives of the monitoring protocol and presents rationale for the recommended sampling program. The second part describes the field, data-analysis, and data-management, and variables that are to be taken into consideration when monitoring (e.g., sea level rise, climate change and urbanization). This protocol provides consistency when monitoring changes in ground-water levels, pond levels, and stream discharge. The monitoring protocol not only establishes a hydrologic sampling network but provides reasoning for measurement methods selected and spatial and temporal sampling frequency. Data collected during the first year of monitoring and hydrologic analyses for selected sites are presented. Long-term hydrologic monitoring procedures performed at the Cape Cod National Seashore may also assist set a template for deciphering findings of other monitoring programs.

Motta, H., M-A. Rodrigues and M. H. Schleyer. 2001. Coral reef monitoring and management in Mozambique, pp. 43-48. In Souter, D., D. Obura and O. Linden, (eds.), Coral reef degradation in the Indian Ocean: Status reports and project presentations 2000. CORDIO, Stockholm, Sweden.

Author Abstract. Mozambique is situated on the eastern coast of Southern Africa, between 10° 27'S and 26° 52'S latitude and 30° 12'E and 40° 51'E longitude. The Mozambican coastline, about 2,770 km long, is the third longest in Africa and is characterized by wide diversity of habitats including sandy beaches, sand dunes, coral reefs, estuarine systems, bays, mangroves and seagrass beds. A survey on coral bleaching was undertaken in 1999, at the end of summer, to look at effects of the ENSO event in the region. Evidence of bleaching was sought on a total of 17 reefs and a visual assessment was made of reef type, faunistic cover and the extent of reef damage attributable to bleaching and crown-of-thorns starfish (COTS). The results show that the effects of El Nino bleaching in Mozambique were most extensive on exposed reefs in the north and this diminished further south except at Inhaca Island where serious recent bleaching was encountered. Extensive COTS damage was also found at Bazaruto and Inhambane. As part of a broader program, monitoring started in the same year with the installation and first visits to stations. Sites were selected for a preliminary survey, according to a number of criteria. The field work was carried out between August and September during 22 days. For the first year of monitoring, 9 "core" reefs were selected for annual survey. These reefs were widely distributed throughout the coast and represent different reef types. Before video transect was done, an observer would conduct a general survey and start a species list. This list was helpful on data analysis of video-transect. The condition of reefs surveyed varied between healthy to heavily impacted by natural and anthropogenic factors. Many reefs are degraded from bleaching and the ravages of crown-of-thorns starfish. Coral cover was highest on the reefs of northern Mozambique and in marine protected areas. The high cover of rock and algal surfaces reflects mortality that was reported at these sites in earlier surveys. There is evidence of recovery on some reefs on which soft corals are the primary colonizers. Carnivores dominated fish populations in the north and in protected areas, following a similar pattern to that of coral cover. High fishing pressure on the other reefs was shown by the small size classes of fish and the dominance of herbivores, which are least, preferred by fishermen. Before the initiation of the monitoring programme, however, participants went through a process of preparation. A training course was held in August 1999, attended by a number of participants from MICOA itself, the Institute of Fisheries Research and the University. Some of the participants were later integrated in the team that started the monitoring programme.

Morelock, J. 2000. Measuring Present Condition of Coral Reefs. University of Puerto Rico, Department of Marine Sciences, Mayagüez, Puerto Rico. Contact information: Phone # (787) 265-3838 or (787) 832-4040 ext. 3443, 3447, Fax # (787) 265-5408. http://geology.uprm.edu/Morelock/GEOLOCN_/corsurv.htm

This article discusses ways to measure the present health condition of coral reefs. Methods used include: linear transect, the quadrat, and the photoquadrat. Linear transects can be used as a reference (i.e., coral cover is estimated or measured in some way along either side of the line) or cover can be point-counted at regular intervals beneath it. A popular method used includes draping a 10 m chain so that it follows the topography of the reef surface. Each individual links in the chain found at the top of each substrate type is counted.

Quadrats however are randomly tossed at each position or arranged along a pre-determined transect. Coral cover can then be estimated within each sub-square or point-counted at the intersections of a grid within the quadrat frame. Photo transects may include the use of a Nikonos with strobes at a fixed distance above the bottom to photograph the coral cover within a quadrat. The image can be point counted using any quadrat-based or the area can be measured based on photo quadrat. However if permanent reference points (i.e., rigid pins in the reef) are instituted, then the photographic series can be repeated accurately at another time. Additional information on methods used to monitor and measure coral health can be obtained from the source mentioned above.

Pernetta, J. C. 1993. Monitoring Coral Reefs for Global Change, a Review of Interagency Efforts. 102 pp. IUCN Publications Unit, Cambridge, England.

This paper discusses basic biological and physical parameters for monitoring coral reefs as well as methods used for monitoring. Biologic parameters that are used for monitoring coral reefs include: percent cover of corals (scleractinian and non-scleractinian), algae (calcacerous rods, macroalgae and turf algae) and sponges (ascidians, sand, rubble and bare dead coral). Parameters are assessed using the Line Intercept Transect and Manta-tow methods on the Great Barrier Reef and in Asian countries. The Line Intercept Transect (LIT) methods estimates percent cover of corals, algal cover and other organisms. Transect are also used to assess fish abundance, species diversity and approximate biomass. Physical parameters that are recommended to be monitored include water temperature (temperatures taken from water representative of the shallow transects), salinity, sedimentation, sea level using a high quality local datum (Global Positioning System) to measure/interpret water level, and storms using visual. Methods used to monitor each parameter are described in this document. See publication for additional information needed on parameters and methods.

Rogers, S. C., G. Garrison, R. Grober, A-M. Hillis and M. A. Franke. 2001. Coral Reef Monitoring Manual for the Caribbean and the Western Atlantic. Virgin Islands National Park, St. John, USVI, Phone # (340) 693-8950.

This manual presents the physical, chemical and biological parameters that are to be considered when monitoring coral reefs. The physical and chemical parameters that are recommended to be monitored include: temperature (increase in temperature results in bleaching of the corals); dissolved oxygen (important for the survival of marine animals); salinity (reefs may experience some fresh water influx); pH changes (which may indicate the reef has a new or additional sources of pollution); light transmission (the amount of light available for photosynthesis of algae influence coral growth); sedimentation (sediments may reduce light availability reducing photosynthetic rates and cause depletion of dissolved oxygen); nutrient availability (species abundance may be reduced if nutrients are depleted); and current speed and direction (currents transport nutrients, sediments and pollutants).

Biological monitoring of coral reefs should include monitoring the condition of corals, its growth, whether bleached or not, diseases, and algal overgrowth; using quadrats to measure the percent cover, species diversity, relative abundance, density and size, and monitor coral, octocorals, sponges, seagrasses, and algae; using linear transect for measuring percent cover, species diversity, and relative abundance; and estimating the spatial index.

Researchers recommend that monthly observations be conducted when monitoring individual coral colonies; quadrat and transect surveys be performed within six-week intervals to provide sufficient data for percent cover and species diversity changes to be assessed. Monthly observations may also aid in reducing threats that may damage reef organisms while conducting surveys. Researchers further advised that short-term data be used for data analysis instead of large amounts of raw data. See publication for additional information on techniques used for coral reef monitoring.

Samways, M. J. and M. J. Hatton. 1999. An appraisal of two coral reef rapid monitoring manuals for gathering baseline data. *Bulletin of Marine Science* 69:471-485.

Author Abstract. There is concern worldwide that many coral reefs are suffering degradation and loss of biodiversity. In response, some rapid coral reef health monitoring manuals have been developed that purport to have wide biogeographical applicability and user friendliness. These manuals however, have been little tested in areas beyond their centers of origin. This study uses two of the manuals (involving line-intercept transects; English et al., 1997) and corallivorous chaetodont behavior to do a first, expeditionary assessment on a relatively inaccessible coral reef in the Seychelles, Western Indian Ocean. Future revisions of the manuals should perhaps consider the following points as extra guidance for newcomers to the methodologies. At any one time and site, at least ten, rather than five, transects should be done. Sensitivity of many fishes to line-transect diver activities suggests that the Stationary Visual Census Method is much preferred to line-intercept counts. Line-intercept coral data are well-illustrated by simple rank-abundance curves, flagged with species identifications. Such curves also apply well to specific fish taxa, but not to the general fish assemblage. Statistical correlations between fishes and benthos cannot be done from line-intercept data within transects as they are not independent variables, and this should be made explicit in the manuals. Stationary visual censuses would overcome this problem. Data gathered according to the practical manuals are amenable to multivariate analysis. Clarke and Warwick's (1994) manual and associated software are strongly recommended for follow-up analysis. Obligate corallivorous butterfly fishes clearly have potential for monitoring coral reef health but that the metric requires calibration and cross-referencing with other metrics. Further recommendations on coral reef health monitoring relative to the manuals are given, with emphasis on the importance of clearly defining the biodiversity and conservation questions before monitoring is started.

Shafer, D. J., B. Herczeg, D. W. Moulton, A. Sipocz, K. Jaynes, L. P. Rozas, C. P. Onuf and W. Miller. 2002. Regional Guidebook for Applying the Hydrogeomorphic Approach to Assessing Wetland Functions of Northwest Gulf of Mexico Tidal Fringe Wetlands, U.S. Army Engineer Research and Development Center, Vicksburg, Mississippi. Technical Report ERDC/EL TR-02-5.

This manual is designed to provide practitioners with guidelines for monitoring and assessing wetland functions. The manual outlines protocols used for collecting and analyzing data needed to assess wetland functions in the context of a 404 permit review or comparable assessment setting. When assessing tidal fringe wetlands in the northwestern Gulf of Mexico the researcher must define the assessment objectives by stating the purpose (for e.g., assessment determines how the project impacts wetland functions); characterize the project area by providing a description of the structural characteristics of the project area (for e.g., tidal flooding regime, soil type, vegetation and geomorphic setting);

use screen for redflags; define the wetland assessment area; collect field data using a 30-m measuring tape, quadrats and color infrared aerial photography; analyze field data; and apply assessment results. This document provides additional detail information on criteria selection and methods used for assessing tidal fringe wetlands.

Steyer, G. D., C. E. Sasser, J. M. Visser, E. M. Swenson, J. A. Nyman and R. C. Raynie. 2003. A proposed coast-wide reference monitoring system for evaluating wetland restoration trajectories. *Journal of Environmental Monitoring and Assessment* 81:107-117.

Author Abstract. Wetland restoration efforts conducted in Louisiana under the Coastal Wetlands Planning, Protection and Restoration Act require monitoring the effectiveness of individual projects as well as monitoring the cumulative effects of all projects in restoring, creating, enhancing, and protecting the coastal landscape. The effectiveness of the traditional paired-reference monitoring approach in Louisiana has been limited because of difficulty in finding comparable reference sites. A multiple reference approach is proposed that uses aspects of hydrogeomorphic functional assessments and probabilistic sampling. This approach include: a suite of sites that encompass the range of ecological condition for each stratum, with projects placed on a continuum of conditions found for that stratum. Trajectories in reference sites through time are then compared with project trajectories through time. Plant community zonation complicated selection of indicators, strata, and sample size. The approach proposed could serve as a model for evaluating wetland ecosystems.

Trippel, E. A. 2001. Marine Biodiversity Monitoring: Protocol for Monitoring of Fish Communities. A Report by the Marine Biodiversity Monitoring Committee (Atlantic Maritime Ecological Science Cooperative, Huntsman Marine Science Centre) to the Ecological Monitoring and Assessment Network of Environment Canada. http://www.eman-rese.ca/eman/ecotools/protocols/marine/fishes/intro.html#Rationale

This document presents a monitoring protocol for estimating species diversity of bottom dwelling or demersal fish species inhabiting the Canadian continental shelf regions. Monitoring protocols presented in this document can be used to monitor and evaluate fish communities in regions other than the Canadian continental shelf. Methods used to estimate the abundance of different demersal fish species include random stratified sampling and fixed station sampling. Using these standardized procedures helps to maintain precision. Some factors taken into consideration when monitoring fish communities include depth, temperature, salinity, seasonal shifts and diurnal behavior patterns. Additional information found in this document includes size of area and sampling intensity, sampling gear, sampling procedures, and treatment of data.

United States Environmental Protection Agency (USEPA). 1992. Monitoring Guidance for the National Estuary Program. United States Environmental Protection Agency, Office of Water, Office of Wetlands, Washington DC. EPA Report 842-B-92-004.

This document provides guidance on the design, implementation, and evaluation of the required monitoring programs. It also identifies steps to be taken when developing and implementing estuarine monitoring programs and provides technical basis for discussions on the development of monitoring program objectives, the selection of monitoring program components, and the allocation of sampling effort.

Some of the criteria listed for developing a monitoring program and described in this document include: monitoring program objectives, performance criteria, establish testable hypotheses, selection of statistical methods, alternative sampling designs, use of existing monitoring programs, and evaluate monitoring program performance. Additional information on guidelines for developing a monitoring program is described in this document.

United States Environmental Protection Agency (USEPA). 1993. Volunteer Estuary Monitoring. A Methods Manual. 176 pp. U.S. Environmental Protection Agency, Washington, DC, Office of Water. EPA Report- 842-B-93-004. http://www.epa.gov/owow/estuaries/monitor/

This document presents information and methodologies specific to estuarine water quality. Information presented in the first eight chapters include: understanding estuaries and what makes them unique, impacts to estuarine habitats and human's role in solving the problems; guidance on how to establish and maintain a volunteer monitoring program; guidance for working with volunteers and ensuring that they are well-positioned to collect water quality data safely and effectively; ensuring that the program consistently produces high quality data; and managing the data and making it readily available to data users. Also presented are water quality measures that determine the condition of the estuary are physical (e.g., substrate texture), chemical (e.g., dissolved oxygen) and biological parameters (e.g., plant and animal presence and abundance). The importance of each parameter and methods used to monitor the conditions are described in a gradual process. Proper quality assurance and quality control techniques must also be described in detail to ensure that the data are beneficial to state agencies and other data users.

APPENDIX III: LIST OF CORAL REEF EXPERTS

The expert listed below has provided his contact information so practitioners may contact him with questions pertaining to the restoration or restoration monitoring of this habitat. Contact information is up-to-date as of the printing of this volume. The list below includes only those experts who were 1) contacted by the authors and 2) agreed to submit their contact information. Some of those listed also reviewed the associated habitat chapter. In addition to these resources, practitioners are encouraged to seek out the advice of local experts as well faculty members and researchers at colleges and universities. Engineering, planning, and landscape architecture firms also have experts on staff or contract out the services of botanists, biologists, ecologists, and other experts whose skills are needed in restoration monitoring. These people are in the business of providing assistance in restoration and restoration monitoring and are often extremely knowledgeable in local habitats and how to implement projects on the ground. Finally local, state, and Federal environmental agencies also house many experts who monitor and manage coastal habitats. In addition to the National Oceanic and Atmospheric Administration (NOAA), the Environmental Protection Agency (EPA), the Army Corps of Engineers (ACE), Fish and Wildlife Service (FWS), and the United States Geologic Survey (USGS) are important Federal agencies to contact for assistance in designing restoration and monitoring projects as well as potential sources of funding and permits to conduct work in coastal waterways.

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CHAPTER 4: RESTORATION MONITORING OF OYSTER REEFS

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Roger Mann, Virginia Institute of Marine Science[2]
Richard Dame, Coastal Carolina University[3]
Loren Coen, South Carolina Department of Natural Resources[4]

INTRODUCTION

Oyster reefs form when densely packed individual oysters grow adjacent to each other, thereby creating heterogeneous hard surface habitats (see Hargis and Haven 1999) (Figure 1). They are found in brackish to marine waters with salinities at 12-28 parts per thousand (ppt) or higher in some cases (Dame 1996), and are particularly abundant in estuarine systems along the Atlantic and Gulf of Mexico coasts of the United States. These reefs are three-dimensional, complex habitats in the intertidal and subtidal zones and vary in structure and function. Differences in oyster reef structure and function, such as patterns in species abundance and habitat use, have been attributed to the physical stress of exposure and the amount of time predators have to forage in the different habitats (Dame 1996). Natural oyster reefs are created and maintained by living oysters. Shells of living and deceased oysters provide protected habitat for oyster spat, larvae (veligers) that settle and recruit to hard substrates (Roegner and Mann 1990; Bartol and Mann 1997). Recruitment of oysters to the reef and subsequent survival of oysters to maturity provide the mechanism by which the reef's vertical relief is maintained and increased.

Oyster reefs are complex ecological systems that are highly optimized and evolutionarily selected for high productivity (Dame 1996). They are comprised of many interacting species, with feedback loops at many scales of observation, and the resulting dynamics are often non-linear (i.e., the causes are not proportional to the consequences). These characteristics can lead to unpredictable or surprising behavior, particularly when these systems are faced with environmental changes they have never experienced. Under such circumstances, these systems may shift to an alternate state or even collapse. Thus, the restoration and management of oyster reefs require flexible and innovative long-term planning and monitoring.

Historically, oyster reefs were the dominant ecological communities in many estuarine

Figure 1. Intertidal oyster reefs along fringing marsh tidal creeks in Charleston, SC. Photo courtesy of Loren Coen, Marine Resources Research Institute, South Carolina Department of Natural Resources.

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[3] P.O. Box 261954, Conway, SC 29528.
[4] P.O. Box 12559, Charleston, SC 29422.

Figure 2 Picking oysters by hand at low tide. Photo courtesy of Bob Williams, Willapa Bay, WA. Publication of the NOAA Central Library. http://www.photolib.noaa.gov/fish/fish0744.htm

habitats because of the numerous and critical ecosystem services that they provide. Such services or functions include benthic-pelagic coupling (i.e., coupling of organisms between the bottom surface and water column) through the filtering activity of oysters (e.g., Newell 1988) and the provision of physical habitat for benthic invertebrates and numerous fish and bird species that use oyster reefs for feeding, breeding, and nursery grounds (Kaufman and Dayton 1997; Peterson and Lubchenco 1997; Harding and Mann 1999; Jackson et al. 2001; Coen and Luckenbach 2000). Additionally, the hard structure of the oyster reef stabilizes sediments (Hargis and Haven 1999), providing shoreline protection for adjacent fringing marshes. The reefs also have a significant economic value for the U.S. seafood industry as they support many recreationally and commercially valuable animals such as fish, crabs, shrimps, and oysters.

Oysters (e.g., eastern oysters, *Crassostrea virginica*) provide the main structural and functional components of oyster reefs. These animals are sessile molluscs in the class *Bivalvia*. They are suspension-feeders that consume food by removing floating (suspended) particulate matter from the water column (Newell 1988; Dame and Libes 1993; Mann 2000). There are approximately 100,000 species of molluscs of which approximately 8,000 are bivalves. Bivalves are characterized by their two opposing calcareous shells that protect the soft body mass. Their shells are joined by an elastic ligament, two adductor muscles acting in opposition to the ligament in order to close the shell (Figure 3), and an extendable foot to help these animals walk or bury themselves in

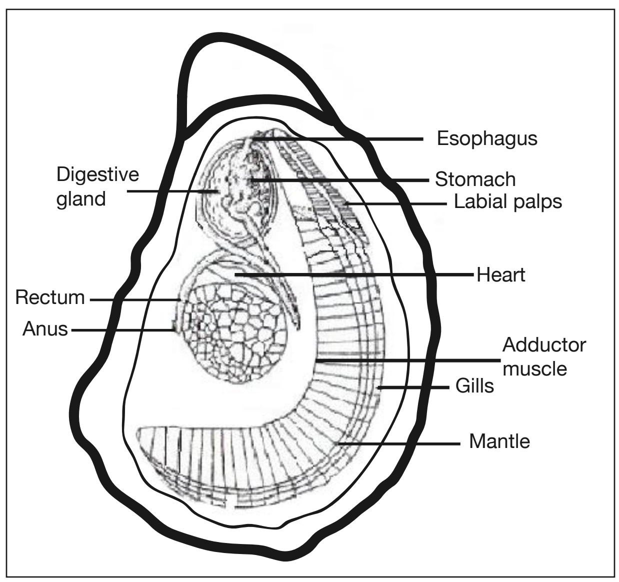

Figure 3. Oyster anatomy. Diagram courtesy of Felicity Burrows, NOAA National Centers for Coastal and Ocean Science. Modified from Galtsoff 1964.

sediment. Of all the bivalves, only the oysters and scallops have forsaken both an adductor muscle and the foot, thus limiting burial as a form of predator protection. Scallops generally compensate by swimming. Oysters, however, have extraordinary plasticity in morphological form. Their diversity and aggregative settlement behavior results in reef formation over extended periods of time. The resulting reefs are biological and geological features that, prior to estuarine degradation by human actions, served to dominate the benthos (i.e., biota on the bottom of lakes, estuaries, and seas) of temperate and subtropical estuaries worldwide. The strange limitations of this single muscle (monomyarian) form are countered by the advantages of reef formation.

Eastern oysters (Figure 4) are native to the United States and occupy habitats from Prince Edward Island, Canada to the Yucatan peninsula, Mexico and beyond, depending on taxonomy opinions. This species has also been introduced in other locations for aquaculture purposes such as on the U.S. west coast. Their range is set by thermal tolerances and habitat requirements necessary for adult growth, reproduction, and larval survival (e.g., salinity and substrate).

Adult eastern oysters are broadcast spawners and generally reproduce when water temperatures are between 20 and 30°C (Galtsoff 1964; Mann et al. 1994; Dame 1996; Kennedy et al. 1996; Luckenbach et al. 1999) (Figure 5). If the optimum temperature of a particular oyster species is exceeded, spawning may be limited and larval development may be reduced (Kennedy et al. 1996). After fertilization, the zygote develops into a planktonic (free-swimming) ciliated larva in about six hours. A fully shelled veliger (i.e., the larval stage of a mollusc identified by its velum) is formed within 12 to 24 hours. The larva is planktonic for about two to three weeks during which it is dispersed by the tidal currents. At the end of the planktonic larval period, the larva develops a foot, then settles to the bottom of the water column, searching for a suitable hard substrate (preferably clean oyster shell) and attaching itself (Bahr and Lanier 1981; Kennedy et al. 1996; Kennedy 1996).

Site selection for settlement from the plankton to the benthos by the oyster larva is influenced by a suite of environmental factors including substrate type and location. Once a larva permanently cements itself to hard substrate, it

Figure 4. Oysters recruited onto newly planted shell (cultch) during restoration efforts. Photo courtesy of Loren Coen, Marine Resources Research Institute, South Carolina Department of Natural Resources, Charleston, SC.

Figure 5. A natural bed of healthy intertidal oyster clusters in South Carolina. Photo courtesy of Ray Haggerty (retired), South Carolina Department of Natural Resources.

remains fixed in that location for life (Roegner and Mann 1990; Bartol and Mann 1997; Baker 1997; Baker and Mann 1999). The duration of the larval period is influenced by environmental conditions including water temperature, salinity, and dissolved oxygen concentration (Baker and Mann 1992; Baker and Mann 1994). Temperature and salinity also influence growth of oyster larvae (Davis and Calabrese 1964). Eastern oyster larvae, for example, can grow between 30 and 32.5°C (i.e., the upper thermal limit), although the suggested range for optimal growth is in water temperatures between 14 and 28˚C (Shumway 1996) and in water salinity between 12 and 28 ppt (parts per thousand) (Dame 1996). Any abrupt change in salinity or temperature above or below their optimum level may influence larval development.

Native species of oysters that are locally or occasionally seen along American coastal waters (Carlton and Mann 1996) include the:

- Eastern oyster (*E. virginica*)
- Olympia oyster (*Ostrea conchaphila, O. lurida*) found on the west coast of North America between Sitka, Alaska, and Panama (Baker 1995; Turgeon et al. 1998; Gillespie 2000)
- Frond oyster (*Dendostea frons*) in the tropical Western Atlantic (e.g., the Caribbean)
- Crested oyster (*Ostrea equestris*) found naturally from the Carolinas to Texas, and
- Sponge oyster (*Cryptostrea (Ostrea) permollis*)

In the Pacific Northwest, several non-native or exotic oysters are commonly grown commercially for aquaculture, including the:

- Pacific oyster (*Crassostrea gigas*) (MacKenzie 1996)
- Asian oyster, also known as Suminoe oyster (*Crassostrea ariakensis*), and
- Crested oyster (*Ostrea equestris*)

Native species of oysters are the only species currently acceptable for oyster restoration. Non-native species, however, may eventually be used as candidates to rebuild reefs along the United States coasts (Luckenbach et al. 1999; National Research Council 2004) such as Virginia and Maryland. Before considering the use of non-native species for oyster reef restoration, one must be aware of the federal and local laws regulating and/or prohibiting introduction and transfer of invasive species because of the environmental impact they may have on native oyster populations. These non-native species can grow rapidly in cases where conditions are suitable and become problematic because their unlimited growth displaces and outcompetes native oyster species for food, habitat, and other resources. If the environmental tolerances of non-native species are matched to target certain habitats, however, environmental and political issues related to the intended introduction of these species may be resolved. Another important factor to consider when introducing a non-native or invasive species for any purpose - including restoration - is the substantial amount of formal scientific examination and review of the expected consequences (e.g., legal, ecological, economic) of their introduction.

Despite the importance of oyster reefs, they have been degraded in most of their natural range by various human activities including pollution, increased suspended sediment loading, and over-harvesting (Rothschild et al. 1994; Lenihan and Peterson 1998; Hargis and Haven 1999; Gagliano and Gagliano 2002). Because healthy oyster reefs support a thriving ecological community and are also economically important to the oyster and finfish industries, restoration efforts should be considered to ensure that these habitats and their estuarine environments are returned to a naturally sustainable functioning state and are then monitored and managed efficiently. Some researchers caution practitioners to clearly define their goals in order to differentiate between fisheries enhancement and ecological restoration of ecosystems (Coen and Luckenbach 2000).

In bays and sounds along much of the U.S. Atlantic and Gulf coasts, oyster reef restoration efforts are now underway to enhance or restore the ecosystem functions provided directly and indirectly by oyster reefs (Coen et al. 1999b). When restoring oyster reefs, the primary ecological goal is to restore oyster populations to self-sustaining levels that mimick historic (pre-exploitation) oyster populations in the same habitats because oysters are keystone species central to oyster reef communities. Improvement in water quality will follow the restoration of oyster populations because of their ability to filter water through benthic-pelagic coupling. Water quality may not improve, however, without healthy oyster populations and other filter feeders that use the hard substrate habitats provided by oyster shell (e.g., barnacles and mussels). Figures 7-10 show two methods to create oyster reefs. Figures 6 and 7 display the use of a high pressure water system to distribute oyster shells into the water from a barge along the nearshore.

Oyster reefs are created by recycling and bagging oyster shell and placing the shell bags on which oysters can settle (Figures 8 and 9). Over time, oysters will grow through the bags and attach themselves to one another and hard substrates to form a reef (Brumbaugh et al. 2000; Hadley and Coen 2002; Leslie et al. 2004). Trays filled with oyster shell rubble may also be placed along the coastline to create subtidal reefs (Lehnert and Allen 2002).

HUMAN IMPACTS TO OYSTER REEFS

Like other coastal habitats, oyster reefs are threatened by various human-induced impacts that can affect the physical structure and functionality of oyster reefs, as well as oyster growth rates. Some of these impacts include:

- Physical damage
- Water pollution, and
- Sedimentation

Restoration Strategies

Not all oyster reef restoration strategies work equally well across sites, but site selection is critical. Local hydrographic patterns as well as historical data on reef presence and success must be considered in selecting a site. Practitioners must also consider tidal, hydrographic/current conditions, depth, bottom condition, and substrate type in the development of restoration strategies.

Figure 6. Large-scale oyster restoration shell planting in 2002 in Folly Creek, South Carolina. Photo courtesy of Loren Coen, Marine Resources Research Institute, South Carolina Department of Natural Resources.

Figure 7. Intertidal shell planting in 2002 along tidal creeks of Bull Creek, South Carolina. Photo courtesy of Ray Haggerty (retired), South Carolina Department of Natural Resources.

Physical Damage from Harvesting, Over-Harvesting, Boating Activities, and Coastal Development

Over-harvesting threatens reefs by reducing the reef acreage and changing reef structure which can ultimately reduce oyster standing stock and spawning biomass (Rothschild et al. 1994; Hargis and Haven 1999; Lenihan and Micheli 2000; Jackson et al. 2001). The size of the oyster spawning population is critical to egg production and density is directly related to fertilization efficiency in these broadcast spawners. If an oyster reef has a higher density, the chance of fertilization is increased. A reef with oysters spaced further apart will have decreased fertilization (Mann and Evans 1998). If both the reef and its oyster populations decline, the abundance and diversity of associated species living on or adjacent to the reef may also be reduced.

Figure 8. Volunteers use bags filled with recycled oyster shells to build large footprint reefs onto which oysters will settle, as part of South Carolina Oyster Restoration and Enhancement (SCORE) reef building project, South Carolina Aquarium. Photo courtesy of Loren Coen, Marine Resources Research Institute, South Carolina Department of Natural Resources.

Figure 9. Volunteers place bags filled with oyster shells along the shoreline to form reefs. SCORE reef building project, South Carolina Aquarium. Photo courtesy of Loren Coen, Marine Resources Research Institute, South Carolina Department of Natural Resources.

In some areas where oyster reefs may be frequently harvested, the acreage of oyster reefs as well as the number of organisms living there may also decrease (Rothschild et al. 1994). The continued decline of oyster reefs may shift the estuarine ecosystem to an alternate trophic structure (food webs) (Newell 1988; Dame 2004). Prior to the 1900s, for example, oyster reefs were dominant ecological units in the Chesapeake Bay and the benthic-pelagic coupling services provided by oyster populations were the major determinant in trophic structure (Baird and Ulanowicz 1989; Newell et al. 1999). In the absence of historic oyster populations (Hargis and Haven 1999), the Chesapeake Bay's trophic structure in the 21st Century is dominated by a planktonic community rather than a benthic oyster reef community (Baird and Ulanowicz 1989; Newell et al. 1999).

Oyster reefs have declined since the mid-1880s along the East and Gulf coasts of the U.S. (Bahr and Lanier 1981). This decline was due in part to the frequent mining of oyster reef resources and the techniques used. Many of these techniques are still being used for various reasons and in some cases, have damaged the reefs and caused ecological changes and a decline in the distribution of reefs (Lenihan and Peterson 1998; Hargis and Haven 1999; Lenihan and Micheli 2000). Dredging and building of ports for example, can disrupt or even destroy oyster reefs. If reefs are destroyed, important recreational and commercial fish species may also be directly damaged or may migrate to regions that are more favorable.

In North Carolina, researchers investigated popular oyster harvesting techniques such as dredging, hand-tonging, and diver-collecting to determine how these methods alter oyster reef morphology and cause incidental mortality to un-harvested subtidal oysters (Lenihan and Peterson 2004). Reef height controls local hydrology flow, which in turn affects recruitment, growth, and survival of oysters. Reefs that were harvested by divers, rather than dredging, experienced the lowest incidental mortality (Lenihan and Peterson 2004). Boating activities (i.e., use of boat propellers and anchors) may also damage or destroy oyster reefs (Chose 1999; Grizzle et al. 2002). For example, in Mosquito Lagoon within the Canaveral National Seashore, Florida, some intertidal eastern oyster reefs adjacent to major navigation channels were severely damaged by boat anchors and propellers, causing oyster mortalities (Grizzle et al. 2002).

Water Pollution from Agricultural, Municipal, and Industrial Sources

Terrestrial runoff from various sources such as municipal sewage discharges, agricultural fertilizers, and industrial processes may affect the survival and growth of oysters by reducing dissolved oxygen levels. In many cases, runoff contains toxins or fertilizers (i.e., nutrients) which may promote algae growth and cause a reduction in oxygen levels around the reef (Lenihan and Thayer 1999). Sewage discharges may also promote algae growth which can then reduce oxygen levels and distribute coliforms into the water column, thus impairing water quality. As a result of algal overgrowth and low oxygen levels, oysters may be unable to grow, filter feed, and provide nutrients to other species that rely on them.

Impacts of Construction

Construction activities can damage reefs indirectly as well, as channelization associated with the building of dikes can divert freshwater into oyster reef communities, thereby significantly reducing salinity levels and making the environment unfavorable for oyster growth (Powell et al. 1995).

Chemicals such as tributyltin (TBT), a fouling inhibitor on painted ships, also negatively affect the growth of oysters if leached into the water. At low levels, TBT can cause structural changes, such as inhibiting growth and thickening oyster shells which increases their weight (Waldock and Thain 1983; Alzieu 1998). Oyster exposure to TBT may also affect its ability to resist diseases. Along the northern Gulf of Mexico and the Atlantic coast of North America where eastern oysters (*C. virginica*) are found, a protozoan pathogen, *Perkinsus marinus* infected these oysters, reducing oyster populations and depleting oyster fisheries in this area (Fisher et al. 1999). When exposed to environmental levels of TBT, increased infection intensity and oyster mortality occurred (Fisher et al. 1999). Oyster response to chemicals, however, will vary based on species type, as well as level and type of chemical. These examples depict how oysters may be affected by TBT and potentially other chemicals.

Sedimentation and Agriculture

Increased sedimentation may result from dredging. Constant dredging disturbs sediments and can bury oysters, reducing filtration efficiency and respiration/oxygen exchange for individual oysters. As a result of low oxygen, oyster growth, feeding, and ultimately survival rates are reduced. Another land-based activity that contributes to increased sedimentation affecting oysters is agriculture. The erosion of topsoil as a result of intensified agricultural activities has been identified as a major contributor to increased suspended sediment loads in the Chesapeake Bay and the subsequent demise of the Bay's oyster reefs (Rothschild et al. 1994).

MONITORING

When developing a restoration plan, practitioners should ensure that monitoring is included to track progress of the project. Monitoring the reef's structural and functional characteristics before, during, and after restoration at both the reference and restored sites should be conducted to:

- Evaluate the physical habitat
- Evaluate existing natural populations of target organisms
- Understand the role that each physical characteristic plays in supporting plants and animals, and
- Assess the interaction of organisms on and around the reefs

Adequate replication is often difficult to achieve in ecosystem experiments or restoration projects due to limitations such as small numbers of experimental systems, time, logistics, and expenses (Carpenter 1989). In such cases, paired-system experiments (one reference and one experimental system) are often preferable, even though classical statistics cannot be used to detect manipulation effects (Carpenter 1989). The Before After Control Impact (BACI) method with replicated controls can be used to identify non-random changes in manipulated systems (Stewart-Oaten et al. 1986; Underwood 1994; Dame et al. 2000; Dame et al. 2002). The resulting data can be used in various statistical tests to examine the efficacy of the restoration, including testing the differences in mean abundances of a particular species between the restoration and comparison sites (see Stewart-Oaten et al. 1986; Dame et al. 2000; Dame et al. 2002).

Parameters selected for monitoring should be based on the particular goals and objectives of the restoration project. Both project objectives and thresholds (i.e., points at which effects can be observed) to evaluate progress should be established *before* restoration and monitoring activities begin. Monitoring restoration efforts allows the practitioner to determine whether modifications must be made to the project and to track the success of the restoration project (Coen et al. 2004). Monitoring should also be conducted to (Luckenbach et al. 2004):

- **Evaluate sites proposed for restoration:** Assess the site-specific history of natural oyster population success (i.e., whether the site has ever supported a self-sustaining oyster population) as well as current conditions including tidal flow, local hydrographic conditions, bottom/substrate condition, water quality (e.g., dissolved oxygen), susceptibility to harmful algal blooms, and natural recruitment of oysters.
- **Evaluate stressors:** Assess conditions (e.g., salinity, dissolved oxygen levels, presence of disease, etc.) at existing, but degraded oyster reefs that may be targets for restoration.
- **Facilitate adaptive management:** Measure those elements that can be modified during the restoration process. For instance, monitoring the quality of the substrate in the years after initial planting can reveal whether or not it is necessary to add substrate to provide clean settlement sites. In addition, monitoring for oyster recruitment during the early years of the restoration process can indicate whether the site is recruitment-limited and brood stock enhancement might be justified. It is worth noting that years of data are required to practically evaluate

or describe a restoration project and its surrounding habitats.

- **Assess restoration efforts:** Track the reef's condition, as well as size and number of organisms utilizing the reef. Also determine whether any modifications should be made to the project (e.g., extend the project's timeframe, change methods used, monitor another parameter, etc.).

STRUCTURAL CHARACTERISTICS OF OYSTER REEFS

This section presents the structural characteristics of oyster reefs applicable to restoration monitoring. These characteristics refer to the biological, physical, hydrological, and chemical features of the habitat that may influence the oyster reef restoration project. They may be potential parameters used to gather baseline information and monitor restoration efforts. Not all structural characteristics described herein, however, must be measured or monitored in every restoration project. Additional information is provided to help educate the reader on the ecology of oyster reefs.

The practitioner must first identify a suitable area to locate reefs and then determine whether the site is appropriate for restoration by interpreting site-specific information. Following oyster reef restoration efforts, the structural characteristics of the habitat targeted for restoration in relation to the project goals are monitored (O'Beirn 1996; O'Beirn et al. 2000; Cressman et al. 2003; Coen et al. 2004; Nelson et al. 2004). Some structural characteristics of this habitat include:

Biological
- Habitat created by animals (i.e., oysters)
- Diseases

Physical
- Bathymetry/Topography
- Sediment (e.g., grain size, sedimentation and basin for materials)
- Turbidity/Light availability

Hydrological
- Tides and currents
- Water sources (e.g., upland, groundwater; as related to water quality)
- Water temperature

Chemical (as related to water quality)
- Dissolved oxygen
- Salinity

Ideally, a reference site should be identified and used as a comparative baseline for the restored site before restoration work begins. The reference site should be as pristine as possible and should have naturally occurring oyster populations and similar, well-documented physical, chemical, hydrological, and biological characteristics (see Chapter 15 for methods to select Reference Conditions). Practitioners should monitor structural characteristics such as settlement and growth at the reference site to determine if conditions are favorable for successful oyster reef restoration. Once reefs have been either built as three-dimensional shell piles or stocked with oysters, it could be years before complex communities that can perform various functions to support plants and animals are observed. Nevertheless, the practitioner can develop a timeline to begin monitoring the reef's functioning capacity over time, such as enhancing oyster survival and providing feeding, nursery, and breeding grounds for fish and other marine organisms. Long-term monitoring (multiple years) of restoration projects is vital for the practitioner to track improvements in the restored reef's condition (e.g., increased size, increased number of oysters and other organisms utilizing the reef, etc.) as compared to reference sites.

BIOLOGICAL

Habitat Created by Animals (i.e. oysters)

As mentioned in the introduction, oyster reefs are formed when individual oysters accumulate and form a complex structure that rises above the bottom of the estuary or channel. The structure of the reef forms a three-dimensional habitat that is an emergent property of the interactions of the organisms living on the reef and the surrounding aquatic environment. Both intertidal and subtidal reefs are composed of multiple year classes of oysters which also provide microhabitats for many different species of animals (Meyer 1994; Kennedy et al. 1996; Hargis and Haven 1999). Intertidal oyster reefs may be found throughout the entire intertidal zone, from near bottom to depths where the top of the reef breaks the surface of the water at low tide (Chesapeake Bay Program 2002). Subtidal oyster reefs extend slightly above the bottom yet below the intertidal zone; fringing oyster reefs extend directly outward from the shoreline in the direction of the current.

Recruitment, settlement, and growth of oysters over time increases the vertical relief and basal area of the oyster reef. Habitat used by reef-associated fauna may be monitored by recording their presence/absence, relative abundance, biomass, size of species, species richness/diversity, or percent cover for sessile/encrusting organisms. Such data collected by restoration practitioners can provide information on the types of organisms present and whether the constructed habitat supports these organisms.

Diseases

Oyster diseases can affect the survival and recruitment of eastern oysters and thus progress of oyster restoration efforts. There are two types of oyster diseases: the Dermo disease caused by the parasites *Perkinsus marinus,* and the MSX disease promoted by the *Haplosporidium nelson* parasites (Burreson et al. 2000). *P. marinus* is endemic to the Atlantic coast from Virginia to the Gulf of Mexico, but has spread throughout Maryland to the coast of Maine within the last ten to fifteen years (Reece et al. 2001). *H. nelsoni,* however, is a natural parasite of *Crassostrea gigas* in Korea and Japan, and was possibly introduced to the East coast of the United States when *C. gigas* was introduced (Burreson et al. 2000). Beginning in the 1960s, this parasite caused massive oyster mortalities in the Delaware and Chesapeake Bays. Since then, this parasite has spread through other natural populations. Disease outbreaks resulting from these parasites are one of the primary factors restricting the natural rebuilding of oyster reefs and challenging oyster reef restoration efforts. Once infected with any of these diseases, oyster functioning capacity, such as its ability to reproduce successfully (Kennedy et al. 1995) and filter feed, eventually deteriorates and may affect other animal communities. In cases when infections are severe, diseases cause oyster mortalities. This has been seen throughout the East coast of the United States (Burreson and Calvo 1994; Ford 1996; Andrews 1996; Soniat 1996; Bobo et al. 1997; Burreson et al. 2000).

In areas where oyster diseases may be a significant problem, practitioners should consider measuring disease prevalence and intensity because knowledge of disease levels can:

- Affect adaptive management decisions by understanding mortality patterns, and
- Help develop oyster populations with greater disease tolerance over time by following disease dynamics

Practitioners generally assess both types of oyster diseases by observing and documenting an infection level following the use of Ray's fluid thioglycollate medium culture method (see Ray 1956; Mackin 1962; Mackin 1971).

Monitoring: oyster populations

There are various structural characteristics that should be considered when conducting pre-and post-restoration monitoring. The characteristics that should be considered when evaluating and monitoring oyster reef restoration include (O'Beirn 1996; Coen et al. 2004):

- **Natural oyster recruitment levels**: The level of natural oyster recruitment should be evaluated before, during, and after restoration efforts. Data collected can be statistically analyzed using the BACI method (previously discussed in the "Monitoring" section). Without new recruits, the restoration effort - which in most cases involves planting some shell - is ineffective. Oyster recruitment should be monitored for a minimum of three to four years following the construction of reef foundation at both reference and restoration sites to allow the restored habitat to develop a natural scale of ecological services and allow comparisons between the reefs to be made (Newell et al. 1991; O'Beirn 1996; Harding and Mann 1999; Coen et al. 2004).

- **Availability and integrity of substrate** (O'Beirn et al. 1994; Wesson et al. 1999; Coen et al. 2004): The history of oyster growth and settlement at a site (i.e., whether the site historically supported oyster populations) should be evaluated. It is considered best to locate reef restoration projects where natural reefs formerly thrived to take advantage of inherent hydrographic and local circulation conditions that may enhance settlement, local recruitment, and overall population success. Where adequate substrate for settlement is limited, restoration efforts should begin with the addition of substrate(s), or cultch, to the site. Additional substrate(s) may not be necessary where oyster recruitment and survival rates are sufficient to maintain a self-sustaining natural oyster population where natural recruitment at least balances mortality, or where material is rapidly covered with oysters and provides substratum for additional oyster recruitment over time. Additional substrate(s) may be necessary where oyster recruitment and survival rates are low, and competition with other epifauna occurs. Substrate degradation caused by boring sponges and sedimentation may reduce the availability of clean substrate (generally oyster shell) for oyster settlement and may need to be supplemented. Assessing the availability of adequate substrate prior to recruitment each year can provide a basis for making adaptive management decisions (e.g., whether supplemental substrate is needed).

There are several components to this monitoring need that can lead to different adaptive management decisions and assessments of success (Luckenbach et al. 1999). The relevant components for a particular project should be established in advance with a clear progression of sampling and data analyses in support of the established goals. In all cases, multiple years of data using the same protocols are required for a particular site such that natural variability within a system is incorporated into the restoration strategy. These components may include:

Spat Abundance

- Spat collectors (e.g., shells, tiles, or other materials) may be placed near reef restoration projects to assess the "potential recruits" to the reef
- Predictions about the abundance of newly settled oysters will vary locally, but some minimal level of oyster recruitment will be required for successful restoration
- If oyster settlement rates are low over multiple years, the restoration project must either
  - be relocated, or
  - be enhanced by adding oyster brood stock seed or settling spat to the area

Spat Survival Post-Settlement and Through Recruitment

- Standard stock assessments of oysters (e.g., young-of-the-year recruits) provide a measure of success of the reef substratum and may suggest some remediation if the success is low. It is important to obtain quantitative estimates at sufficient frequency and over more than one recruitment season.
- If the number of settling oysters is sufficiently high, but the number of surviving new recruits is low, it may be

possible to identify the cause(s) of this mortality and changes may result.

For example, early post-settlement survival was observed in Virginia's Eastern shore, the Chesapeake Bay, and the James River in Virginia. Reef foundations were constructed of alternative substrates (surf clam shell and coal ash pellets) in the intertidal zone and found to have similar settlement abundances as reefs of oyster shell, but much higher predation-induced mortality rates (Wesson et al. 1999). The result was that restoration efforts using the alternative substrate as bases had chronically low recruitment, while those using oyster shells had greater recruitment levels (Luckenbach et al. 1999).

- **Abundance and distribution of oysters on the reef:** The size and number of oysters on the reef provide information on population age structure. Multiple years of data collection at the same sites with the same protocols provide valuable information on population age structure, growth rates, and mortality rates.

Sampling and Monitoring Methods

Calipers - Size-frequency and oyster recruitment may be determined by measuring the shell height (i.e., hinge to growth edge or beak, in millimeters) or other shell linear dimensions with calipers, a tool used to measure oyster shell height or length (Coen et al. 2004). Growth of the oysters may be monitored by first marking each oyster and then measuring the size of the oyster in each quadrat along transects at selected time intervals. Each measurement can be used to calculate the change in size between measuring dates.

Plankton tows - Plaknton tows may be used to sample oyster larvae in a restoration site to determine larval concentrations in a given area (Southworth and Mann 1998; Harding 2001). Plankton nets are generally towed horizontally below the water surface, in the direction of the currents and parallel to the oyster reef. Practitioners can determine how long (number of minutes) each tow should be and the frequency of tows per day.

Quadrats - Oyster density on intertidal reefs may be measured by counting live oysters with the use of quadrats. Quadrats are square or rectangular shaped frames, typically 0.25-1.0 square meters in size, and are placed randomly or at fixed positions. Oyster density can be determined by calculating the mean of samples collected from each study area. Oyster recruitment may also be measured by collecting, counting, and documenting the number of live oysters (O'Beirn 1996; Luckenbach et al. 1999). The use of quadrats for assessing the oyster size and abundance is shown in Figures 10 and 11.

Abundance and size data for subtidal oyster populations may also be determined using diver surveys, dredges, or patent tongs (Mann and Evans 1998; Mann and Evans 2004; Mann et al. 2004).

Diver surveys - Diver surveys may involve scuba divers using underwater digital cameras or video recordings to permanently document reef subtidal areas along transect lines or grids. The diver then swims along the transect line and photographs subtidal oyster populations in a selected area. Each study site can be revisited over time to document the condition of the oyster reef. Comparisons of photographs or video recordings from multiple site visits allow change in reef conditions to be identified.

Dredges - A dredge contains a metal rectangular frame with a net of metal rings attached to it. The frame is connected to a towing cable that drags it along the bottom. The lower end of the frame is commonly called a raking bar and usually has a jaw-like structure used to dig up the bottom. Dredges can be used to collect semi-quantitative

Figure 10. Assessing oyster recruitment in 2003 at large-scale restoration effort by sampling shell planted one year earlier in Hamlin Creek, South Carolina using 0.25 m^2 quadrats. Photo courtesy of Loren Coen, Marine Resources Research Institute, South Carolina Department of Natural Resources.

Figure 11. Assessing the size and condition of oysters along the shoreline by sampling with quadrats. Photo courtesy of Loren Coen, Marine Resources Research Institute, South Carolina Department of Natural Resources.

data on population trends. A disadvantage to dredges is that they gather organisms while moving over the bottom, but may not collect organisms consistently throughout a single dredge haul, potentially biasing the samples (Powell et al. 2002; Mann et al. 2004).

Patent tongs - Patent tongs sample oysters on and below the oyster reef surface. The tongs are hinged so they open while being lowered and close as they are elevated. The tongs are attached to a cable used to lower and raise them in and out of the water. Data collected from patent tong surveys can provide estimates of oysters by size and volume (Mann and Evans 1998; Mann et al. 2004).

High-resolution remote sensing - High-resolution remote sensing methods are also used to assess intertidal oyster reefs (Chauvaud et al. 1998; Cracknell 1999; Smith et al. 2001; Wilson et al. 2000; Vincent et al. 2002; Finkbeiner et al. 2003; Corbley 2004). Multiple image processing, photography, spectral clustering, and digital texture analysis are used to determine the boundaries and spatial characteristics of oyster reefs, and provide rapid and accurate means to qualify and quantify changes in marine habitat. Restoration practitioners may also use digital and analog aerial photography to gather baseline information on the restoration site, including reef and adjacent land activities, and to assess the structure and acreage of the oyster reef over time following restoration. Assessment of habitat acreage can help determine whether oyster recruitment and establishment are successful. Figure 12 shows an aerial photograph of intertidal oyster reef distribution at a specific study site in South Carolina.

PHYSICAL

Bathymetry/Topography

Bathymetry which is the science of measuring the depths of the oceans, and mapping the corresponding topography, or physical features of those depths. Both reef bathymetry and topography create zones that support various organisms or life history stages by providing shelter, feeding grounds, breeding areas or substrates for attachment. Topography of intertidal oyster reef has a distinct three-dimensional structure consisting of a core and a veneer. The core consists of living oyster shell, shell fragments, sand, silt, or clays (Bahr and Lanier 1981; Hargis 1999). The veneer (i.e., a thin layer of shell matieral permanently bonded to the core) consists of living oysters, shells of recently dead oysters, biological associates, and other depositional materials. Materials that consist of the core and veneer characterize the rough and hard reef texture and provide a place of attachment for sessile organisms. The presence of these organisms may also contribute to the unique texture of the oyster reef. The reefs provide vertical relief and structural heterogeneity (e.g., the height and width of the oyster shells that form reefs) that attracts many grazers, browsers, and predators as well as sustains many transient fish species (Lenihan 1999; Harding and Mann 1999) such as:

Figure 12. Aerial photograph of intertidal oyster reef construction in Inlet Creek, South Carolina, part of a six-year study by the Oyster Recovery Partnership (ORP). Photo courtesy of George Steele and Loren Coen, South Carolina Department of Natural Resources.

Striped bass (*Morone saxatilis*)
Redfish (*Sebastes marinus*)
Snook (*Centropomus spp.)*
Rockfish (genus *Sebastes*)
Snappers (genus *Lutjanus*)
Bluefish (*Pomatomus saltatrix*), and
Weakfish (*Cynoscion regalis*)

These transient nekton (i.e., swimming organisms that move independent of water currents, including most fish, mammals, turtles, sea snakes, and aquatic birds) also function as mobile links between the oyster reefs and other sub-systems in the estuarine ecosystem. Other features of the reef that contribute to its structural heterogeneity are the interstices between shells and shell fragments that provide places where the sediment particles and reef wastes from upper levels may be sequestered. In addition, many micro-organism and small macro-organism species colonize shell surfaces and interstitial spaces in reefs and utilize reef waste for sustenance (Hargis and Haven 1999). Particulate material dropping away from reef heights can also settle onto the adjacent estuary bottom or be swept away from the reef by currents. Increased reef elevation due to shell added to the core and by new spatfall and growth in the veneer keeps the living oysters away from the bottom (Hargis and Haven 1999).

Reef topography also increases the overall surface significantly, thereby providing a place for growing oysters. On subtidal oyster reefs, vertical height affects animal abundance and utilization (Breitburg 1999; Harding and Mann 1999; Harding and Mann 2001a, b; Harding and Mann 2003), as well as growth and survival rates for individual oysters by maximizing circulation benefits (Lenihan et al. 1999; Peterson et al. 2003). The vertical structure of oyster reefs physically elevates oysters off the bottom and allows oysters to avoid anoxic conditions (Lenihan and Peterson 1998) or being smothered during sedimentation (Coen et al. 1999a and b). The size of the reef's vertical relief can also influence water quality. For example, if the reef is large, the number of oysters is greater and therefore reef filtration rates may be greater (Hargis and Haven 1999).

Several researchers indicated that some oyster harvest practices (e.g., dredging) can also affect the reef's topography by reducing the height of oyster reefs. Negative impacts to subtidal oyster reefs that may result from dredging include (Lenihan and Peterson 1998; Lenihan et al. 1999):

- Damage to the reef's structure increasing susceptibility to future storm damage
- Remove live and dead oysters decreasing the possible number of spawning adults (spawning stock biomass) and suitable areas available for settlement by oyster larvae
- Lower depth in the water column exposing newly settled oysters to lower oxygen and increased sediment, and
- Reduce interstitial spaces in the reef that provide a place of refuge and foraging areas for juvenile fish (see Street et al. 2004)

Along the Neuse River in North Carolina, researchers determined that dredging practices caused the reduction in the height of oyster reefs (Lenihan 1999; Lenihan and Thayer 1999; Lenihan and Peterson 1998). As a result of reduced reef height, water flow speeds were also reduced, causing an increase in sedimentation. In addition, the quality of suspended food materials for oysters was also reduced (Lenihan 1999; Lenihan and Thayer 1999). This explained why oyster growth on reefs disturbed by harvesting was slow, their health was relatively poor, and mortality rates were higher. However, this is one of many studies in which results vary depending on factors such as the reef's location, water quality, and frequency of physical disturbance to the reef. In some cases, these factors may be primarily responsible for oyster reef decline in a given area rather than changes in oyster reef topography.

Sampling and Monitoring Methods

Chain transects - Evaluations on intertidal reef topography involve assessment of surface rugosity (i.e., texture of the reef's surface) (Coen et al. 2004; McCormick 1994). The chain transect method and random point heights may be used to assess surface rugosity (McCormick 1994). The chain transect method involves placing a lightweight chain on the reef along the measuring tape, and recording the number of chain links of each sessile organism or the relative substrates. This method provides a better estimate of vertical complexity and thus allows for a better understanding of the habitat quality of the oyster reefs (Coen et al. 2004; McCormick 1994).

Remote Sensing - Reef footprints (i.e., historical structure), distribution and abundance patterns, and the effect of channels on the reef structure may be characterized using low-altitude aerial imagery and geographical information system (GIS)-based mapping (Grizzle and Castagna 2000; Grizzle et al. 2002; Grizzle et al. 2003). Patterns seen using aerial imagery can indicate how water movements influence reef development and whether the patterns changed over time (Grizzle and Castagna 2000). The same information gathered using aerial imagery and GIS mapping may also be obtained from historical maps of many locations along the U.S. East coast. Some of these maps are more than 100 years old and are available from various sources such as the Virginia Institute of Marine Sciences (e.g., see www.vims.edu, "oyster restoration map atlas") and NOAA historic maps and charts(e.g., http://nauticalcharts.noaa.gov/csdl/ctp/abstract.htm). The maps can then be compared to identify changes in reef patterns and channels.

Underwater hydroacoustic technology - Underwater hydroacoustic technology with reflected sound energy may also be used to identify surface objects, texture, size, fragmentation, and density disturbances, as well as classify bottom coverage (Dealteris 1988; Simons et al. 1992; Wilson et al. 1999; Smith et al. 2001). This technique involves a precision survey echo sounder operating at 200 kilohertz (kHz), and a side-scan sonar system operating at 100 kHz. Researchers have also used side-scan sonar and acoustic seabed classification systems to assess oyster reef structures, a fathometer to assess bottom relief, and a global positioning system (GPS) to determine accurate position (Simons et al. 1992). Data collected on the quality and quantity of oyster shell resources can then be integrated into a GIS to assess oyster habitat (Jefferson et al. 1991; Smith et al. 2001). Using this method, practitioners may be able to evaluate changes in subtidal oyster reef topographic features and bottom coverage over time following restoration efforts.

It is worth noting that aerial imagery, GIS-based mapping, acoustic profiling (i.e., seabed classification) and side-scan sonar are costly and involve high-tech methods, and therefore may not be accessible to all laypersons. Data collected using these methods, however, may be available from experts who have used such technology to assess reefs within or near the restoration site.

Sediment

Grain size

Intertidal oyster reefs are often associated with fine, soft sediment with low wave energy (Figure 13), whereas subtidal reefs are often associated with coarser sediments in high wave energy that generally contain oyster shell hash (Dame 1996; Hargis and Haven 1999). Variation in sediment type, to a large extent, may be locally related to wind fetch that is partially related to long-term removal of oyster reefs as buffer structures. As sediments and water flow are correlated,

Figure 13. Oyster reefs growing in muddy, fine grain sediment are harvested to evaluate impacts and recovery of multiple intertidal fishery practices; project followed recovery for 2 or 3 years. Photo courtesy of Loren Coen, Marine Resources Research Institute, South Carolina Department of Natural Resources.

sediment gradients are generally found in coastal waters and the intertidal zone.

Sedimentation

Although oysters have the ability to filter sediments (Newell 1988), large amounts of sediments can affect the reef. The primary concern is when the sediment becomes unstable due to human disturbances or by other means. The disturbed sediments (increased sedimentation) can affect oyster reefs by clogging oyster filtering structures, resuspending and burying newly settled oyster larvae, and covering substrates preventing attachment by adult oysters (Dame 1996).

Exposure to polluted sediments through increased sedimentation may cause stress that can reduce an oyster's ability to resist diseases and parasites, causing mortality of embryos and larvae, and a reduction in spat (i.e., immature bivalve mollusc) growth and setting (LeGore 1975; Umezawa et al. 1976; Mahoney and Noyes 1982; Marcus 1989; Encomio and Chu 2000; Geffard et al. 2001; Geffard et al. 2003). As a result of oyster larvae exposure to polluted sediments, oyster reef development and growth processes may be limited. Although oysters growing on three-dimensional reefs extend out of the sediment and up into the water column, it is important for practitioners and environmental managers to consider assessing the quality of sediments, as they store nutrients to support the benthic community as well as pollutants that may negatively affect oyster reef communities.

Basin for materials

Oyster reef sediments can act as both a nutrient basin and source, providing food for benthic organisms and serving as a reservoir for different dissolved constituents (Lenihan and Micheli 2000; Newell 2004). Inputs from industrial chemical or agricultural (fertilizers) sources may also be absorbed by reef sediments. Finer sediments, however, can contain higher nutrient and pollutant levels because they are not as porous as coarser sediments, and thus can retain pollutants longer (Lenihan and Micheli 2000). During nutrient cycling through the ecosystem, some percentage of nutrients is deposited in bottom sediments. If sediments are disturbed by means of dredging or boating activities, nutrients may be placed back into the water column where they may stimulate the growth of phytoplankton, and contribute to increased turbidity levels and depletion of oxygen.

Sampling and Monitoring Methods

Corers - Many types of coring devices and sediment traps can be used to collect underwater sediment samples. They are generally operated by driving the instrument into the bottom sediment and extracting the sediment sample from the corer tube. Two of these sampling devices are hand corers and piston corers (Miller and Bingham 1987; United States Army Corps of Engineers 1996; Radtke 1997).

Hand corers or also known as push corers are hollow tubes that are pushed into sediment to obtain samples. The corer is driven into the sediment to the point marked on the instrument and then removed and stored. Once retrieved, the corer can be divided so that separate samples from different depths of sediment can be distinguished (Radtke 1997).

Piston corers can use either gravity or hydrostatic pressure to function. As the instrument penetrates the sediments, an internal piston remains at the level of the sediment/water interface to prevent sediment compression (United States Army Corps of Engineers 1996).

Grain size and nutrient analysis - Sediment can also be characterized by analyzing grain size through dry sieving, and using pipettes (McManus 1988) as well as a laser coulter counter (Volety et al. 2002). Percent carbon and oxygen present in sediment samples are determined using acid dissolution, while the percent organics is determined via ignition. To conduct carbon and nitrogen isotope analyses, sediment samples are dried and acidified with 10 percent hydrochloric acid to eliminate all carbonates. The samples are then dried again and analyzed for carbon and nitrogen (Volety et al. 2002). Data collected from nutrient analyses of sediment samples can indicate whether nutrient levels have increased or decreased significantly over time. An increase in nutrient levels, for example, may be an indication of agricultural runoff, causing increased algal growth and thus reduced oxygen levels. Nutrient concentration is just one of many physical parameters that should be monitored to determine whether a selected site is suitable for restoration or whether restoration progress is limited as a result of changes in nutrient concentration and additional physical parameters.

Sedimentation rate - Sediment traps (Figure 14) are also used for sampling sediments (Soutar et al. 1977; Asper 1987; Hayakawa et al. 2001). The traps are deployed from the side of a boat at different depths and collect particles settling in the water column in order to determine the sediment types and sedimentation rate. The size of the particles collected depends on the mesh size of the trap; particles smaller than the mesh size of the trap escape back into the water.

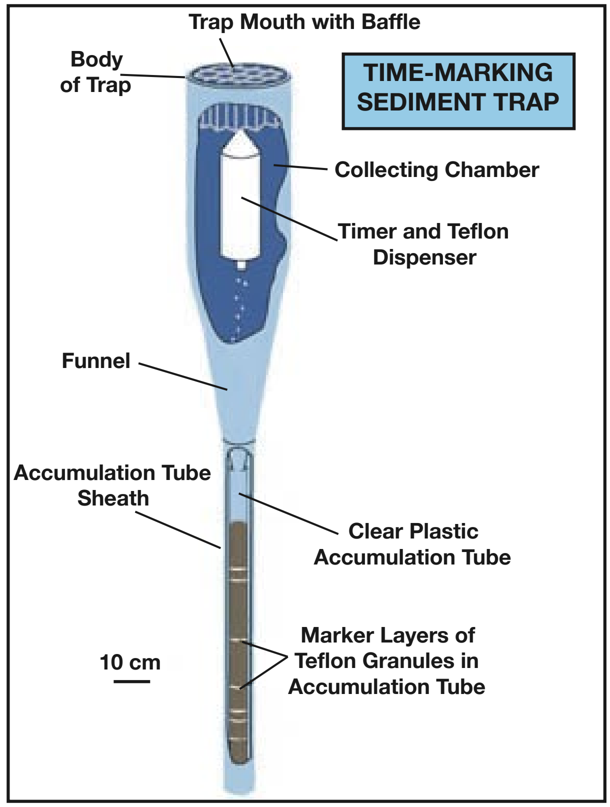

Figure 14. Diagram of a sediment trap. Photo courtesy of United States Geological Survey, Earth Surface Process Division. http://climchange.cr.usgs.gov/info/lacs/sedtraps.htm

Turbidity/Light Availability

Although oysters filter water and improve its quality, an increase in turbidity can influence oyster reef growth and survival. An increase in suspended sediment in the water column may be caused by high energy tides, waves, agriculture, forestry, mining, dredging of sediment (Cairns 1990), boat propellers, as well as other factors, can also smother oyster larvae and disturb the filter feeding process of oysters. High and persistent levels of sedimentation cause permanent changes in oyster reef community structure (e.g., reduced diversity, density, biomass, growth, and rates of reproduction in oysters), cause increased mortality rates, and alter local food webs (Cairns 1990). Generally, mortality from direct burial or smothering caused by harvesting or sediment dredging is an issue only for organisms with restricted mobility (e.g., attached eggs, juveniles, burrowing infauna, oysters) (Lunz 1938; Barnes et al. 1991). Normal sediment movement as a direct result of increased harvesting is less than 10-30 centimeters, a depth not considered to cause mortality to small infauna (Barnes et al. 1991).

In addition to sedimentation, oyster reef communities are affected by excess nutrients in sediments from runoff that promotes algae growth and increases turbidity. Resulting algal blooms can cause local depletion in oxygen available for organisms such as oyster larvae and fish (Cheney et al. 2001). Studies have shown that hypoxic and anoxic conditions affected eastern oyster larval settlement, juvenile growth, and juvenile survival (Baker and Mann 1992). Results showed that oyster settlement was reduced significantly ($P < 0.05$) in hypoxic treatments and practically no settlement occurred in anoxic treatments. Thus, hypoxic and anoxic waters can have potentially harmful effects on oyster settlement and recruitment (Baker and Mann 1992).

Sampling and Monitoring Methods

Turbidimeter - A turbidimeter measures water turbidity by passing a beam of light through the sample and measuring the quantity of light scattered by particulate matter (Rogers et al. 2001). The turbidity measurements are then displayed in nephelometer turbidity units (NTUs) (Rogers et al. 2001).

Secchi disc - Water Clarity can also be determined using a secchi disc (Figure 15) to measure the depth of light penetration in the water column (Lee 1979; Parsons et al. 1984; Steel and Neuhausser 2002). It is a circular-shaped instrument with alternating black and white quadrants, attached to a rope or another type of extension line and lowered into the water column from the shore, pier, or boat until the disc is no longer visible. As light travels through the water column, some of it is absorbed by phytoplankton and dissolved material. The remaining light reflects off the secchi disc and travels back through the water column where more is absorbed. As the disc is slowly lowered in the water, it gradually becomes harder to see, as increasing amounts of light are absorbed. The depth at which the disc can no longer be seen is the depth where light is being absorbed as it passes down and back up through the water column. This is recorded as the secchi disc depth (in meters). This procedure can be performed multiple times (three times on average) in the same location to determine the average water clarity value (Steel and Neuhausser 2002).

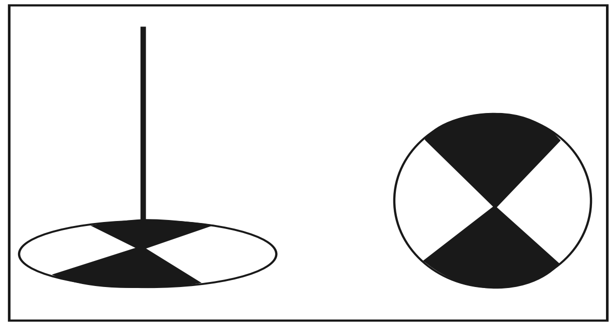

Figure 15. Diagram shows a secchi disc. Diagram courtesy of Felicity Burrows, NOAA National Centers for Coastal and Ocean Science.

HYDROLOGICAL

Tides/Hydroperiod and Currents

Local tides and currents have a major influence on the dispersal of oyster larvae (Carriker 1951; Pritchard 1953; Wood and Hargis 1971; Mann 1988; Ruzecki and Hargis 1989; Southworth and Mann 1998). Larvae place themselves in ebb and tidal currents (vertical motion) so they can be distributed throughout estuaries (Cake 1983). Oyster larvae spend about two to three weeks drifting with tidal currents, feeding on algae, and preparing to attach permanently to the bottom where they spend the rest of their lives, adding to the reef's vertical relief and complexity (Ruzecki and Hargis 1989; Southworth and Mann 1998).

As oyster reefs develop over time, oyster shells occasionally alter tidal currents and increase deposition of particulates, preventing sediment build-up on reefs which can ultimately reduce oxygen levels. Reduced tidal currents with increased sedimentation (e.g., as a result of dredging) can have an indirect effect on oysters as well. If tidal currents are too low and sediment builds up on the reef, oyster recruitment may be reduced because oysters are not able to successfully attach to substrates covered largely by silt (Visel et al. 1989).

Tides and currents also play a significant role in oyster reef functioning by delivering particulate food and carrying away inorganic byproducts of metabolism. They also act as a flushing system, preventing feces and biodeposit build-up on or burial of the reef (Lund 1957; Haven and Morales-Alamo 1968). Biodeposits[5] are generally utilized by detritus feeders. In turn, detritus feeders provide sustenance to higher trophic levels. A robust community of detrital feeders may be considered part of the holistic oyster reef community; otherwise a large amount of accumulated oyster feces may result (Haven and Morales-Alamo 1968). Biodeposits not utilized by detritus feeders are transported away from the oyster reef to help prevent oysters from being inundated with their own feces and pseudofeces[6]. If feces and pseudofeces accumulate on reefs, oysters may not be able to filter feed. Sewage effluents can also be distributed by tidal currents, affecting growth and development of the oyster reef by increasing nutrients in the water column and promoting the growth of algae, which in turn reduces oxygen levels.

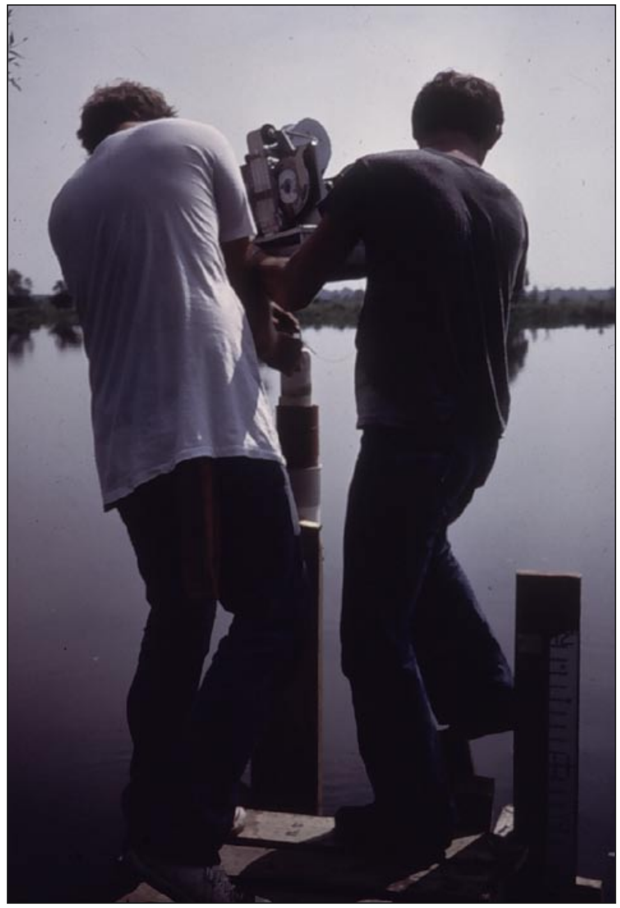

Figure 16. Tide gauge. Photo courtesy of Commander Gerald B. Mills, NOAA Corps. Publication of the NOAA Central Library. http://www.photolib.noaa.gov/historic/c&gs/images/big/theb2373.jpg

Sampling and Monitoring Methods

Tide gauges - Tide gauges (Figure 16) are mechanical devices usually placed on piers or pilings to record water levels (IOC 1985; Carter et al. 1989; Emery and Aubrey 1991; Giardina et al. 2000). The tide gauge consists of a data logger that reads and stores data from different sensors and a modem that communicates with a computer (IOC 1985). The water level sensor should be even from a stable bench mark and calibrated at regular intervals to ensure accurate water level measurements.

Acoustic Doppler flow meters - Acoustic Doppler flow meters can be used to evaluate tidal flow by measuring velocity and particles moving through the water. Acoustic signals are transmitted from the instrument, then reflected off of particles and collected by a receiver. The signals received are then analyzed for frequency changes. The mean value of the frequency changes can directly relate to the average velocity of the particles moving through the water.

Drifters - Drifters (Figure 17) (Southworth and Mann 1998) have been used along with focused plankton sampling around restored reefs to monitor the distribution and abundance of oyster larvae around a restored reef. These devices are available in a variety of sizes and are easily deployed from a small vessel. Regular monitoring of the drifter and recording of the drifter's location in the estuary with handheld GPS devices throughout the tidal cycle provides a quantitative method for evaluating larval dispersal.

[5] Nutrient-rich feces and pseudofeces easily assimilated by organisms.

[6] Substance discarded by suspension feeders or deposit feeders as potential food.

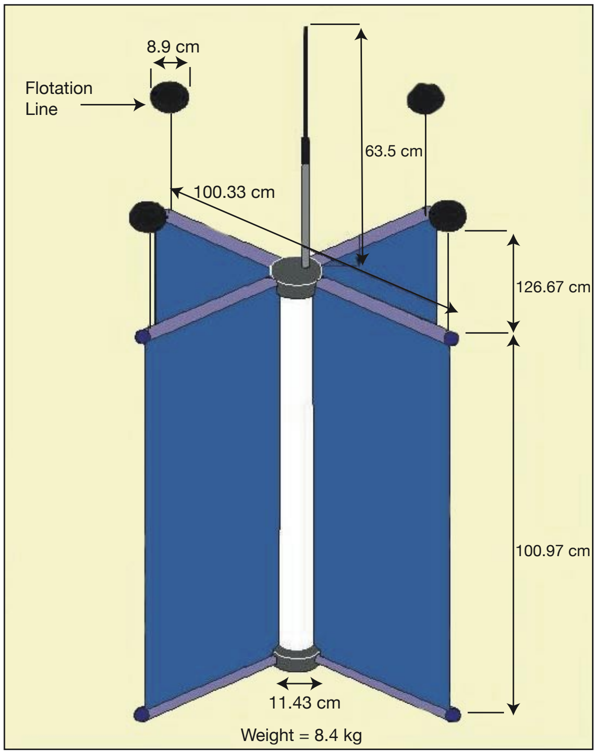

Figure 17. Diagram represents a drifter used for assessing tides and currents. Its main components consist of a waterproof tubular body, sails, spherical floats, and a data collection/transmitter package. Diagram courtesy of NOAA Ocean Explorer. http://oceanexplorer.noaa.gov/technology/tools/drifters/media/fig2.html

Dye studies - Dye studies have been used to evaluate oyster larval dispersal with tidal cycles. This method, currently being performed by Mann and other investigators at the Virginia Institute of Marine Science (see www.vims.edu/vsc), along with focused hydrographic modeling, is an extremely powerful predictive tool and valuable for restoration work.

Harmonic analysis - Harmonic analysis is a relatively straight forward method used to assess hydroperiod in various wetland types (Nuttle 1997). It allows quantitative sampling by gauging the breadth and timing of the main periodic element in a time series of water levels (Nuttle 1997). Quantitative measures of hydroperiod display the relationships between hydroperiod and functioning of oyster reef communities.

Water Sources

Large amounts of water inflow (e.g., from rivers, lakes, and industrial plant discharges) or runoff in proximity to oyster reef communities should be taken into consideration when developing a restoration plan, as this can influence the successful restoration of a naturally sustainable oyster reef habitat. If the source of inflow is not incorporated in the decision making process, monitoring parameters may be poorly selected. By knowing the source of water input, the practitioner will be more equipped to handle impacts to the habitat and select appropriate parameters to track restoration progress over time.

Water quality is a significant parameter that affects oyster reef communities. The source of water inflow can influence nutrient concentrations, oxygen levels, toxins, and ultimately the condition of the oyster reef. The chemical concentration and physical characteristics of water around oyster reefs can be influenced by various environmental factors including:

- Climate
- Tides
- Surface water, and
- Human inputs (e.g., upstream land use) (see “Human Impacts to Oyster Reefs” section)

Upstream land uses, for example, that may result in runoff from agricultural, industrial, or municipal water sources and reduce water quality and adversely affect the condition of the oyster reef and animal community (Scott et al. 1996; Zoun 2003). Oyster embryos and larvae are more sensitive to toxic chemicals than adults and juvenile oysters (Funderburk et al. 1991). Chronic effects on oysters are seen when oysters are exposed to the chemical TBT and petroleum hydrocarbons (Funderburk et al. 1991). Juvenile oysters, however, may experience acute toxicity and sublethal effects when exposed to chlorinated pesticides and polychlorinated biphenyls (PCBs). Heavy metals and polynuclear aromatic hydrocarbons (PAHs) can also cause acute toxicity, resulting in oyster mortality and sublethal stress on all life stages of oysters. In addition, such toxic chemicals can inhibit reproductive development, release of gametes, fertilization, larval development, and growth of juvenile oysters (Wendt et al. 1990; Sanger and Holland 2002).

Runoff from sewage can promote fecal coliform presence which further degrades water quality and negatively affects oyster health. If the health of the oysters deteriorates, the animal community they support may also be affected (i.e., species numbers and diversity may be reduced) (Rodriguez 1986; Zoun 2003). By evaluating oyster reef water sources and their potential impacts, restoration practitioners can design an effective restoration plan with monitoring parameters to measure water quality.

Upstream land source

While oysters are filter feeders, they cannot readily filter substances in high concentrations. In some cases, oysters become infected with diseases or simply decline in health because of exposure to high chemical concentrations. The Chesapeake Bay oyster population has decreased significantly because of municipal and industrial waste discharged into the Bay (Chen and Roesijadi 1994). The chemical pollutants that primarily threatened oysters were:

- Trace heavy metals (e.g., arsenic, cadmium, chromium, copper, mercury, tin, and zinc)
- Organic compounds (e.g., pesticides, phthalate ester, Polycyclic Aromatic Hydrocarbons (PAHs)), and
- PCBs

High levels of both trace metals and organic compounds were found in the sediment of the Bay (Chen and Roesijadi 1994). Because oysters are sedentary bottom dwellers, they are exposed to high concentrations of these toxins (Chen and Roesijadi 1994) which can result in their decline and reduce their ability to function. Thus, monitoring and recording the source of oyster reef water supply and adjacent land use is a priority.

Runoff from land activities has proven to be a significant factor in the reduction of oyster populations. Many researchers have studied the impacts of land use activities on coastal area reefs (Marcus 1989). Such land use activities included recreational marinas, an industrial point source wastewater discharge, and agricultural non-point source pesticide runoff. Results showed that recreational marinas displayed the lowest pollutant levels in oysters with no harmful biological effects. The industrial point source activity showed the highest pollutant levels in oysters and significantly detrimental biological effects. The agricultural runoff activity showed moderate pollutant levels in oysters, but significantly harmful biological effects.

A good reference for monitoring water sources is the *Standard Methods for the Examination of Water and Wastewater* which covers all aspects of water and wastewater analysis techniques. This is a joint publication of the American Public Health Association, American Water Works Association, and Water Environment Federation (see Clesceri et al. 1998). The U.S. Environmental Protection Agency has also developed a methods manual for assessing water quality (see USEPA 1983).

Water Temperature

Temperature may influence the oyster distribution and their physiological rate processes such as feeding and growth rates (Dame 1996). The optimal temperature range for oyster growth is between 14 and 28˚C (Shumway 1996), although oyster tolerance to temperature change varies among species type, life stage, and geographical location. For example, oyster larvae cannot tolerate a wide range of temperatures as compared to adult oysters. Eastern oyster larval growth may be harmed once water temperatures increase above 30˚C (Hidu et al.1974; Roegner and Mann 1995; Dekshenieks et al. 1996; Kennedy et. al. 1996). Extremely high temperatures may cause mortality in both larvae and adult oysters. Within the Indian River Bay, Delaware, evidence of oyster mortality was seen after water temperatures increased above 35˚C (Tinsman and Maurer 1974). In other locations, however, eastern oysters generally respond (i.e., reduction in growth rate, feeding process, or mortality) to temperatures above 35˚C. As oysters respond to significant increases in temperatures, they respond similarly when temperatures drop significantly below optimum temperatures (i.e., approximately below 20˚C) (Cake 1983; Dekshenieks et al. 1993).

Water temperature changes also influence the rate at which water is pumped through the oyster's gill system. For eastern oysters, water temperatures between 20 and 32˚C are favorable for pumping rates to provide requirements for oxygen, food, and waste disposal (Collier 1954; Loosanoff 1958). If temperatures drop below 7˚C, pumping may be reduced significantly. The ability of oyster to filter feed is affiliated with the pumping rates. Feeding begins when the oyster pumps water containing particles through the gill system. Food particles present in the water are then consumed; particles that cannot be consumed are excreted as pseudofeces. The remaining water is then released back into the water column (Haven and Morales-Alamo 1966). Thus, pumping rates will ultimately affect feeding rates, which in turn affects oyster growth.

Oyster reproduction is another biological process influenced by temperature. In the mid-Atlantic coastal waters, eastern oysters spawned when temperatures were above 20˚C. Adult oysters in 35˚C water temperature, however, experienced increased rates in gametogenesis and spawning (Quick 1971). In Galveston Bay, Texas, oysters spawned after temperatures exceeded 25˚C (Hopkins 1931) while mass spawnings occurred in Apalachicola Bay, Florida, when temperatures exceeded 26˚C (Ingle 1951). In the Gulf of Mexico, spawning occurred when temperatures were near 25˚C. As mentioned earlier, an oyster's biological response to temperature change will vary depending on species type, life stage as well as geographical location.

Measuring and Monitoring Methods

Water temperature can be measured using a thermometer below the water surface. A maximum/minimum thermometer can be left at the site to record the warmest and coldest water temperatures since the last readings were recorded at the study site (Rogers et al. 2001).

Some commercial instruments may be used to measure temperature, although no one type of commercial instrument can be recommended here. The basic procedure when using any one commercial instrument is to place the sensor probe into the water while the temperature reading is displayed.

CHEMICAL

Dissolved Oxygen

Dissolved oxygen (DO) plays a role in oyster survival and growth. In some cases, low dissolved oxygen has resulted in oyster mortalities and a subsequent reduction in reef size. Air exposure causes eastern oysters to close their shells tightly, almost completely isolating themselves from the air. There are reports of oysters being buried in anaerobic dredge spoil for a month yet were still alive (Galstoff 1964). Within the oyster shell, the tissues of the oyster may become hypoxic and significantly acidic as a result of accumulated carbon dioxide (CO_2) (Dwyer and

Burnett 1996). Some researchers have found that oyster metabolism may be vulnerable to hypoxia and the production of reactive oxygen intermediates by oyster hemocytes, considered one of the main defense mechanisms against pathogens, may be inhibited due to low dissolved oxygen (Boyd and Burnett 1999). Also, in cases when oxygen levels have decreased near lethal levels, oyster reef fishes, xanthid, and blue crabs migrate to areas on the reef with higher oxygen concentrations (Breitburg 1992).

In Bon Secour Bay, Alabama, a continuous decrease of oxygen levels caused a significant decline in oysters and reduced reef structure (Rikard et al. 2000). Along Puget Sound, Washington and Tomales Bay, California, an increased rate of oyster mortalities was also seen as a result of long periods of low dissolved oxygen (Cheney et al. 2001). During the evenings, there was a long period of neap tides with low and slow-moving water which resulted in daily and successive reductions in dissolved oxygen levels and caused oyster decline. Dissolved oxygen reductions also resulted in macroalgae blooms and high phytoplankton densities which altered oyster communities. As previously mentioned, oyster reductions throughout the Neuse River in North Carolina were a result of low dissolved oxygen. In addition, the number of fishes and invertebrates occupying oyster reefs were also reduced (Lenihan and Thayer 1999). These examples show that dissolved oxygen plays a role in oyster survival and should be taken in consideration when monitoring restoration success over time.

Sampling and Monitoring Methods

There are several methods used to measure dissolved oxygen including, dissolved oxygen meters, and commercial fiber optic oxygen sensor. The titration-based drop count technique can also be used that calculates dissolved oxygen concentrations by adding an indicator to the sample, then use the dropper to add the titrant until the color changes. Practitioners must record the number of drops it takes to change the color of the water sample. Each drop equals 1 mg/1 of dissolved oxygen. A dissolved oxygen meter consists of a sensor and the meter (Hargreaves and Tucker 2002). The fiber optic oxygen sensor consists of an optical fiber with a sensor tip containing a thin layer of oxygen-sensitive fluorescent dye. Once the sensor is placed into the water sample, the optical fiber stimulates the dye to release fluorescent light that travels to a photo detector. Oxygen diffusing into the sensor tip reacts with the fluorescent dye, reducing the intensity of light emission to indicate the oxygen concentration (Hargreaves and Tucker 2002).

Salinity

Oyster reefs can be found along a salinity gradient ranging from freshwater to marine salinity (12-28 ppt or higher in some cases) (Dame 1996). Depending on location, salinity is influenced by freshwater runoff, river input, and precipitation. Such changes in salinity levels may influence oyster spawning activities. Most spawning activities occur when salinities are above 10 ppt. However, the optimal salinity level for oyster growth and development is 12 to 28 ppt; optimum salinity ranges for gonadal development is from 15 to 25 ppt (Lough 1974; Dame 1996). If salinity levels drop below 10 ppt, then spat set may be hindered. Extreme salinity fluctuations affect the survival, growth, and distribution of oysters that form reefs as well as the abundance and distribution of other macroinvertebrates. Within a ten-mile area of the Newport River estuary in North Carolina, there was a steady decline of organisms in oyster communities when salinity levels were significantly high (Wells 1961). Most bivalves respond instantly to changes in the environment by closing their shells and isolating themselves from the external salinity environment. This isolation helps to reduce the rate of associated changes in the cell volume and allows the oyster to self-regulate osmotic pressure. Rapid changes in salinity may also cause reduced physiological rates of feeding and respiration (Hawkins and Bayne 1992; Dame 1996).

During severe storms, salinity changes occuring in estuaries may promote oyster diseases (Powell et al. 1995). Dermo disease increases during periods of high salinity. During periods of low rainfall, Dermo disease may occur as salinity increases, thus causing oyster mortality (Powell 1994). The effect of environmental changes such as salinity on the eastern oyster population was investigated using computer simulation models (Dekshenieks et al. 2000). The simulations revealed that salinity is the primary factor controlling the spatial degree of oyster distribution. Such studies show that salinity plays an important role in the spat and survival of oysters and should be measured and closely monitored during restoration efforts.

Measuring and Monitoring Methods

Among many commercial instruments used to measure salinity is the hand-held refractometer. This instrument measures how much the light rays are refracted (i.e., bent) as they pass through seawater (Rogers et al. 2001). Salinity is measured on a calibrated refractometer by placing a few drops of the seawater under a transparent slide, and reading the salinity value by looking through the eye piece (Rogers et al. 2001).

A hydrometer measures salinity by comparing the density of the seawater samples to fresh water samples. The glass tube hydrometer is placed in a cylinder of sampled seawater to measure how high it floats in the cylinder - the higher it floats, the greater the salinity. The number on the hydrometer scale at the water surface and the water temperature are used together to determine the salinity; values are referenced on tables that accompany the hydrometer (Rogers et al. 2001).

In the absence of digital recording equipment, salinity can be determined from water samples collected from just above the bottom and at the water surface with a Niskin bottle. The Niskin bottle has stoppers on both ends that are held in place by springs. The bottle is prepared by cocking open both ends of the bottle, then attached to a support (winch) line and lowered to the preferred depth. A small weight known as a messenger is attached to the line and released to trigger the stoppers and seal the bottle. The sample of the water from that depth is contained in the bottle.

FUNCTIONAL CHARACTERISTICS OF OYSTER REEFS

Oyster reefs perform important functions, such as:

Biological

- Provide places for oysters to recruit and grow
- Provide habitats for plants, fish, and invertebrates
- Provide breeding, feeding, and nursery grounds for fish, crustaceans, other invertebrates, and birds species
- Supports carrying capacity
- Biomass production
- Create a place of refuge against larger predators
- Provide a place on which sessile organisms attach

Physical

- Protect coastal areas from erosion, and
- Stabilize sediments and filter particles in the water column

Chemical

- Trap and rapidly recycle essential nutrients in coastal environments

By performing these functions, reefs are able to support important local and commercial fisheries as well as maintain the diversity and abundance of flora and fauna. If the health of the reef is degraded in any way, it can affect habitat function, such as its ability to filter suspended sediments and enhance the cycling of nutrients in the estuary (Dame et al. 1989), and provide nursery and breeding grounds for organisms (Anderson and Connell 1999; Harding and Mann 2001a, b; Harding and Mann 2003). Understanding how oyster reefs function as communities can help the practitioner select suitable parameters to track restoration efforts and achieve a naturally sustainable habitat.

This section concentrates on the biological, physical, and chemical functions performed by oyster reefs. Also provided are several methods to sample, measure, and monitor the functional parameters affiliated with oyster reef characteristics. Oyster reefs, for example, may be used as breeding and feeding grounds by many species of animals other than oysters (Harding and Mann 2001a). These functions are measured by identifying and counting the numbers and types of animals observed in the habitat and quantifying diet and/or size. Not all functional characteristics described in this chapter, however, are expected to be measured. This information simply illustrates the importance of oyster reef habitat, and the methods discussed herein are examples of the numerous methods that can be used. Sources are cited throughout the text to guide readers to additional information.

BIOLOGICAL

Provides Habitat

Oyster reefs provide habitat for many animals (such as oysters which are keystone[7] species) that contribute to the reef's composition. The formation of three-dimensional intertidal reefs results after years of successive settlement and survival of larval oysters that attach to adult oyster shells (Morales-Alamo and Mann 1990; Bartol and Mann 1997; Bartol et al. 1999). The complex structure of the reefs provides surface and interstitial heterogeneity that can ultimately support oyster settlement and survival as well as many other organisms. Types of organisms may also vary between intertidal and subtidal areas because organisms in intertidal areas must be able to adapt to frequently air-exposed conditions, whereas at subtidal depths, organisms must adapt to areas usually submerged by water. Some studies suggest that microscale variations in tidal elevation and substrate depth can significantly affect settlement processes and therefore should be considered when constructing reefs (Bartol and Mann 1997; Bartol et al. 1999).

[7] Essential to the functioning of the ecosystem.

Oyster reefs also support a complex trophic structure and biodiversity by providing food and shelter for many species other than oysters including crustaceans, benthic invertebrates, and many valuable commercial and recreational fisheries (Zimmerman et al. 1989; Coen et al. 1999b; Harding and Mann 1999, 2001a; Lehnert and Allen 2002). Crustaceans such as crabs occupy the crevices inside the oyster reef and may be significant predators on juvenile oysters (Eggleston 1990a, b). Benthic invertebrates like grass shrimp (*Palaemonetes spp.)* are commonly found occupying the bottom areas. Fish use the oyster reef in various ways by laying eggs (see "Providing Breeding and Nursery Grounds" section) and finding protection for juveniles in oyster shells.

Benthic-pelagic coupling reaches its zenith with the dense assemblages of oysters that form oyster reefs (Dame et al. 2002). Oysters can directly and indirectly control the availability of resources to other species by causing physical state changes in abiotic and biotic materials (Jones et al. 1994). Thus, oyster reefs passively and actively move particulate and dissolved materials between themselves and the water column, and thus, both directly and indirectly influence their ecosystems by processing their phytoplankton food and building hard structured reefs. The loss of this keystone species can dramatically alter the ecosystem (Dame 1996). These attributes are exemplified by the role of oyster reefs in processing and recycling carbon, nitrogen, and phosphorus in coastal ecosystems (discussed further in "Supporting Nutrient Cycling" section).

Habitat use and natural sustainability of the habitat should be monitored regularly since any deterioration in the habitat's condition will likely affect animal abundance and survival. Some of the animal species that live amongst oyster reefs include:

Oysters
Fiddler crabs (genus *Uca*) (Figure 18)
Blue crab (*Callinectes sapidus)*
Grass shrimp (*Hippolyte* spp.*)*
Mussels (*Mytilus edulis*)
Rockfish (genus *Sebastes*)
Oyster toadfish (*Opsanus tau)*, and
Sea squirts (*Molgula manhattensis)*

Common vegetative species that live on oyster reefs, including seaweeds and algae, are food sources for many species of fish and crustaceans. These vegetative species include:

Spiny seaweed (*Acanthophora spicifera*) (Kilar and McLachlan 1986), and
Algae (*Carpophyllum scalare* Suhr*, Anatheca dentata* [Suhr] Papenfuss*, Ceramium obsoletum,* and *C. agardh)*

Measuring and Monitoring Methods

Vegetation - Oyster reef vegetation is measured by evaluating its cover, distribution, and abundance. Quadrats provide reference frames to estimate abundance, cover, and biomass of flora. They can be placed randomly or at a fixed position. Species abundance is estimated by calculating the mean of samples collected from each study area. Monitoring frequency for vegetation growth is based on a species

Figure 18. Male fiddler crab, *Uca pugilator*, sporting its large claw as it attempts to hide under the glasswort, *Salicornia sp*. Photo courtesy of NOAA National Estuarine Research Reserve Collection. Publication of the NOAA Central Library. http://www.photolib.noaa.gov/nerr/images/big/nerr0324.jpg

growth rate and time of year. Practitioners may therefore want to consider tracking change in vegetation species richness and percent cover over time.

Vegetation can also be measured and recorded as visual information using fixed viewpoint photography (Moore 2001). Taking regularly scheduled photographs at a specific location allows the recording of changes that occur in the habitat's physical structure. This also shows whether visual photographs taken of these changes in smaller areas are a good representation of larger areas (Moore 2001). A single lens reflex camera with a 50 mm lens, a 35 mm or 28 mm wide angle lens, and a fixed focal length will ensure repeatability of the view angle each time a photo is taken (Moore 2001). Photos can then be compared to determine whether vegetation has increased or decreased over time.

Provides Breeding and Nursery Grounds

Reefs provide breeding and nursery grounds for many species such as crustaceans, fishes, and birds. For instance, mussels commonly attach and spawn in areas adjacent to oyster reefs. Oyster toadfish (*Opsanus tau)* also attach their eggs to the underside of articulated empty oyster shells while striped blennies (*Chasmodes bosquianus*), gobies (e.g., *Gobiosoma bosc, G. ginsburgi*), and skilletfish (e.g., *Gobiesox strumosus)* lay their eggs in dead oyster shell beds (Breitburg 1999; Coen et al. 1999a). In estuaries, eastern oyster shell-covered bottoms also supported juvenile seabass (e.g., *Centropristis striata*), groupers (*Epinephelus* spp.) (Figure 19), snappers (e.g., *Lutjanus* spp.*),* and crustaceans (Lehnert and Allen 2002). Other recreationally and commercially valuable finfishes that commonly use oyster reefs as nursery grounds (Harding and Mann 1999; Harding and Mann 2001a, b; Harding and Mann 2003) include:

Figure 19. Nassau grouper (*Epinephelus striatus*). Photo courtesy of NOAA OAR/National Undersea Research Program. Publication of the NOAA Central Library. http://www.photolib.noaa.gov/nurp/images/big/nur00526.jpg

Striped bass (*Morone saxatilis*)
Bluefish (*Pomatomus saltatrix*), and
Weakfish (*Cynoscion regalis*)

Provides Feeding Grounds

Reefs provide feeding grounds for many mobile and sessile species but only a few examples are discussed here. Juvenile crustaceans (e.g., crabs) feed on invertebrates and molluscs that are present in oyster reef crevices and sediments near oyster reefs. Recreationally and commercially important fish, especially apex predators (i.e., predators at the top of the food chain) such as striped bass, bluefish, and weakfish, commonly feed on crustaceans, shrimps, marine worms, and other fish species (Harding and Mann 1999). Smaller fish such as naked gobies (*Gobiosoma bosc*), and in some cases striped blennies consume oyster larvae and as a result, may influence recruitment success within oyster reef communities (Harding 1999).

Intertidal reefs are also important habitat and foraging grounds for shorebirds. These birds commonly feed on small fish such as naked gobies and striped blennies in shallow waters near oyster reefs. Oysters that are exposed on intertidal flats provide food for some shorebirds such as the American oystercatcher (*Haematopus palliates)* (Figure 20). Near Fisherman's Island, Virginia, some researchers

Figure 20. American oyster catcher, (*Haematopus palliates*). Photo courtesy of NOAA National Estuarine Research Reserve Collection. Publication of the NOAA Central Library. http://www.photolib.noaa.gov/nerr/images/big/nerr0086.jpg

observed the roosting and foraging behavior of the American oystercatcher within and adjacent to thirteen reefs consisting of surf clam shell, oyster shell, and coal ash pellets (Crockett et al. 1998). The American oystercatcher was seen resting and feeding mainly on reefs composed of oyster shell (Crockett et al. 1998). As a result, oyster reefs serve as important resting and feeding areas for birds (Crockett et al. 1998). If oyster reefs are degraded in any way, bird communities occupying the reefs within a specific area may be forced to migrate to other areas where environmental conditions are suitable and food is available.

Sampling and Monitoring Methods

Invertebrates - Reef invertebrate species may be quantified using quadrats and transects (Nestlerode 2004). Quadrats are used to identify invertebrate species cover and density on oyster reefs (Grizzle and Castagna 1996; Harris and Paynter 2001; Murray et al. 2002). Species diversity is estimated by calculating the mean of two to three samples collected from each study area. To keep track of organisms counted in quadrats, some organisms, if not to small, can be marked as they are counted and the results recorded on a data sheet. Quadrats can be fixed so that a sample area can be measured repeatedly. Transects are also used to collect field data by recording the number of organisms and species in each sampling unit along the line or by collecting samples of species along a line or within a habitat (Michener et al. 1995; Haws et al. 1995).

Fish - Fish should be sampled both during the day and night to accurately assess habitat use. Their numbers are relatively greater at night, but sampling near shallow water or intertidal oyster reefs in the dark may be dangerous, so caution must be taken when sampling at night. Many fish species show diurnal variability in habitat use (Harding and Mann 2001a). If sampling is performed only during the day, then the number, size, and type of organisms in a habitat may be gravely underestimated.

Different types of nets can be used to sample fish and other nekton in oyster communities, including seines, lift nets, and gill nets. Seine nets may be appropriate in intertidal habitats, and are composed of a bunt (bag or loose netting) with long ropes to pull the seine out the water. The nets have floats to keep the top part of the net afloat and weights to keep the bottom of the net submerged to prevent the fish from escaping from the invisible net-enclosed area. Fish caught within the net are then identified and counted (Crabtree and Dean 1982; USEPA 1993).

Lift nets may be more appropriate for subtidal habitats. These nets consist of a bag-shaped structure with the opening facing upwards while the bottom of the bag remains submerged. Fish that swim over the opening of the bag are then enclosed as persons holding the net lift it out of the water (Wenner et al. 1996).

Advantages to the use of a lift net are:

- The habitat in the area to be sampled will experience minimal damage

- The size and shape of the net system can fit a variety of habitats
- No permanent structures, other than a shallow perimeter trench, are present to act as attractants, and
- It is inexpensive to purchase and maintain gear (Wenner et al. 1996)

Both intertidal and subtidal reef habitats may be sampled with gill nets with predetermined mesh sizes (Figure 21). Nekton are captured when they swim into the invisible mesh net and struggle to escape. As they struggle, they become entangled within the net. Practitioners then separate the fish from the nets so that they can be identified, counted, and analyzed to determine diet, age, and fecundity (Nielson and Johnson 1983; Harding and Mann 1999; Harding and Mann 2001a, b; Harding and Mann 2003).

In habitats with low turbidity, visual surveys may be used to identify and assess fish species during daylight hours. Underwater visual census is used for estimating fish abundance via snorkeling, scuba diving, or video cameras when visibility conditions permit. Organisms are counted using quadrats, transects, or fixed point counts (Samoilys and Carlos 2000). Transects are marked to define the boundaries of the study area. Fixed point counts entail counting from a specific point while rotating in the quadrat (Samoilys and Carlos 2000).

Figure 21. Using nets to collect samples of fish and other marine organisms along oyster reefs, as part of Fisherman Island Project, Virginia's Eastern Shore. Photo courtesy of Mark Luckenbach, Eastern Shore Laboratory, Virginia Institute of Marine Science.

Fish may also be captured on both natural (reference) and created oyster reefs to compare the number, type, and size of the fish between the two reef types. Species type, abundance, density, and diversity are recorded in a given area for both natural and created reefs (Harding and Mann 1999; Harding and Mann 2001a). Quantitative measurements of fish abundance and large mobile crustaceans on oyster reefs and on nearby sedimentary habitat can be analyzed. Densities can be compared for each species by size on oyster reefs and sedimentary bottom to estimate how oyster reef restoration on sedimentary bottom may increase fisheries abundance. Published information on growth rates of each species and empirical data on age-specific survivorship can also be analyzed for change in species and abundance over time. The per-unit-area enhancement of fish production and large mobile crustaceans expected from the addition of oyster reef habitat can then be calculated (Peterson et al. 2003).

Another method to assess the use of restored oyster reefs by numerous organisms, particularly finfishes, is the Essential Fish Habitat (EFH)[8] system. This system measures certain parameters in four levels:

- Level 1 - presence/absence data
- Level 2 - distribution and abundance
- Level 3 - the functional relationship between species and habitat: reproduction, growth, survival, and
- Level 4 - habitat-specific fish production

This four-level system can provide the practitioner with basic parameters to monitor the functional ecological relationship between oyster reefs and trophic communities that they support (Benaka 1999; Harding and Mann 2001a, b; Harding and Mann 2003). In addition,

[8] Under the Magnuson-Stevens Fisheries Conservation and Management Act, Essential Fisheries Habitat (EFH) is defined as waters and substrate necessary to fish for spawning, breeding, feeding, or growth to maturity, and is applied in regulating coastal fisheries.

this system can be used to show whether the habitat is important (i.e., a significant role in supporting animals) or essential (i.e., the primary role in supporting animals) (Harding and Mann 2001a).

Invertebrates - Aerial surveys and direct counts can be used to monitor birds along coastal and estuarine habitats. Aerial surveys inventory migrant shorebirds (Erwin et al. 1991) and monitor wintering populations (Morrison and Ross 1989). Surveys are used to estimate relative abundance of migratory and wintering populations, and to assess population trends of migratory shorebirds. Direct counts are used to estimate shorebird density. Data collected on the number of birds in a habitat can be recorded on audio tape and then copied onto data sheets. In some cases, video cameras and aerial photography are used with aerial surveys (Dolbeer et al. 1997). Aerial photographs provide precise estimates of birds and visual records of the structure of oyster reef habitats.

Crustaceans - Crustacean recruitment, particularly crabs, can be quantified using settlement trays filled with either air-dried oyster shells or artificial seagrass. This allows the practitioner to determine the preferred habitat type for the different life stages of crabs (Etherington et al. 1996). Seagrasses should be assessed because they are considered an associated habitat of oyster reefs and influence reef communities. Some researchers have placed trays on unstructured seafloor to assess recruitment of blue crab megalopae (i.e., the postlarval stage of a crab). The effects of patch shape (square versus thin) and patch location ("edge" versus "center") on density were also quantified. Using this method, researchers were able to show that blue crabs relied on both seagrass and oyster reefs as a place for settlement and refuge; thus both habitat types function as an interconnected community (Etherington et al. 1996).

The abundance of mud crabs (*Panopeus herbstii* and *Eurypanopeus depressus*) on intertidal oyster reefs can be determined with regard to surface oyster reef shell cover, surface oyster cluster volume, subsurface shell content, substrate sand and silt composition, and oyster reef elevation (Meyer 1994) using quadrats during low tide. Quadrats allow researchers to effectively assess crab abundance at selected areas throughout the study site in order to obtain a good representation of the number of crab species (Meyer 1994) within the restoration site.

Provides Substrate Attachment

Oyster reefs form when substrates, including both living and dead oysters, accumulate and serve as a base for organisms (Wells 1961; Bahr and Lanier 1981; Rheinhardt and Mann 1990) such as:

Mussels (Figure 22)
Serupilid worms
Bryozoans
Hydroids
Barnacles
Macroalgae, and
Spawn of oyster

Crustose algae and other macroalgae, for instance, are found attached to oyster shell substrate especially in shallow shoreline areas. Figure 23 shows clusters of oysters and sponges attached to shells. Oyster shells also support mussels and barnacles, which in turn provide protection and food for:

Juvenile dungeness crab (*Cancer magister)*
Shore crabs (*Hemigrapsus spp.)*
Tube building gammarid amphipods (e.g., *Amphithoe* and *Corophium)*
Caprellid amphipods
Tanaids, and
Annelids (Dumbauld 2002)

Figure 22. A small oyster reef with mussels attach to it in the Choptank River, Maryland. Photo courtesy of Mary Hollinger, NOAA National Oceanographic Data Center. Publication of the NOAA Central Library. http://www.photolib.noaa.gov/coastline/images/big/line0797.jpg

Figure 23. Oyster shell with fouling sponges attached. Photo courtesy of South Carolina Department of Natural Resources.

Reefs also support recruitment of oysters, thereby contributing to the increase in size of the reef's structure. Along Fisherman's Island, Virginia, intertidal reefs were constructed using oyster shell (O'Beirn et al. 2000). Oyster recruitment and settlement occurred on oyster shell reefs at various tidal heights (high-, mid-, and low- intertidal), allowing continuous growth of the reef and supporting various organisms.

Provides Refuge from Predation

Oyster reefs provide refuge from predation for numerous species such as:

- Newly metamorphosed and young oysters (Eggleston 1990a, b; Baker and Mann 1998)
- Resident predators, such as rock crabs (e.g., *Nectocarcinus intigrifrons)* and gobies, and
- Transient predators, such as blue crabs and pinfish (*Lagodon rhomboides*)

Small fishes and other organisms such as xanthid crabs also hide within spaces in the reef to avoid being preyed on by predators that feed on the reef surface (Meyer 1994; Anderson and Connell 1999; Coen et al. 1999a). Benthic organisms hide from crustaceans such as blue crabs within interstitial spaces formed between oyster shells as well.

Supports Carrying Capacity/Biomass Production

Carrying capacity may be defined as the maximum living oyster reef biomass that can be supported in a particular ecosystem (see Dame and Prins 1998). While it is considered both a structural and functional characteristic of oyster reefs and their environment, carrying capacity is discussed here as a function of oyster reefs. In an ecosystem dominated by oyster reefs, carrying capacity is a function of water mass turnover time, phytoplankton production time, and oyster clearance time (Dame and Prins 1998). Massive bivalve suspension-feeder systems are usually found in ecosystems with relatively short water mass residence times (less than 40 days) and short phytoplankton production times (less than 4 days) (Dame and Prins 1998).

When considering an ecosystem for oyster reef restoration, the three turnover time characteristics aforementioned should be determined for

Figure 24. Small-scale experiments to assess the impact of boat wakes[9] on newly planted Gulf shell in Inlet Creek in April 2000. Photo courtesy of Loren Coen, Marine Resources Research Institute, South Carolina Department of Natural Resources.

the target sites. This determination requires estimates of the total water mass flushing rates (flushing is important for removing excess materials); total phytoplankton biomass (usually Chl *a*) in the water near the reef because excess growth of phytoplankton can contribute to reduce oxygen levels affecting oyster growth; and total or expected total oyster biomass in the ecosystem.

PHYSICAL

Reduces Shoreline Erosion

Oyster reefs serve as barriers that protect shorelines from erosion by reducing wave energy entering coastal habitats such as marshes. As the waves approach the shoreline, the physical structure of oyster reefs reduces the force of the waves and helps protect the shoreline from erosion (Figure 24). Once oyster reefs slow wave energy, they are able to stabilize sediments, reduce vegetation loss, conserve other habitats, and promote animal use of the habitat without the threat of being swept away by waves (Hargis 1999; Hargis and Haven 1999; Meyer and Townsend 2000).

Filters Water and Stabilizes Sediments

Oysters pump and filter volumes of water in order to consume sufficient phytoplankton as food. This process takes place when water is pumped through the gills, allowing potential food particles to be trapped by the mucus of oysters and then transported to the mouth by its frontal cilia where it is either consumed or discarded. Other particles too large or too small to be utilized by oysters are rejected as pseudofeces (Dame 1996). Oysters also help maintain water quality in estuarine environments by filtering suspended solids and nutrients (discussed further in “Supporting Nutrient Cycling” section) as well as altering hydrology

[9] The wave of water resulting from passage of a boat’s hull through the water. The wave generated, depending on size and speed of the vessel, can be large and affect oyster reefs.

patterns which further assist particulate removal. Oysters reduce particulate inorganic material and organic material suspended in the water column (Dame et al. 1984; Newell 1988). During the filtration process, sediments settle out of the water column and onto the bottom (Meyer and Townsend 2000; Mugg et al. 2001). If oysters are infected by disease or otherwise degraded, their ability to stabilize sediments may be reduced, allowing increased sedimentation which can ultimately affect algae productivity and oyster feeding and development.

Measuring and Monitoring Methods

For on-site evaluation of oyster filtration capacity, a flow-through plastic tunnel[10] is a feasible method of determining significant changes in tidal water materials passing over an oyster reef (Dame et al. 1984). The reef reduces the amount of particulate organic carbon and chlorophyll *a* (Chl *a*) while increasing the amount of ammonia in the water column. Observations can help determine the magnitude of particulate organic carbon removal and filtration ability of the oyster reef.

Laboratory observations of individual or groups of oysters may provide an efficient, reliable method to evaluate changes in filtration rates and feeding ability in relation to environmental conditions. Laboratory studies also provide an opportunity to examine filtration response across gradients of environmental conditions and combinations of conditions that are difficult or impossible to observe in the habitat.

CHEMICAL

Supports Nutrient Cycling

Oysters play a role in nutrient cycling of carbon, phosphorus, and nitrogen (Figure 25). The animals on the reefs remove large quantities of suspended organic particulate material (phytoplankton) from the water column. The organic matter is processed by the animals and microbes inhabiting the reef with inorganic matter that is readily utilized by the phytoplankton being released into the water column (Dame 1996; Newell 2004). In most instances, the net result is that the community of organisms living on oyster reefs short-circuits the typical pelagic food web and moves carbon, nitrogen, and phosphorus through these ecosystems at much faster rates (Dame 1996).

As a consequence of these material flows, both negative and positive feedback loops are established that increase the complexity, productivity, and stability of estuarine ecosystems. Nutrient processing by oysters for example, can increase nutrient levels in nutrient-limited areas and may help regulate primary production (Dame 1996). Essentially, oyster reefs increase the functional and structural sustainability of their ecosystems (Dame 1996). An oyster's ability to cycle nutrients was seen along intertidal oyster reefs in Bly Creek, South Carolina. Researchers demonstrated that oysters were able to process carbon at high rates and return inorganic nitrogen and phosphorus to the water column, while the returned inorganic nitrogen was taken up by phytoplankton (Dame et al. 1989).

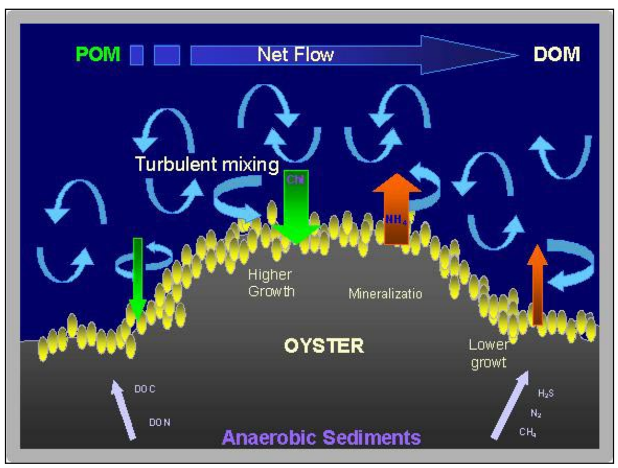

Figure 25. Diagram of nutrient processing in oysters. Diagram courtesy of Richard Dame, Marine Science Department, Coastal Carolina University, South Carolina.

[10]The tunnel method has been successfully used in the United States, as well as The Netherlands, France, and Germany.

Reef Food Webs

Organisms living on the reef may not short-circuit the pelagic food web in all habitats, such as places that were or still are dominated by benthic communities, thereby resulting in benthic-pelagic coupling by filter feeders. In this case, oyster reefs do not short circuit the process but help to restore its naturally functioning state (Dame 1996).

Sampling and Monitoring Methods

There are various methods to measure nutrient concentrations, which in turn can be used to calculate nutrient flux with assistance from experts. These methods include the automated gas segmented continuous flow colorimetric method which measures nitrite and nitrate (Zhang et al. 1997), and the automated colorimetric method which measures orthophosphate (Zimmerman and Keefe 1997).

Nitrate levels can be determined using the automated colorimetric method by (1) reducing the nitrite in a buffer solution, (2) determining nitrite by treating the sample with a dye, and (3) measuring absorbance proportional to the concentration of nitrite + nitrate in the sample. Nitrate is then determined by subtracting the nitrite values (see Zhang et al. 1997).

There are a number of high-tech methods to measure nutrient flux rates as well as oxygen levels such as the automated benthic chamber device. This device is deployed on a line from a vessel, uses one chamber, and contains a sealed waterproof computer as all operations are completely programmable. As the device is lowered into the water, nutrient flux measurements are taken at various intervals. The dissolved oxygen concentrations can also be electronically monitored and stored by the computer (see Grenz et al. 1991; Nicholson et al. 1999).

PARAMETERS FOR MONITORING STRUCTURAL/FUNCTIONAL CHARACTERISTICS OF OYSTER REEFS

The following matrices present parameters for restoration monitoring of the structural and functional characteristics of oyster reefs. These matrices are not exhaustive, but represent those elements most commonly used in such restoration monitoring strategies. These parameters have been recommended by experts in oyster reef restoration as well as in the literature on oyster reef restoration and ecological monitoring. The closed circle (●) denotes a parameter that should be considered in monitoring restoration performance. Parameters with an open circle (❍) may be considered, depending on specific restoration goals.

Parameters to Monitor the Structural Characteristics of Oyster Reefs

Structural Characteristics

Parameters to Monitor	**Biological**		**Physical**		**Hydrological**				**Chemical**
	Habitat created by animals	Habitat created by plants	Sediment grain size	Topography / Bathymetry	Current velocity	Tides / Hydroperiod	Water sources	Wave energy	pH, salinity, toxics, redox, dissolved oxygen
Geographical									
Acreage of habitat types	●	●							
Biological									
Plants									
Species, composition, and % cover of									
Algae		❍							
Phytoplankton diversity and abundance		❍							
Animals									
Vertical relief	●			●					
Hydrological									
Physical									
Shear force at sediment surface					❍			❍	
Upstream land use							❍		
Water column current velocity					❍				
Tides/Current/Water level fluctuation over time						●	●		
Temperature						●	●		
Chemical									
Dissolved oxygen									●
Nitrogen and phosphorus									❍
pH									❍
Salinity						●	●		●
Toxics									❍
Soil/Sediment									
Physical									
Geomorphology (slope, basin cross section)				●		●			
Organic content			❍			❍			
Sedimentation rate and quality			❍	❍	❍	❍			
Chemical									
Pore water nitrogen and phosphorus									❍

Parameters to Monitor the Functional Characteristics of Oyster Reefs

Parameters to Monitor	Functional Characteristics: Biological								Physical			Chemical	
	Provides breeding grounds	Provides feeding grounds	Provides nursery areas	Provides refuge from predation	Provides substrate for attachment	Supports a complex trophic structure	Supports biomass production	Supports biodiversity	Alters turbidity	Reduces erosion potential	Reduces wave energy	Modifies chemical water quality	Supports nutrient cycling
Geographical													
Acreage of habitat types	●	●	●	●	●	●	●	●	●	●	●	●	●
Biological													
Plants													
Species, composition, and % cover of:													
Algae	○	○	○	○	○	○	○	○	○	○	○	○	○
Interspersion of habitat types	○	○	○	○		○	○	○	○	○	○	○	○
Phytoplankton diversity and abundance		○				○	○	○	○			○	○
Animals													
Species, composition, and abundance of:													
Birds	○	○	○	○		○	○	○					
Fish	○	○	○	○		○	○	○					
Invasives	○	●	●	●			●	●	●				
Invertebrates	○	○	○	○		○	○	○					
Vertical relief of reef	●	●	●	●	●	●			●	●	●		
Hydrological													
Physical													
PAR							●		●				
Secchi disc depth							●		●				

Parameters to Monitor the Functional Characteristics of Oyster Reefs (cont.)

Parameters to Monitor	Biological: Provides breeding grounds	Biological: Provides feeding grounds	Biological: Provides nursery areas	Biological: Provides refuge from predation	Biological: Provides substrate for attachment	Biological: Supports a complex trophic structure	Biological: Supports biomass production	Biological: Supports biodiversity	Physical: Alters turbidity	Physical: Reduces erosion potential	Physical: Reduces wave energy	Chemical: Modifies chemical water quality	Chemical: Supports nutrient cycling
Hydrologic													
Physical (cont.)													
Trash		○							○				
Upstream land use									○			○	
Water column current velocity									○	○			
Water level fluctuation over time	●	●	●	●					●	●			●
Chemical													
Dissolved oxygen	○		○			○		○				○	○
Nitrogen and phosphorus	○		○				○	○	○			○	○
Toxics	○	○										○	
Soil/Sediment													
Physical													
Basin elevations	○	○	○	○	○			○					
Geomorphology (slope, basin cross section)	●	●	●	●	●			●	●	●		●	
Sediment grain size (OM[11]/sand/silt/clay/gravel/cobble)					○		○	●	○	○	○	○	○
Sedimentation rate and quality								○	○	○		○	○

[11] Organic matter.

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Zoun, R. J. 2003. Estimation of fecal coliform loadings to Galveston Bay. Thesis, Master of Science in Engineering, University of Texas at Austin. http://www.crwr.utexas.edu/reports/pdf/2003/rtp03-05.pdf

APPENDIX I: OYSTER REEFS ANNOTATED BIBLIOGRAPHY

This annotated bibliography contains summaries of restoration case studies and basic ecological literature. It is designed to provide restoration practitioners with examples of previous restoration projects as well as overviews of papers from the ecological literature that offer more detail than that covered in the associated chapter. Entries are presented from both peer reviewed and grey literature. They were selected through extensive literature and Internet searches as well as input from reviewers. They are not, however, a complete listing of all of the available literature. Entries are arranged alphabetically. Wherever possible, web addresses or other contact information has been included in the reference to assist readers in easily obtaining the original resource. Summaries preceded by the terms '*Author Abstract*' or '*Publisher Introduction*' or similar descriptors were taken directly from their original source. Summaries without such descriptors were written by the author of the associated chapter.

Bartol I. K. and R. Mann. 1995. Small scale patterns of recruitment on a constructed intertidal reef: The role of spatial refugia, pp. 159-170. In Luckenbach, M. W., R. Mann and J. Wesson (eds.), Oyster Reef Habitat Restoration: A synopsis and synthesis of approaches. Virginia Institute of Marine Science, College of William and Mary, VIMS Press, Williamsburg, VA .

Researchers constructed a three-dimensional oyster reef using oyster shell in the Piankatank River, Virginia, and evaluated settlement and mortality patterns of oysters from June 1993 to September 1994. The reef extended from 2.5 m below mean low water (MLW) to 0.75 m above MLW and covered 150 x 30 m. In 1993 twelve intertidal hummocks were sampled along upstream and downstream transects using transects on two mounds (one sheltered from wave currents and one exposed to wave currents) during each period of sampling. On the reefs transects were marked to prevent re-sampling. In 1994, eight hummocks were partitioned into 64 x 20 cm plots using rope and reinforced bars, and experimental sites. Three tidal heights were considered, 25 cm above MLW, MLW, and 90 cm below MLW. Sampling was then conducted at each of these levels. In intertidal and subtidal locations, settlement and mortality occurrences were monitored at the reef surface and within the reef depths interstices of 10 cm. In subtidal locations settlement was greater and showed no difference in settlement intensity between surface and subsurface environments. Along the intertidal-subtidal continuum survival rates for most of the year were highest at MLW. At this location, physical and predatory influences were minimal. The results indicate that both reef tidal elevation and substrate thickness provide microscale refugia for settlement and survival of early oyster life history stages.

Breitburg, D. L., L. D. Coen, M. W. Luckenbach, R. Mann, M. Posey, and J. A. Wesson. 2000. Oyster reef restoration: Convergence of harvest and conservation strategies. *Journal of Shellfish Research* 19:371-377.

This paper focuses on oyster reef restoration, protection, and construction to meet harvest, water quality, and fish habitat goals in order to view an overall image of why oyster reef monitoring, restoration, and management is important ecologically and economically. The restoration actions that are considered useful and described in this document are constructing reefs at different depths and using different base materials; constructing reefs with varying spatial dispersion patterns; positioning constructed reefs in varying proximity to other landscape elements; constructing reefs in areas with different tidal ranges and water quality and harvesting status; and constructing reefs with varying shapes and vertical structure. Good monitoring and restoration efforts are important to ensure that future restoration efforts are improved, and can enhance the basic information needed to recognize the ecology of oysters and their role in estuarine and coastal systems. Additional information on techniques used to monitor and restore oyster reefs are described in this document.

Bushek, D., J. Keesee, B. Jones, M. Neet and D. Porter. 2000. Shellfish health management: A system level perspective for *Perkinsus marinus*. *Journal of Shellfish Research* 19: 642-643.

Author Abstract. This paper provides information on a study conducted on 2 South Carolina estuaries on shellfish health. The paper presents data from three years of spatial seasonal monitoring of *P. marinus* infection intensities in the 2 estuaries. The data include El Niño, La Niña and normal rainfall years and indicate that water residence time and flushing rates, are primary determinants of infection intensity. Landscape-level anthropogenic impacts that alter these hydrological processes (e.g., upland ditching and drainage, channel dredging, jetty construction, etc.) may be more important factors in intensifying oyster mortality from *P. marinus* than pollutants commonly associated with development. Shellfish health management should include, 1) via site selection for planting, cultivating and harvesting oysters, 2) for selecting sanctuaries and reserves, and 3) to identify potential management regulations and mitigation efforts for coastal development.

Clarke, D., D. Meyer, A. Veisholw and M. LaCroix. 1999. Alabama Oyster Reef Restoration. Virginia Institute of Marine Sciences, pp. 102-106. In Luckenbach, M. W., R. Mann, and J. Wesson (eds.), Oyster Reef Habitat Restoration: A Synopsis and Synthesis of Approaches. Virginia Institute of Marine Science, College of William and Mary, VIMS Press, Williamsburg, VA.

In 1952, Alabama originally contained approximately 2,353 hectares of reefs. By 1971, Alabama had 1,240 hectares of public reefs indicating great loss over time. This paper discusses some techniques used to restore the oyster reef habitats. The Marine Resources Division (MRD) conducted a project involving evaluations made on oyster shell planting. Post planting dredge tows were taken from 1984-1988 to assess spat set success. The results of these tows include 625 shells that were examined with 29% spat; 6510 shells, with 1.6% containing spat; 360 shells, with 19% containing spat; 2619 shells, with 0.4% containing spat; and 1929 shells, with 1.55% containing spat.

There were three basic culture techniques examined. These techniques include: cultchless oysters in horizontal suspended bags; cultchless oysters in bags on racks; and remote set oysters in trays on the bottom. Oysters that were placed in horizontally suspended bags achieved harvestable size within sixteen months. These oysters were then grown in a region of Mobile Bay where oyster production is minimal. Results showed that the cultchless oysters grown on racks averaged 71 mm and remote set oysters on the bottom averaged 82 mm after sixteen months. Despite success with this technique, Alabama is no longer utilizing these techniques.

Coen, L. D., E .L. Wenner, D. M. Knott, B. Stender, N. H. Hadley, M.Y. Bobo, D. L. Richardson, M. A. Thompson and R. E. Giotta. 1997. Intertidal oyster reef habitat assessment and restoration: Evaluating habitat use, development and function. *Journal of Shellfish Research* 16: 262.

Author Abstract. This abstract presents a study conducted in South Carolina 1994 where researchers evaluated the role of intertidal oyster reefs in southeastern estuarine ecosystems. This information was then used to formulate strategies for habitat management and restoration and mitigation methods. The authors experimented in constructing replicate experimental reefs to follow habitat recruitment and succession, using transient and resident species. Two sites were studied, each with three replicate experimental reefs of 23 m^2. Environmental data was collected (DO, salinity, pH, turbidity, intertidal and subtidal temperatures), monitoring of oyster diseases (monthly Dermo and MSX) and other life history parameters (SPF growth, spat set, reproduction) on experimental, and adjacent natural reefs. Results at this time showed more than 34 species of fish and decapod crustaceans that were transient were collected, with densities often exceeding 5,600 individuals/23 m^2 reef. Within seven months (May, 1995), large densities of xanthid crab recruits (<1.5-3 mm cw) were observed on both natural and experimental reefs.

Dame, R. F., E. Koepfler, L. Gregory, T. Prins, D. Allen, D. Bushek, C. Corbett, D. Edwards, B. Kjerfve, A. Lewitus, J. Schubauer-Berigan and S. Thomas. 1998. Testing the role of oyster reefs in the structure and function of tidal creeks with a replicated ecosystem scale experiment: System level variability and response to removal of oysters. *Journal of Shellfish Research* 17:1297.

Author Abstract. Data from an ongoing replicated ecosystem level study that addresses the ecological role of oyster reefs in tidal creeks. The geomorphology and hypsometry were determined for eight similar tidal creek systems in North Inlet Estuary, South Carolina, U.S.A. Oyster biomass, which ranged from 2 to 24 g dry wt. m^{-3} of water, was standardized to 8 g dry weight m^{-3}. Afterward, water quality, phytoplankton and bacterial productivity, oyster growth and recruitment, nekton utilization, total creek metabolism and nutrient cycling were monitored in each creek for one year to determine system variability. After the first year of monitoring was complete (Jan. 1998), oyster reefs were removed from four of the eight creeks in a randomized block design. Monitoring continued so that the before and after reef removal data can be compared among control (no reefs removed) and impact (reefs removed) creeks in completely replicated BACI design. Pre-reef removal data indicated high seasonal variability and significant variability among creeks. Relative differences among creeks were stable - creeks generally maintained the same rankings throughout the year. Analysis of subsequent monitoring viewed changes in the behavior of creek attributes before and after oyster reef removal. The BACI design accounts for such overriding effects, enabling only the impacts of removing oysters to be examined, but also enabling differences in system response to major perturbations when oyster reefs are present or absent to be examined.

Dekshenieks, M. M., E. E. Hofmann, J. M. Klinck and E. N. Powell. 2000. Quantifying the effects of environmental change on an oyster population: A modeling study. *Estuaries* 23:593-610.

Author Abstract. Three models are combined to investigate the effects of changes in environmental conditions on the population structure of the Eastern oyster, *Crassostrea virginica*. The first model, a time-dependent model of the oyster population as described in Powell et al. (1992, 1994, 1995a,b, 1996, 1997) and Hofmann et al. (1992, 1994, 1995), tracks the distribution, development, spawning, and mortality of sessile oyster populations. The second model, a time-dependent larval growth model as described in Dekshenieks et al. (1993), simulates larval growth and mortality. The final model, a finite element hydrodynamic model, simulates the circulation in Galveston Bay, Texas. The coupled post-settlement-larval model (the oyster model) runs within the finite element grid at locations that include known oyster reef habitats. The oyster model was first forced with 5 yr of mean environmental conditions to provide a reference simulation for Galveston Bay. Additional simulations considered the effects of long-term increases and decreases in freshwater inflow and temperature, as well as decreases in food concentration and total seston on Galveston Bay oyster populations. In general, the simulations show that salinity is the primary environmental factor controlling the spatial extent of oyster distribution within the estuary. Results also indicate a need to consider all environmental factors when attempting to predict the response of oyster populations; it is the superposition of a combination of these factors that determines the state of the population. The results from this study allow predictions to be made concerning the effects of environmental change on the status of oyster populations, both within Galveston Bay and within other estuarine systems supporting oyster populations.

Ellis, M. S., J. Song and E. N. Powell. 1993. Status and trends analysis of oyster reef habitat in Galveston Bay, Texas. *Journal of Shellfish Research* 12:154.

Author Abstract. This study was conducted to test a new technique for determining the status and trends of oysters (*Crassostrea virginica*) populations in Galveston Bay, Texas. An acoustic profiler was used to differentiate substrate type, a fathometer to assess bottom relief and a global positioning system to accurately establish position. The acoustic profiler chart interpreted sediment characteristics and reefall according to the amount of return generated. Researchers were able to distinguish oyster reef from mud, sand, and shell hash. The bathymetry, sediment type, and geographic position data were computerized and processed for use by a Geographic Information System (GIS) to produce the maps. Arc/Info software was used to produce maps covering the majority of Galveston Bay, Trinity Bay, East Bay, and West Bay. The reefs were then compared to those in the late '60s and early '70s by the Texas Parks and Wildlife Department. See publication for additional information on techniques used. The amount of oyster reef and oyster bottom recorded in this study was higher than that depicted on the TPWD charts.

Harding, J. M. and R. Mann. 2001. Oyster reefs as fish habitat: Opportunistic use of restored reefs by transient fishes. *Journal of Shellfish Research* 20:951-959.

Author Abstract. Under the Magnuson-Stevenson Fisheries Management Act of 1996, current fisheries management practice is focused on the concept of Essential Fish Habitat (EFH). Application of the EFH concept to estuarine habitats relates directly to ongoing oyster reef restoration efforts. Oyster reef restoration typically creates complex habitat in regions where such habitat is limited or absent. While healthy oyster reefs provide structurally and ecologically complex habitat for many other species from all trophic levels including recreationally and commercially valuable transient finfishes, additional data is required to evaluate oyster reef habitats in the context of essential fish habitat. Patterns of transient fish species richness, abundance, and size-specific habitat use were examined along an estuarine habitat gradient from complex reef habitat through simple sand bottom in the Piankatank River, Virginia. There was no clear delineation of habitat use by transient fishes along this cline of estuarine habitat types (oyster reef to sand bar). Atlantic croaker (*Micropogonias undulatus*), Atlantic menhaden (*Brevoortia tyrannus*), bluefish (*Pomatomus saltatrix*), silver perch (*Bairdiella chrysoura*), spot (*Leiostomus *xanthurus*), spotted seatrout (*Cynoscion regalis*), striped bass (*Morone saxatilis*), and weakfish (*Cynoscion nebulosus*) were found in all habitat types examined. In general, the smallest fish were found on the sand bar, the site with the least habitat heterogeneity. As habitat complexity increased along the gradient from oyster shell bar through oyster reef, transient fish size and abundance increased. Opportunistic habitat use by this suite of generalists relates variations in habitat quality as related to habitat-specific productivity and suggested that oyster reefs may be important but not essential habitat for these fishes.

Harris, C. S. and K. T. Paynter, Jr.. 2001. The effect of local population density on growth and condition in the eastern oyster *Crassostrea virginica,* pp. 279. Aquaculture 2001: Book of Abstracts. World Aquaculture Society, Louisiana State University, Baton Rouge, LA.

Author Abstract. The restoration of oysters and oyster reefs is an important component in the restoration of the Chesapeake Bay estuary. The impact of oyster stocking density on oyster growth, mortality, condition, and parasite prevalence has not been widely studied. In order to maximize the effectiveness of oyster restoration, it is important to determine how stocking density may affect these parameters. In addition, the effect of increased oyster reef habitat on the surrounding benthic community is important to understand. In the fall of 1999, twelve 0.2 acre experimental plots were constructed in the Patuxent River by placing fossilized oyster shell on a former, but now barren, natural oyster bar. The plots were randomly assigned one of four treatments, including zero oysters/m^2, 124 oysters/m^2, 247 oysters/m^2 or 494 oysters/m^2, in a randomized design. Samples were collected by divers using quadrats from each site in November 1999 and May 2000. In May 2000, shell height of high-density oysters (mean 37(± 1.6 SEM) mm) was not significantly different than that of low density oysters (40 ± 1.4 mm). However, low-density oysters had a mean condition index of 13.2(± 0.65) but the mean condition index of the high density oysters was significantly lower at 11.1 (± 0.62). Condition index is a measure of dry tissue weight unit per pallial volume and is often used as an indicator of oyster health. This may suggest that density may play a role in the health of oysters and that oysters in high densities may be stressed by limiting environmental factors such as food or dissolved oxygen. The results of this study will provide further insight on the importance of local population density in oyster restoration projects.

Jordan, S. J., K. Greenhawk and G. F. Smith. 1995. Maryland oyster geographical information system: Management and scientific applications. *Journal of Shellfish Research* 14:269.

Author Abstract. A microcomputer geographical information system (GIS) has been developed to manage and interpret data from Maryland's oyster monitoring and management programs. The GIS was initiated to portray annual monitoring information geographically, but has been expanded to include physical and chemical habitat data, management-related information, and data from special studies. Complete biological and physical information about an individual oyster bar, a region, or the entire Maryland Chesapeake Bay can be retrieved to a user's specification almost instantaneously, and portrayed in a variety of graphical and tabular formats. The system has proved especially useful in supporting the information needs of the state's Oyster Recovery Action Plan. For example, we have provided managers, scientists, and policy-makers with clear, graphical portrayals of oyster habitat, population and disease status, salinity gradients, and management history with a minimum of effort. As new experimental management efforts develop, the GIS maintained a standard, geographically precise database for documenting and tracking their performance. The use of GIS with biological monitoring data greatly simplifies the spatial aspects of analysis, allowing the analyst to focus on temporal variations: the GIS tested hypotheses about historical changes in the aerial extent of oyster physical habitat, spatfall, and diseases. Besides its utility for management and scientific investigations, the GIS proved to be a valuable educational tool for students and tour groups.

Koles, T. and K. T. Paynter. 1999. Oyster restoration in Maryland: Measuring progress and productivity. National Shell Fisheries Association. *Journal of Shellfish Research* 18:330.

Author Abstract. A study conducted in 1997, in cooperation with the Maryland Department of Natural Resources and the Army Corps of Engineers, in which five sites in both the Choptank and Patuxent Rivers, extending from the mouth of each river to approximately eight miles upstream, were identified for restoration. At each site, fossil oyster shells were deposited in a configuration of two 0.5-acre flat areas and one mound approximately three to four meters high. Some of these areas were then planted with hatchery reared spat (1 million/acre; 247/m^2) while the rest were left unplanted. Divers obtained quadrat samples from each of the flats and mounds and YSI 6000 continuous water quality monitors to measure ambient water temperature, salinity, pH, and dissolved oxygen. The samples were analyzed for oyster size, abundance, mortality, fouling community, and parasite (*Perkinsus marinus*) prevalence and intensity. In both rivers, the oysters appeared to be growing dynamically. Parasitic activity was very low with only a few oysters in each river infected with *P. marinus*. Mortality was also low overall and the unplanted mounds in both rivers recruited higher numbers of natural spat set than the unplanted flat areas nearby. Results were used to evaluate the differences in bottom morphology and differing water characteristics (i.e., salinity) on oyster recruitment, growth, mortality, and disease pressures.

Lenihan, H. S., C. H. Peterson, J. E. Byers, J. H. Grabowski, G. W. Thayer and D. R. Colby. 2001. Cascading of habitat degradation: Oyster reefs invaded by refugee fishes escaping stress. *Ecological Applications* 11: 764-782.

Author Abstract. In this study researchers evaluated the structurally complex, species-rich biogenic reefs created by the eastern oyster, *Crassostrea virginica*, in the Neuse River estuary, North Carolina, USA. Researchers first sampled fishes and invertebrates on natural and restored reefs and on sand bottom to compare fish utilization of these different habitats and to characterize the trophic relations among large reef-associated fishes and benthic invertebrates, and secondly, tested whether bottom-water hypoxia and fishery-caused degradation of reef habitat combine to induce mass emigration of fish that then modify community composition in refuges across an estuarine seascape. Experimentally restored oyster reefs of 1 m tall "degraded" or 2 m tall "natural" reefs were constructed at 3 and 6 m depths. Samples were taken of the hydrographic conditions within the estuary over the summer to monitor onset and duration of bottom-water hypoxia/anoxia, resulting from density stratification and anthropogenic eutrophication. Reduction of reef height caused by oyster dredging exposed the reefs located in deep water to hypoxia/anoxia for >2 wk, killing reef-associated invertebrate prey and forcing mobile fishes into refuge habitats. Refugee fishes gathered at high densities on reefs in oxygenated shallow water, where they depleted epibenthic crustacean prey populations. However, physical disturbances can impact remote, undisturbed refuge habitats by movement and abnormal concentration of refugee organisms that have strong trophic impacts. The results show that reserves placed in proximity to disturbed areas may be impacted indirectly but may serve as an important refuge function on a scale comparable to the mobility of consumers.

Luckenbach, M. W., J. Harding, R. Mann, J. Nestlerode, F. O. Beirn and J. A. Wesson. 1999. Oyster reef restoration in Virginia, USA: Rehabilitating habitats and restoring ecological functions. *Journal of Shellfish Research* 18:720-721.

Author Abstract. Repletion efforts in response to declines in abundance of the eastern oyster, *Crassostrea virginica,* have historically relied upon transplanting of oyster seed and planting of a suitable settlement substrate. These efforts have generally failed to revitalize the fishery because they (1) failed to rehabilitate degraded reef habitat and (2) placed little emphasis upon reestablishing a population age structure capable of sustaining a self-supporting reef. More recently restoration efforts in Virginia have focused on reconstructing 3-dimensional reef habitats and establishing brood stock sanctuaries with an emphasis on restoring lost ecological functions of reefs. Manipulative studies of reef placement, construction material and interstitial space have lead to the development of design criteria for maximizing oyster recruitment, growth, and survival on constructed reefs. Further, we have characterized the successional development of resident macrofaunal communities on restored reefs and have begun to relate that development to specific habitat characteristics. Utilization of these restored reef habitats by transient species has been characterized through extensive field collections and underwater video observations; gut analyses of finfish are beginning to elucidate trophic linkages between the reefs and adjacent habitats. In addition, these structures appear important to the early developmental stages of juvenile fishes, some of which have considerable recreational and commercial importance. These studies are helping us to (1) clarify the ecological functions supported by oyster reef habitat, (2) define design criteria for reconstructing reefs, and (3) establish success criteria for such restoration projects. While destructive fishing of oyster reefs appears inconsistent with meeting these goals, an emerging paradigm is that reef sanctuaries can be used to support desired ecological functions as well as supply recruits to adjacent areas which can be managed from a fisheries perspective.

McCollough, C., S. J. Jordan and M. L. Homer. 2000. Chesapeake Bay oysters: Trends in relative abundance and biomass. *Journal of Shellfish Research* 19:623.

Author Abstract. Oyster populations are distributed patchily over more than 400,000 acres in Chesapeake Bay, so it is not feasible to assess their absolute numbers or biomass. Traditionally, landings data, with their inherent inaccuracies and biases, have been the only consistent means of estimating trends. A long term monitoring program in Maryland has recorded relative numbers and size distributions of oysters, along with other population and disease data annually; 43 fixed sites have been monitored consistently since 1990, with many records from these sites available from earlier years. In 1999, we obtained shell height measurements and dry tissue weights from samples of 10 oysters from each site (selected to represent the range of sizes present). By applying the resulting length: weight equation to size-frequency data from earlier surveys, we computed an index of relative biomass that varied from year to year according to the relative abundance and size distribution of the oyster populations. The index is useful for portraying trends and tracking the performance of restoration efforts. It reflects interannual variations in recruitment and growth, as well as mortality caused by the oyster parasites *Haplosporidium nelsoni* and *Perkinsus marinus.*

Meyer, D. L. 1994. Habitat partitioning between the xanthid crabs *Panopeus herbstii* and *Eurypanopeus depressus* on intertidal oyster reefs in southeastern North Carolina. *Estuaries* 17:674-679.

Author Abstract. The abundances of the xanthid crabs *Panopeus herbstii* and *Eurypanopeus depressus* were examined relative to surface oyster shell cover, surface oyster cluster volume, subsurface shell content, substrate sand and silt composition, and oyster reef elevation. During August 1986 through July 1987, xanthid crabs were collected monthly from twelve 0.25 m^2 x 15 cm deep quadrats, during low tide, from intertidal oyster reefs in Mill Creek, Pender County, North Carolina, USA, with respective quadrat details recorded. The abundance of *P. herbstii*, and to a lesser degree of *E. depressus*, was positively correlated with surface shell cover. The abundance of *E. depressus*, and to a lesser degree *P. herbstii*, was positively correlated with surface cluster volume. The majority of *P. herbstii* inhabited the subsurface stratum of the oyster reef, whereas the majority of *E. depressus* inhabited the cluster stratum. Seasonality (i.e., temperature) appeared to influence the strata habitation of both species, with a higher incidence of cluster habitation during warmer months and a lower incidence during colder months. Crab abundance was not related to other factors examined, such as subsurface shell, substrate sand and silt composition, or elevation within the oyster reef. The analyses show that *P. herbstii* and *E. depressus* have partitioned the intertidal oyster reef habitat, with *E. depressus* exploiting surface shell clusters and *P. herbstii* the subsurface stratum. Refer to publication for additional information on methods used.

Meyer, D. L. and E. C. Townsend. 2000. Faunal utilization of created intertidal eastern oyster (*Crassostrea virginica)* reefs in the southeastern United States. *Estuaries* 23: 34-45.

Author Abstract. Oyster cultch was added to the lower intertidal marsh-sandflat fringe of three previously created *Spartina alterniflora* salt marshes. Colonization of these created reefs by oysters and other select taxa were then examined. The created reefs supported numerous oyster reef-associated faunas at equivalent or greater densities than adjacent natural reefs. Eastern oyster (*Crassostrea virginica*) settlement at one site of created reef exceeded that of the adjacent natural reefs within 9 months of reef creation. Within 2 years, harvestable-size *C. virginica* (>75 mm) were present in the created reefs along with large numbers of *C. virginica* clusters. The created reefs also had a higher number of molluscan, fish, and decapod species than the adjacent natural reefs. After 2 yr the densities of *C. virginica*, striped barnacle (*Balanus amphitrite*), scorched mussel (*Brachidontes exustus*), Atlantic ribbed mussel (*Geukensia demissa*), common mud crab (*Panopeus herbstii*), and flat mud crab (*Eurypanopeus depressus*) within the created reefs was equivalent to adjacent natural reefs. Data collected indicate that created oyster reefs can readily acquire functional ecological attributes of their natural counterparts. Based on the results, reef function and physical and ecological linkages of oyster reefs to other habitats (marsh, submerged aquatic vegetation, and bare bottom) should be taken into consideration when reefs are created in order to provide resources that are able to maintain estuarine systems.

O'Beirn, F. X., M. W. Luckenbach, J. A. Nestlerode and G. M. Coates. 2000. Toward design criteria in constructed oyster reefs: Oyster recruitment as a function of substrate type and tidal height. *Journal of Shellfish Research* 19: 387-395.

Author Abstract. Restoration of degraded oyster reef habitat generally begins with the addition of substrate that serves as a reef base and site for oyster spat attachment. Remarkably, little is known about how substrate type and reef morphology affect the development of oyster populations on restored reefs. Three-dimensional, intertidal reefs were constructed near Fisherman's Island, Virginia: two reefs in 1995 using surf clam (*Spisula solidissima*) shell and six reefs in 1996 using surf clam shell, oyster shell, and stabilized coal ash. Researchers monitored oyster recruitment and growth quarterly at three tidal heights (intertidal, mean low water, and subtidal) on each reef type since their construction. Oyster recruitment in 1995 exceeded that observed in the two subsequent years. High initial densities on the 1995 reefs decreased and stabilized at a mean of 418 oyster/m^2. Oyster settlement occurred on all reef types and tidal heights in 1996; however, post-settlement mortality on the surf clam shell and coal ash reefs exceeded that on the oyster shell reefs, which remained relatively constant throughout the year (mean = 935 oysters/m^2). Based on the field observations, predation accounts for most of the observed mortality and that the clam shell and coal ash reefs suffer greater predation. Oyster abundance was consistently higher in the intertidal zone on all reefs for each year studied. Based on patterns observed, researchers concluded that the provision of spatial refugia (both intertidal and interstitial) from predation is important for successful oyster reef restoration in this region. Finally, high levels of recruitment can provide a numerical refuge, whereby the oysters provide structure and increase the probability of an oyster population and reef structure.

Oliver, L. M. and S. A. Fisher. 1995. Comparative form and function of oyster *Crassostrea virginica* hemocytes from Chesapeake Bay, Virginia and Apalachicola Bay, FL. *Diseases of Aquatic Organisms* 22:217-225.

Author Abstract. Oysters *Crassostrea virginica* from Chesapeake Bay, Virginia, and Apalachicola Bay, Florida, USA, were collected in March and October 1992 to investigate possible differences in defense-related hemocyte activities between individuals from geographically separate populations. In March, hemolymph drawn from Chesapeake Bay oysters contained an average of 1.08 x 10^6 hemocytes/m hemolymph, significantly lower than the average 1.63 x 10^6 hemocytes/ml hemolymph obtained from Apalachicola Bay oysters. Hemocyte number did not differ significantly in the October comparison. At both times of year, Chesapeake Bay oyster hemolymph samples contained significantly greater proportions of granular hemocytes compared to Apalachicola Bay hemolymph samples. Hemocyte samples from Chesapeake Bay oysters demonstrated a higher percentage of mobile hemocytes and greater particle binding ability than Apalachicola Bay oyster hemocytes when tested in March, but the reverse was found in the October experiments. Chesapeake Bay oyster hemocytes produced significantly more superoxide anion as measured by nitroblue tetrazolium reduction than did Apalachicola Bay oyster hemocytes in both March and October. Oyster hemolymph levels of the protozoan parasite *Perkinsus marinus* did not differ significantly between the two sites at either time of year. These results demonstrate the importance of background studies to characterize site-specific differences in oyster hemocyte defense-related functions.

Posey, M. H., T. D. Alphin, C. M. Powell and E. Townsend. 1995. Use of oyster reefs as habitat for epibenthic fish and decapods, pp. 229- 237. In Luckenbach, M. W., R. Mann, and J. Wesson (eds.), Oyster Reef Habitat Restoration: A Synopsis and Synthesis of Approaches. Virginia Institute of Marine Science, College of William and Mary, VIMS Press, Williamsburg, VA.

Researchers examined the use of intertidal oyster beds by epibenthic decapods and fish in southeastern North Carolina. Sampling of mobile epifauna at low tide was performed using quadrats; and fish and mobile decapods at high tide were sampled using sweep nets. Estimates were made of large fish and decapods that may be able to avoid being caught in sweep nets when the beds were submerged by diver observations. Laboratory mesocosm studies examined the potential use of oyster patches by the grass shrimp, *Palaemonetes pugio* when predators are present. See publication for additional information on methods used. Results showed that fish and decapods were abundant over oyster beds compared to adjacent sandflat areas and were used more by grass shrimp, pinfish, and blue crabs. Laboratory studies indicated significant use of oyster patches by grass shrimp when threatened by predatory fish compared to treatments with no fish or a non-predatory fish. Overall oyster habitats are important for epibenthic decapods and fish. Therefore oyster reef management is required to sustain fisheries around the reefs as well as provide protection for reefs that provide habitats for other species.

Saoud, I. G., D. B. Rouse, R. K. Wallace, J. E. Supan and S. Rikard. 2000. An *in situ* study on the survival and growth of *Crassostrea virginica* juveniles in Bon Secour Bay, Alabama. *Journal of Shellfish Research* 19: 809-814.

Author Abstract. For this study experimental plots were established at a relic oyster reef on the eastern side of Mobile Bay, Alabama between July 1998 and November 1999 to determine whether elevated beds might improve oyster survival and growth. Oysters *(Crassostrea virginica)* were spawned in a hatchery and the spat were allowed to settle on small oyster shell fragments and on whole oyster shell. Two-month-old juveniles (15-18 mm) were deployed in polyethylene oyster bags on bottom and on underwater shell pads 20 cm and 40 cm above bottom. Oysters on whole shells were deployed outside bags in order to evaluate predation. Remote sensing data loggers were used to measure temperature, salinity, and oxygen concentration. Growth (increase in height), survival, and condition of oysters in bags at the three experimental depths were compared. Temperature and salinity varied between 11.8º C - 32.8º C and 4.4 ppt - 29.7 ppt, respectively. The results showed that oysters at the three experimental levels grew to approximately 55 mm during the first year. Total mortality was observed at all three levels during the second summer when oxygen levels dropped to 0 mg L^{-1} for five consecutive days while water temperature was 28º C.

Southworth, M. and R. Mann. 1998. Oyster reef broodstock enhancement as a mechanism for rapid oyster reef replenishment. *Journal of Shellfish Research*. 17:1101-1114.

Author Abstract. Natural oyster populations in the Chesapeake Bay have become severely depleted due to a combination of overfishing and disease. Replenishment programs in the form of artificial reefs are currently in effect throughout most of the Virginia portion of the Chesapeake Bay. Shell Bar reef, built in the Great Wicomico River, Virginia in 1996 was supplemented with reproductively active broodstock oysters from Tangier and Pocomoke Sounds. The Great Wicomico River was historically a high seed producing river, but production has decreased in recent years. Oyster larval concentrations (plankton tows), gonad development, and circulation data were collected in the river throughout the 1997 reproductive season. The broodstock oysters spawned from mid-June through mid-August, with a peak occurring from mid-June through mid-July. Larval concentrations were several orders of magnitude higher than the highest reported in the literature over the past 25 years.

Larvae were significantly more abundant on the flood tidal stage, suggesting some vertical migration with the changing tide, thus aiding in their retention in the system. Settlement of larvae on shellstrings and on bottom substrate, was higher than in recent years. The most abundant settlement occurred near the reef and upriver of the reef. Circulation patterns observed are favorable for local retention of larvae in the system. Reef building, and subsequent transplants of broodstock onto these reefs, can be an effective management option provided the circulation patterns of the system are similar to the Great Wicomico.

University of Maryland Center for Environmental Sciences. Restoration Design for Oyster Beds. Sandy Point Integrated Ecosystem Restoration Project, Chesapeake Bay Biological Laboratory, Solomon, MD.

This paper discusses a restoration design for oyster beds. The restoration methods include planting about five acres of submerged aquatic vegetation (SAV) at two locations and constructing about three acres of oyster bars in an L-shape protecting the SAV. The oyster bars were created at various depths and densities to collect information on relative effectiveness of intensive vs. extensive oyster bed construction. Three high-density oyster mounds were positioned at tactical points along the bar. The oyster mounds were used to enhance oyster reef ability to reduce waves; provide added protection to SAV beds; and provide information concerning oyster density and distribution along the bottom and in the water column and how it influences their performance.

Oyster setting tanks were used to acquire oyster larvae from off-site before being relocated to a protected shallow-water oyster nursery. The spat was kept at that position and allowed to solidify for numerous days/weeks before being transported for final seeding. The survival and growth of the oysters, adjacent and nearby SAV beds, and the abundance, diversity, and distribution of small and large fish and foraging birds were monitored.

Virginia Institute of Marine Sciences (VIMS). 1994. Monitoring Programs for Oyster Beds. Virginia Institute of Marine Science, Gloucester Point, VA. Contact information: Dr. Roger Mann, Department of Fisheries Science, Virginia Institute of Marine Science. http://www.vims.edu/mollusc/monrestoration/monoyster.htm#modern

Data are collected by the VIMS Spatfall Survey and the VIMS Dredge Survey on oyster bed health in Virginia waters. The VIMS Spatfall Survey organized shell strings weekly from May to September at stations within the Chesapeake Bay to provide an annual index of oyster settlement and recruitment. Shell strings were suspended 0.5 m from the bottom to provide settlement substrate for oyster veligers. After retrieval, oyster spat (recently settled oysters) on the undersides of ten shells were counted under a dissecting microscope. The average number of spat per shell was calculated for each time and place.

The VIMS Dredge Survey monitored the status of Virginia's public oyster fishery, encompasses more than 243,000 acres. Oyster bars were sampled throughout the state annually to assess trends in oyster growth, mortality, and recruitment using a dredge. At each location three samples of bottom material were dredged. Half-bushel aliquots (25 quarts) were taken from each sample for processing. Researchers then counted the number of spat, small, and market oysters. Averages of counts per bushel of bottom material were calculated so that comparisons can be made between areas and years in which study was conducted. The Patent Tong survey was then initiated in 1993 to provide more quantitative estimates of oyster standing stock in Virginia tributaries. At each station, a patent tong was used to sample one square meter of bottom. Oysters from each sample were examined. Researchers stated that the surveys used to assist in monitoring oyster health was efficient in providing data that support management and restoration of Virginia's oyster resource.

APPENDIX II: OYSTER REEFS
REVIEW OF TECHNICAL METHODS MANUALS

This Review of Technical Methods Manuals includes a variety of sampling manuals, Quality Assurance/Quality Control (QA/QC) documents, standardized protocols, or other technical resources that may provide practitioners with the level of detail needed when developing a monitoring plan for a coastal restoration project. Examples from both peer reviewed and grey literature are presented. Entries were selected through extensive literature and Internet searches as well as input from reviewers. As with the Annotated Bibliographies, these entries are not, however, a complete list. Entries are arranged alphabetically by author. Wherever possible, web addresses or other contact information is included in the reference to assist readers in easily obtaining the original resource. Summaries preceded by the terms '*Author Abstract'* or *'Publisher Introduction*' or similar descriptors were taken directly from their original source. Summaries without such descriptors were written by the authors of the associated chapters.

Campbell, G. and S. Wildberger. 1992. The Monitor's Handbook. Lamotte Company ENC-016429. P. O. Box 329, Chestertown MD 21620. Contact information: Phone # (410) 778-3100, (800) 344-3100 or Fax # (410) 778-6394. Reference No.1507.

Author Abstract. This handbook provides the background and testing procedures for individuals who want to learn more about their local waterways or are involved in a water monitoring program. Aquatic ecosystems, such as streams, rivers, and lakes, are explained and a pre-monitoring sequence of activities is discussed. The handbook outlines sampling techniques and the equipment involved. Information for each of the water quality factors covered in the book (such as hardness, pH, and coliform bacteria levels) include: how to measure the factors, what the significant levels are, and what the measured levels indicate. Tips are provided for assuring the test results' accuracy for each test method. Quality assurance practices that contain calibration procedures and audits are suggested. Readers can find discussions of data analysis and presentation methods. A glossary, bibliography, and conversion table is included in the document. Appendices provide an overview of management concerns for a volunteer water monitoring program and lists of additional resources. Black and white photographs and drawings are found throughout the book.

Davies, J., J. Baxter, M. Bradley, D. Connor, J. Khan, E. Murray, W. Sanderson, C. Turnbull and M. Vincent. 2001. Marine Monitoring Handbook. UK Marine Science Project, and Scottish Association of Marine Science. Joint Nature conservation Committee, English Nature, Scottish Natural Heritage, Environment and Heritage Services. http://www.jncc.gov.uk/marine/mmh/Introduction.pdf.

The UK Marine Science Project developed this hand book to provide guidelines for recording, monitoring, and reporting characteristics and conditions of marine habitats. However based on location and other environmental conditions methodologies will have to be modified to suit the structural characteristics of the habitat. This manual addresses the fundamentals and procedures for monitoring different parameters in marine habitats, management tools, and benefits and costs for developing a monitoring project. Topics presented in this document include establishing marine monitoring programs highlighting what needs to be measured and methods to use; provides guidance when developing a monitoring program; selecting proper monitoring techniques to attain precision and accuracy; and procedural guidelines for monitoring a specific marine habitat. Detailed information on the tools needed for monitoring marine habitats are described within the marine monitoring handbook.

Halse, S. A., D. J. Cale, E. J. Jasinska and R. J. Shiel. 2002. Monitoring change in aquatic invertebrate biodiversity: Sample size, faunal elements and analytical methods. *Aquatic Ecology* 36:395-410.

Author Abstract. Replication is usually regarded as an integral part of biological sampling, yet the cost of extensive within-wetland replication prohibits its use in broad-scale monitoring of trends in aquatic invertebrate biodiversity. In this paper, we report results of testing an alternative protocol, whereby only two samples are collected from a wetland per monitoring event and then analyzed using ordination to detect any changes in invertebrate biodiversity over time. Simulated data suggested ordination of combined data from the two samples would detect 20% species turnover and be a cost-effective method of monitoring changes in biodiversity, whereas power analyses showed about 10 samples were required to detect 20% change in species richness using ANOVA. Errors will be higher if years with extreme climatic events (e.g., drought), which often have dramatic short-term effects on invertebrate communities, are included in analyses. We also suggest that protocols for monitoring aquatic invertebrate biodiversity should include microinvertebrates. Almost half the species collected from the wetlands in this study were microinvertebrates and their biodiversity was poorly predicted by macroinvertebrate data.

McCobb, T. D. and P. K. Wieskel. 2003. Long-Term Hydrologic Monitoring Protocol for Coastal Ecosystems. United States Geological Survey Open-File Report 02-497. 94 pp. http://water.usgs.gov/pubs/of/2002/ofr02497/

The United States Geological Survey (USGS) and the National Park Service have designed and tested monitoring protocols implemented at Cape Cod National Seashore. The monitoring protocols are divided into two parts. Part one of the protocol discusses the objectives of the monitoring protocol and presents rationale for the recommended sampling program. The second part describes the field, data-analysis, and data-management, and variables that are to be taken into consideration when monitoring (e.g., sea level rise, climate change and urbanization). This protocol provides consistency when monitoring changes in ground-water levels, pond levels, and stream discharge. The monitoring protocol not only establishes a hydrologic sampling network but provides reasoning for measurement methods selected and spatial and temporal sampling frequency. Data collected during the first year of monitoring and hydrologic analyses for selected sites are presented. Long-term hydrologic monitoring procedures performed at the Cape Cod National Seashore may also assist set a template for deciphering findings of other monitoring programs.

Michener, W. K., J. W. Brunt and W. H. Jefferson. 1995. New techniques for monitoring American oyster (*Crassostrea virginica*) recruitment in the intertidal zone, pp. 267-273. In Aiken, D. E., S. L. Waddy, and G. L. Conan, (eds.), Shellfish Life Histories and Shellfishery Models. Selected Papers from a Symposium Held in Moncton, New Brunswick, 25-29 June 1990, ICES, Copenhagen (Denmark). ICES Marine Science Symposia 199. ICES, Copenhagen, Denmark.

Author Abstract. Changes in oyster reef size, organism density, and community organization can occur randomly or in relation to controlling biotic and abiotic factors. Non-random spatial discontinuities may be interpreted as ecologically important edges and could provide important insights into habitat quality, settlement, recruitment, competition, predation, and other ecological processes. In this study, vertical settlement tubes were deployed along an estuarine transect to document variable invertebrate recruitment to intertidal oyster reef communities. A Squared Euclidean Distance algorithm with a moving window filter was utilized to identify discontinuities in community recruitment. The sampling and analytical approaches provided useful insights into recruitment patterns which could be related to intra-estuarine physical and chemical variability. These and related techniques can likely be used to address regional and estuary-wide shellfisheries-related problems.

Oregon Watershed Enhancement Board. 1999. Oregon Aquatic Habitat: Restoration and Enhancement Guide. Contact information: 775 Summer street, suite 360, Salem Oregon, 97301, Phone # (503) 986-0178. http://www.oweb.state.or.us/publications/habguide99.shtml

This guide was developed to provide guidance on restoration and enhancement measures that would assist in aquatic ecosystem recovery. The guide is divided into five sections: An overview of Restoration activities, activity guidelines, overview of agency regulatory functions and sources of assistance, grants and assistance, and monitoring and reporting. The purpose of this document is to provide information that will assist in developing effective restoration projects; to define standards and priorities that will be approve by state and receive funding or authorized restoration projects; to identify state and federal regulatory requirements and receive assistance in restoration projects. Additional information on monitoring techniques for salmonid restoration and guidelines and considerations for reporting restoration progress over time are described within the document.

Paynter, K. T. Jr. 2001. Oyster restoration in Maryland: Results from Choptank and Patuxent River experiments, p. 519. Aquaculture 2001: Book of Abstracts, World Aquaculture Society, 143 J.M Parker Coliseum Louisiana State University, Baton Rouge, LA.

Author Abstract. In 1997, this study was conducted in which oysters were planted in the Choptank and Patuxent rivers in Maryland as the initiation of a large scale oyster restoration effort undertaken by the Army Corps of Engineers and the Maryland Department of Natural Resources. Three plots of approximately 1/2 acre in area were prepared by placing fossil shell on the bottom. Two of the three plots were created as flat, rectangular shells beds while the third was constructed as a large mound approximately 10 m in diameter and about 2 m high. Five sites of three plots each were constructed in each river sited from the mouth upstream to the low salinity. In the Choptank, seed was produced from Louisiana brood-stock and in the Patuxent, seed was produced from larvae purchased from Oregon. In 1998, *Perkinsus marinus* prevalence was low throughout the Maryland portion of Chesapeake Bay. In the Patuxent, oyster growth was poor and mortalities were very high due to parasitic activity. However, in the Choptank most stocks planted from the hatchery remained uninfected while natural transplants and local populations acquired significant levels of the disease. Growth and condition index remained vigorous in the planted oysters while the health of natural local populations declined. Researchers concluded that these experiments provide evidence that disease levels may be managed in lower salinity regions like in the central and northern parts of the Maryland's portion of the Chesapeake Bay.

Raposa, K. B. and C. T. Roman. 2001. Monitoring nekton in shallow estuarine habitats. A Protocol for the Long Term Monitoring Program at Cape Cod National Seashore. 39 pp. Narragansett Bay National Estuarine Research Reserve Prudence Island, RI and National Park Service, Graduate School of Oceanography, University of Rhode Island, Narragansett, RI 02882. 39 pp. Contact information: Kenny@gso.uri.edu. http://www.nature.nps.gov/im/monitor/protocoldb.cfm

Author Abstract. Long term monitoring of estuarine nekton has many practical and ecological benefits but efforts are hampered by a lack of standardized sampling procedures. This study develops a protocol for monitoring nekton in shallow (<1m) estuarine habitats for use in the Long Term Coastal Monitoring Program at Cape Cod National Seashore. Sampling in seagrass and salt marsh habitats is emphasized due to the susceptibility of each habitat to anthropogenic stress and to the abundant and rich nekton assemblages that each habitat supports. Extensive sampling with quantitative enclosure traps that estimate nekton density is suggested. These gears have a high capture efficiency in most habitats and are small enough (typically $1m^2$) to permit sampling in specific microhabitats. Other aspects of nekton monitoring are discussed, including seasonal sampling considerations, sample allocation, station selection, sample size estimation, parameter selection, and associated environmental data sampling. Developing and initiating long term nekton monitoring programs will help track natural and human-induced changes in estuarine nekton over time and advance our understanding of the interactions between nekton and the dynamic estuarine environments.

Soniat, T. M., E. N. Powell, E. E. Hofmann and J .M. Klinck. 1998. Understanding the success and failure of oyster populations: The importance of sampled variables and sample timing. *Journal of Shellfish Research* 17: 1149-1165.

Author Abstract. One of the primary obstacles to understanding why some oyster populations are successful and others are not is the complex interaction of environmental variables with oyster physiology and with such population variables as the rates of recruitment and juvenile mortality. A numerical model is useful in investigating how population structure originates out of this complexity. We have monitored a suite of environmental conditions over an environmental gradient to document the importance of short time-scale variations in such variables as food supply, turbidity, and salinity. Then, using a coupled oyster disease population dynamics model, we examine the need for short time-scale monitoring. We evaluate the usefulness of several measures of food supply by comparing field observations and model simulations. Finally, we evaluate the ability of a model to reproduce field observations that derive from a complex interplay of environmental variables and address the problem of the time-history of populations. Our results stress the need to evaluate the complex interactions of environmental variables with a numerical model and, conversely, the need to evaluate the success of modeling against field observations of the results of complex processes. Model simulations of oyster populations only approached field observations when the environmental variables were measured weekly, rather than monthly. Oyster food supply was estimated from measures of total particulate organic matter, phytoplankton biomass estimated from chlorophyll a, and total labile organic matter estimated from a regression between chlorophyll a and total labile carbohydrate, lipid, and protein. Only the third measure provided simulations comparable to field observations. Model simulations also only approached field observations when a multiyear time series was used. The simulations show that the most recent year exerts the strongest influence on oyster population attributes, but that the longer time-history modulates the effect. The results emphasize that year-to-year changes in environment contribute substantially to observed population attributes and that multiyear environmental time series are important in describing the time-history of relatively long- lived species.

Trippel, E. A. 2001. Marine Biodiversity Monitoring: Protocol for Monitoring of Fish Communities. A Report by the Marine Biodiversity Monitoring Committee (Atlantic Maritime Ecological Science Cooperative, Huntsman Marine Science Centre) to the Ecological Monitoring and Assessment Network of Environment Canada. http://www.eman-rese.ca/eman/ecotools/protocols/marine/fishes/intro.html#Rationale

This document presents a monitoring protocol for estimating species diversity of bottom dwelling or demersal fish species inhabiting the Canadian continental shelf regions. Monitoring protocols presented in this document can be used to monitor and evaluate fish communities in regions other than the Canadian continental shelf. Methods used to estimate the abundance of different demersal fish species include random stratified sampling and fixed station sampling. Using these standardized procedures helps to maintain precision. Some factors taken into consideration when monitoring fish communities include depth, temperature, salinity, seasonal shifts and diurnal behavior patterns. Additional information found in this document includes size of area and sampling intensity, sampling gear, sampling procedures, and treatment of data.

U.S. EPA. 1992. Monitoring Guidance for the National Estuary Program. United States Environmental Protection Agency, Office of Water, Office of Wetlands, Washington D.C. EPA Report 842-B-92-004.

This document provides guidance on the design, implementation, and evaluation of the required monitoring programs. It also identifies steps to be taken when developing and implementing estuarine monitoring programs and provides technical basis for discussions on the development of monitoring program objectives, the selection of monitoring program components, and the allocation of sampling effort.

Some of the criteria listed for developing a monitoring program and described in this document include: monitoring program objectives, performance criteria, establish testable hypotheses, selection of statistical methods, alternative sampling designs, use of existing monitoring programs, and evaluate monitoring program performance. Additional information on guidelines for developing a monitoring program is described in this document.

U.S. EPA. 1993. Volunteer Estuary Monitoring. In R. L. Ohrel, Jr., and K. M. Register (eds.), A Methods Manual. U.S. Environmental Protection Agency, Washington, D.C., Office of Water. EPA Report- 842-B-93-004. http://www.epa.gov/owow/estuaries/monitor/

This document presents information and methodologies specific to estuarine water quality. Information presented in the first eight chapters include: understanding estuaries and what makes them unique; impacts to estuarine habitats and human's role in solving the problems; guidance on how to establish and maintain a volunteer monitoring program; guidance for working with volunteers and ensuring that they are well-positioned to collect water quality data safely and effectively; ensuring that the program consistently produces high quality data; and managing the data and making it readily available to data users. Also presented are water quality measures that determine the condition of the estuary: physical (e.g., substrate texture), chemical (e.g., dissolved oxygen) and biological parameters (e.g., plant and animal presence and abundance). The importance of each parameter and methods used to monitor the conditions are described in a gradual process. Proper quality assurance and quality control techniques must also be described in detail to ensure that the data are beneficial to state agencies and other data users.

University of Florida IFAS-Indian River Research and Education Center and South Florida Water Management District. Restoration of the Eastern Oyster, *Crassostrea virginica*, in the St. Lucie Estuary, Contact information: Liberta Scotto, lscotto@gnv.ifas.ufl.edu. http://www.irrec.ifas.ufl.edu/oyster/oysterstory.htm

Two oyster reefs from each of the North and South Forks and the Mid-Estuary of the St. Lucie Estuary (SLE) were monitored to assess their condition. Methods used include: (1) recruitment with various types of "spat" (newly settled oysters) collectors that were placed in the water at oyster reefs sites selected. The collectors were then replaced during the study year and evaluated for spat presence; (2) use of condition index which assessed the oysters physiological condition or overall health; (3) water quality measurements such as temperature, pH, dissolved oxygen, and salinity which were done weekly at replicate sites at each of the oyster reefs in order to relate oyster health to water quality; (4) reproductive potential in which oysters from the Mid-Estuary and the North Fork were collected monthly to evaluate the gonadal state and reproductive potential at different salinity regimes. Histological and image analysis was used to estimate reproductive potential; and (5) *Perkinsus marinus* presence, a protozoan parasite was assessed. Oysters were collected monthly and rated on a Mackin scale for Dermo infection which ranged from 0 (no infection) to 6 (heavy infection). Parameters used in this study to assess oyster health proved effective and contributed to successful restoration of oyster communities by approximately 45%. Additional information on this study can be obtained from the source mentioned above.

Virginia Institute of Marine Sciences (VIMS). 1994. Monitoring Programs for Oyster Beds. Virginia Institute of Marine Science, Gloucester Point, VA. Contact information: Dr. Roger Mann, Dept. of Fisheries Science, Virginia Institute of Marine Science, Virginia U.S.A. http://www.vims.edu/mollusc/monrestoration/monoyster.htm#modern

Data was collected by the VIMS Spatfall Survey and the VIMS Dredge Survey oyster bed health in Virginia waters. The VIMS Spatfall Survey deployed shell strings weekly from May through September at stations throughout the Chesapeake Bay to provide an annual index of oyster settlement and recruitment. Shell strings were suspended 0.5 m from the bottom to provide settlement substrate for oyster veligers. After retrieval, oyster spat (recently settled oysters) on the undersides of 10 shells were counted under a dissecting microscope. The average number of spat per shell was calculated for each time and place.

The VIMS Dredge Survey monitored the status of Virginia's public oyster fishery, comprising over 243,000 acres. Oyster bars were sampled annually and dredge was used to assess trends in oyster growth, mortality, and recruitment. Three samples of bottom material were dredged at each location. Half-bushel aliquots (25 quarts) were taken from each sample for processing. The number of spat, small, and market oysters were counted. Averages counts per bushel of bottom material were calculated for comparisons between areas over periods of time. Patent Tong survey was performed in 1993 to provide quantitative estimates of oyster standing stock in Virginia tributaries. At each station patent tong samples were taken of one square meter of bottom. All of the oysters from each sample were examined. The surveys provided data that support management and restoration of Virginia's oyster resource.

Wenner, E. L. and M. Geist. 2001. The National Estuarine Research Reserves Program to Monitor and Preserve Estuarine Waters. *Coastal Management* 29:1-17.

The National Estuarine Research Reserve (NERR) sites in 1992 coordinated a program that would attempt to identify and track short-term variability and long-term changes in representative estuarine ecosystems and coastal watersheds. Water quality parameters that were monitored include: pH, conductivity, temperature, dissolved oxygen, turbidity, and water level. Standardized protocols were also used at each site so that sampling, processing, and data management techniques were consistent among sites. Statistical techniques are being used to identify periodicity in water quality variables. Periodic regression analysis indicated that diel periodicity in dissolved oxygen is a larger source of variation than tidal periodicity at sites with less tidal amplitude. Authors of this document stress how understanding the functions of estuaries and how they change over time will help predict how these systems respond to change in climate and anthropogenic sources.

Wenner, E., H. R. Beatty and L. Coen. 1996. A method for quantitatively sampling nekton on intertidal oyster reefs. *Journal of Shellfish Research* 15: 769-775.

Author Abstract. We developed a sampling methodology using a 24 m^{-2} super(2) lift net to quantitatively sample intertidal oyster (*Crassostrea virginica*) reefs as a part of a long-term study of their functional ecology. This method can also be used in restoration monitoring of oyster reefs to evaluate reef functionality. The method involved surrounding an area of oyster reef with a buried net at low tide, allowing the water level to rise, raising the net at high tide to trap motile organisms, allowing the water to recede, and collecting the entrapped nekton. Natural and artificially constructed reefs were sampled, monitored and efficiency (mark-recapture) studies were performed to evaluate the method. The advantages of this method are: (1) the habitat in the area to be sampled receives minimal damage; (2) the size and shape of the net system are flexible and can be adapted to fit a variety of habitats; (3) no permanent structures, other than a shallow perimeter trench, are present to act as attractants; and (4) it is relatively inexpensive to purchase and maintain gear. One disadvantage to the method is that it is very labor intensive, typically using three to five people. This method proved more efficient on natural reefs than artificial reefs, and the return rate was slightly better for *Fundulus heteroclitus* than for *Palaemonetes spp.* Seventeen decapod and 24 fish taxa were collected from initial spring, summer, and fall 1995 sampling.

APPENDIX III: LIST OF OYSTER REEF EXPERTS

The experts listed below have provided their contact information so practitioners may contact them with questions pertaining to the restoration or restoration monitoring of this habitat. Contact information is up-to-date as of the printing of this volume. The list below includes only those experts who were 1) contacted by the authors and 2) agreed to submit their contact information. Some of those listed also reviewed the associated habitat chapter. In addition to these resources, practitioners are encouraged to seek out the advice of local experts as well faculty members and researchers at colleges and universities. Engineering, planning, and landscape architecture firms also have experts on staff or contract out the services of botanists, biologists, ecologists, and other experts whose skills are needed in restoration monitoring. These people are in the business of providing assistance in restoration and restoration monitoring and are often extremely knowledgeable in local habitats and how to implement projects on the ground. Finally local, state, and Federal environmental agencies also house many experts who monitor and manage coastal habitats. In addition to the National Oceanic and Atmospheric Administration (NOAA), the Environmental Protection Agency (EPA), the Army Corps of Engineers (ACE), Fish and Wildlife Service (FWS), and the United States Geologic Survey (USGS) are important Federal agencies to contact for assistance in designing restoration and monitoring projects as well as potential sources of funding and permits to conduct work in coastal waterways.

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CHAPTER 5: RESTORATION MONITORING OF KELP AND OTHER MACROALGAE

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Russell Bellmer, United States Fish and Wildlife Service[2]
Katrin Iken, University of Alaska Fairbanks[3]

INTRODUCTION

Marine macroalgae are multicellular photosynthetic organisms (kingdom: Protista) that are generally located in shallow subtidal (usually less than 50 meters water depth) and low intertidal zones of the oceans. They are found attached to hard substrates (Foster and Schiel 1992) and consolidated sediments (hardened sand). Macroalgae range from a few millimeters to several tens of meters in size. Their presence builds a three-dimensional habitat that often supports numerous animal assemblages. There are three categories of macroalgae:

Red (Phylum Rhodophyta)
Green (Phylum Chlorophyta), and
Brown (Phylum Phaeophyta)

Macroalgae are categorized according to different pigments that they use to convert sunlight into energy through photosynthesis. Although the different groups often display the color for which they are named, this can be misleading. All algal types contain at least one type of the green pigment chlorophyll. In addition, red algae contain red and blue pigments called phycobilins, some of which absorb blue light. Since blue light penetrates water to a greater depth than light with longer wavelengths, these pigments allow red algae to photosynthesize and live at greater depths (Woelkerling 1990; Druehl 2000). Green algae contain two types of chlorophyll pigments that give them their green color and allow them to photosynthesize and absorb red light (Druehl 2000). Most green algae are restricted to shallow waters because the red light that they can absorb does not penetrate deep into the water column. Brown algae contain the brown pigment fucoxanthin that reflects yellow light as well as orange pigments called carotenoids (Druehl 2000).

Within the brown algae category, kelp (order: Laminariales) and other species of the orders Dictyotales, Desmarestiales, and Fucales are particularly important as habitat builders and indicator species. Kelp plants in particular can be extremely large and have astonishing growth rates with up to 50 centimeters per day (Wheeler and Druehl 1986). Kelp can be annual (live only one summer) or perennial (live for several years). Some of the largest kelp species (e.g., *Nereocystis luetkeana*) are annual species that reach their full size within only one summer. Kelp is restricted to cold temperatures, occuring in the middle latitudes of both the northern and southern hemispheres - off the West coast of North America from Alaska to Baja California, the Northeast coast of North America, and off the coasts of South America, South Africa, and Southern Australia (Figure 1).

Only benthic brown marine macroalgae (phylum: Phaeophyta, class: Phaeophyceae), particularly kelp species, are discussed in this chapter because most restoration work pertaining to macroalgae is performed in kelp communities. Kelp plant species discussed in this chapter are those found along the West and Northeast coasts of the United States that have potential for successful laboratory culture, transplanting, and reforestation.

Kelp forests are among the most complex, diverse, and productive marine habitats found on the planet. They vary in size from a few to

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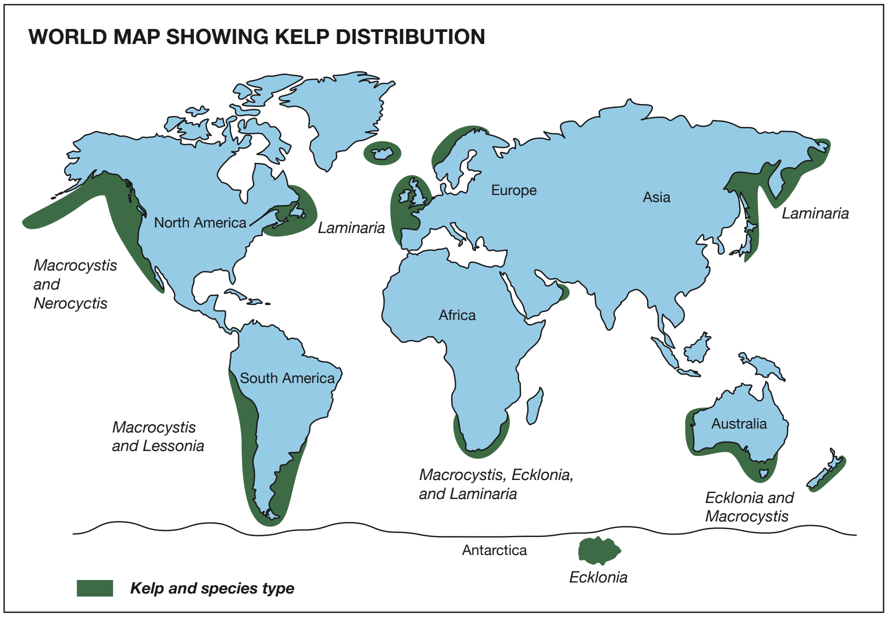

Figure 1. Worldwide distribution of kelp forests. Map courtesy of Raffaelli and Hawkins, (1996), Intertidal Ecology, Chapman and Hall, London, 356 pp.

many plants, and from several square meters to several thousand square kilometers in size. Kelp habitats are often comprised of multiple vegetation layers. The canopy is formed by extremely large kelp species, reaching up to 30 meters from the bottom to the water surface. These canopy-forming species possess gas-filled floating structures which raise the algae to the surface. The understory kelp species form a bed that only reaches several meters above the bottom. Beneath the understory, many other algal species build a turf layer. These layers support hundreds of species of fishes and thousands of invertebrate species.

The dominant kelp species along the U.S. coasts belong to the genera *Macrocystis* (giant kelp) (Figure 2), *Nereocystis* (bull kelp), and *Laminaria* (forest kelp). In areas along the temperate U.S. West coast, *Macrocystis pyrifera* and *Nereocystis luetkeana* are the dominating canopy-forming kelp species, while *N. luetkeana* and *Alaria fistulosa* (winged kelp) dominate in Alaska (Druehl 1978). The extensive kelp forests in Southern California are dominated by the single canopy-forming species, *Macrocystis pyrifera*, which ranges from the low intertidal zone to more than 60 meters deep and found from Sitka, Alaska to San Hipolito Point, Baja California (Abbott and Hollenberg 1976; North 1971). A dense understory can be created by smaller kelp such as *Laminaria*, *Agarum*, *Eisenia,* and *Pterygophora*. Along the U.S. North Atlantic coast, kelp forests are formed by smaller non-canopy species with dominant species being *Laminaria* spp., *Alaria* spp. (winged kelp), and *Agarum* spp. (colander weed). These kelp forests grow from the subtidal fringe to depths of 50 meters and are found from Long Island Sound to beyond Newfoundland.

Figure 2. Giant kelp (*Macrocystis pyrifera)* showing fronds. Photo courtesy of Russell Bellmer, United States Fish and Wildlife Service.

Alaria spp. tend to occupy the low intertidal range, *Laminaria* spp. are often found in the intermediate depths, and *Agarum* spp. occupy the deeper areas. These species and other species of kelp forest understory exhibits inconsistent zonation. Complex interactions driving the structure and zonation of kelp beds include competition for light. *Alaria esculenta* (dabberlocks) for example, grows where *Laminaria* spp. do not overshadow it. Shading by large kelp may also prevent the growth of small juveniles. The abrasive whiplash effect of large kelp blades created by water movement can also prevent the establishment of new kelp recruits. New kelp recruits establish during late winter and early spring when the kelp forests are less dense because the annual species die back. During that time, light penetrates to the bottom.

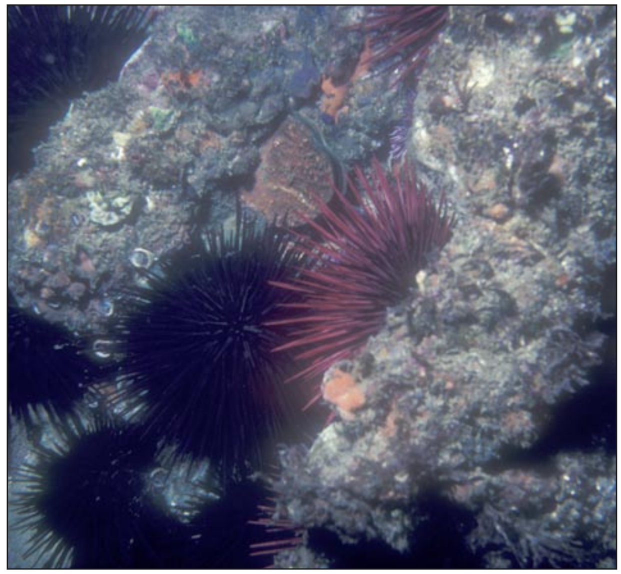

Figure 3. Sea urchins sit attached to rocky substrates. Photo courtesy of Russell Bellmer, United States Fish and Wildlife Service.

Growth of kelp is triggered by the interaction of light and nutrient availability, both of which are needed to support the high growth rates in kelp. While light is abundant in summer, nutrients are often depleted due to thermal stratification and phytoplankton production. In contrast, nutrients usually accumulate during the winter. This results in late winter and early spring as the main growing season for kelp because both light and nutrients are available. Plant growth can become nutrient limited in summer and fall, except where nutrients are continually replenished by tidal mixing. In Southern California Bight, nutrient levels are low in the summer and fall, especially above the thermocline, resulting in reduced *Macrocystis* growth and deterioration of the giant kelp canopies.

Kelp and other macroalgal communities play important ecological and economic roles. Ecologically, they provide shelter, breeding, feeding, and nursery grounds as well as recruitment areas for various marine organisms such as adult and juvenile fish and economically important crustaceans (e.g., lobsters and crabs). Kelp forests also help to reduce wave energy and currents, allowing sediment to settle to the bottom and improving water quality and clarity. These habitats are particularly important as a food source for many grazers including gastropods and sea urchins, and even deteriorating kelp provides detritus for numerous detritivores. Sea urchins (e.g., *Strongylocentrotus* spp.) (Figure 3) are common kelp grazers, and, in areas where urchin abundance is not controlled by predation, large urchin populations can completely eliminate kelp forests (Estes and Duggins 1995). These de-forested areas are called urchin barrens.

In Maine, sea urchin harvesting is an important industry with over 12,000 metric tons landed in 1992 (Johnson and Mann 1993). Sustainable harvesting may help to protect kelp forests from overgrazing. Another natural threat to kelp populations is the explosive populations of encrusting bryozoans (*Membranipora* spp.) which can completely cover the blades, thereby blocking sunlight, physically damaging the blade and stipes, reducing flexibility, and increasing breakage.

Economically, macroalgae are harvested and used to produce alginate, which serves as an emulsifying and binding agent in food and pharmaceutical products (Frey 1971). Kelp species are also an important part of traditional food in many regions of the world, including Asia, South America, and Alaska. Kelp communities also support various recreational activities such as fishing and scuba diving. The use of kelp in commercial products as well as their value in recreational uses contribute largely to the worldwide economy. For instance, the kelp harvest in California was valued at $4 million in 1991 and $3 million in 1992, and the State of California received a percentage of the dollars earned from kelp harvesting.

HUMAN IMPACTS TO KELP AND OTHER MACROALGAE

Over the years, kelp and other macroalgae populations have declined due to natural occurrences and human impacts. Some human activities responsible for this decline include:

- Industrial and sewage discharges
- Oil spills
- Boating, fishing, and diving activities
- Coastal development
- Harvesting, and
- Removal of species

These activities can be placed in three categories of impacts: coastal pollution, physical damage, and removal of species.

Coastal Pollution

Coastal pollution from agricultural, municipal, and industrial sources can impact macroalgal communities. Eutrophication in coastal waters may result in the excessive growth of epiphytes and epifauna on the blades, causing the plants to sink to the bottom or break and die (Dayton 1985). High nutrient levels also increase phytoplankton growth, which results in reduced light penetration and an accompanying reduction in kelp photosynthesis. The turbidity resulting from eutrophication and increased sediment loading may cause burial of kelp and other macroalgae affecting plant growth. Waste materials have the ability to restrict growth and reduce fertility of kelp during its microscopic stages. In addition, sea otter (*Enhydra lutris*) populations may decrease due to poor water quality.

Oil spills also affect kelp communities. Even though oil may not persist following a spill, recovery time for the damaged habitat can be years or even decades. The swimming oil carpet can cover the intertidal range and coat intertidal kelp (e.g., *Alaria* spp.) and other habitat-building algae, such as the ecologically important rockweed (e.g., *Fucus* spp.). Following the *Exxon Valdez* spill in Prince William Sound, Alaska, rockweed did not fully recover until several years after the spill (Stekoll and Deysher 1996). Oil that stays on the surface of the water can cover blades of the kelp canopy, preventing sunlight from reaching the plants. As a result, kelp growth is limited because photosynthesis is reduced or in some cases eliminated. Studies have also shown that the microscopic life stages (gametophytes) of *Macrocystis* spp. are particularly sensitive to oil contamination (Reed et al. 1994). In some cases, cleanup activities following oil spills, such as pressure cleaning, directly affect kelps. The cleanup following the *Exxon Valdez* oil spill devastated some kelp communities and intertidal macroalgae by inhibiting re-sprouts of the holdfast and lowering recruitment rates (De Vogelaere and Foster 1994).

Associated animal communities are also affected by oil spills. Sea otters have thick fur coats that make them particularly susceptible to oil spills. Otters solely rely on their fur for insulation because they lack a blubber fat layer. Oil on otter fur reduces their insulation capacity which can cause otters to experience hypothermia, or even drown if oil coats the air sacks in the fur (Williams et al. 1988). In Alaska, sea urchin populations increased following the decline of the sea otters population due to the *Exxon Valdez* oil spill (Dean et al. 1996). Oil introduced into the intertidal zone will also affect the invertebrate community associated with macroalgae attached to the rocky habitat. Kelp holdfasts in low-energy environments can retain oil for years after a spill, then be weakened until the holdfast-associated animal community is destroyed. For example, a small spill of diesel oil at Macquarie Island in the sub-Antarctic resulted in contamination of kelp holdfasts for at least five years and inhibited the full recovery of the kelp-associated invertebrate community (Smith and Simpson 1998). Similarly, fish communities associated with kelp forests show delayed recovery due to oil spills.

Physical Damage

Construction and logging activities related to coastal development often affect kelp forests directly, resulting in increased sediment loads into coastal waters. The sediments decrease light penetration and thus, photosynthesis and growth of algae, especially the overwintering microscopic life stages of kelp which are susceptible to smothering and abrasion by sediments.

Other human activities that can directly impact kelp communities by uprooting plants and physically damaging kelp forests include:

- Dragging of heavy bottom gear (e.g., groundfish trawls and scallop dredges)
- Hook and line fishing
- Use of crab and lobster pots
- Setting and removing of gill nets
- Boat traffic
- Commercial harvesting by divers, and
- Intense recreational free diving and scuba activities

The exact nature and magnitude of these impacts and the rate of recovery have not been adequately studied. However, observations by scientists in California noted areas as large as several square meters void of kelp because of such activities.

One human activity that directly affects kelp communities is the harvesting of kelp plants. These plants are harvested in both Maine and California and used commercially as fertilizer, animal feed, and packing materials to ship commercial species such as lobsters, marine bait worms, and crabs (White 1993). Kelp plants are also harvested to extract alginic acid (alginate), a colloidal product used for thickening, suspending, stabilizing, emulsifying, and film-forming (McPeak et al. 1988). Approximately half of the alginate produced is used to make ice cream and other dairy products; the remainder is used in products such as shaving cream, toothpaste, rubber, and paint (McPeak et al. 1988). While much research has gone into trying to develop a sustainable commercial kelp harvest in Southern California, there is an increasing potential for this resource to be greatly depleted due to the cumulative impacts of harvesting, chronic oil and chemical spills, industrial and urban runoff, sewage outfalls, and physical plant damage caused by boats and scuba divers. In addition, the fish and invertebrate community associated with the surface layer of the canopy, which is removed in the harvest, becomes impoverished.

Kelp is also harvested extensively in the Gulf of Maine. In the 1940s, up to 3,000 tons of kelp were harvested each year in southwestern Nova Scotia, largely as a source of alginate (Sharp and Carter 1986). Surveys of the same area in the 1980s indicated that the yearly plant production levels had significantly increased and represented “a significant opportunity for exploitation” (Sharp and Carter 1986). There is, however, limited scientific information about the biological effects of kelp harvest on the plants themselves or the associated communities. One effect of the continual removal of kelp in a given area is that light would be able to penetrate deeper into the water column and promote microalgal and macroalgal growth, potentially outcompeting new kelp plant recruitment (Pearse and Hines 1979; Reed and Foster 1984).

Removal of Animal Species

Unlike the other impacts that often directly affect kelp and other macroalgae, ecosystem changes, such as human removal of an animal species that controls the population of another species, can indirectly affect kelp communities. This situation was seen in the North Pacific where the removal of top predators had cascading effects on the trophic structure, allowing kelp grazers to thrive and eliminate kelp forests. It is suggested that industrial whaling during the late 1800s reduced great whale populations in the North Pacific Ocean. Killer whales (*Orcinus orca*), the primary predator of great whales (after humans), were forced to switch prey, first to seals (e.g., *Halichoerus grypus, Phoca vitulina*) and sea lions (e.g., *Eumetopias jubatus, Callorhinus ursinus*), then to smaller prey such as sea otters (*Enhydra lutris*) (Estes et al. 1998; Springer et al. 2003). This has affected sea otter populations to the same or greater extent as the impact from hunting for sea otter pelts in the late 1700s and early 1800s. The sea otter population in the Aleutian Islands is about 10 to 20 percent of their historical levels, causing the sea urchin populations in these areas to explode (Estes and Duggins 1995). Sea urchins have removed much of the kelp forests, resulting in loss of species diversity and nearshore productivity. Sea otter populations along the California coast have been declining recently, possibly due to a combination of infectious diseases, parasites, and pollution.

Biological communities that are integrally dependent on physical structures formed by living organisms (e.g., kelp forests, coral reefs) are inherently slow to recover from severe impacts such as the ones discussed above. In some cases where the structure-forming species (e.g., kelp) actually stabilize the habitat, permanent habitat modification can result from an acute incident that destroys the key structuring species. Kelp recovery from impacts may depend on:

- The actual impacts from commercial and recreational activities
- Toxicological and biological damage associated with incidents (e.g., oil spills)
- Damage incurred during cleanup operations
- The persistence of contamination
- Timing of incidents and time between incidents
- Impacts on predators of kelp grazers, and
- The inherent ability of the community to recover

These examples of functional inter-relationships highlight the complexity of kelp and other macroalgal ecosystems, as well as the need to monitor restoration activities and their benefits to adjacent ecosystems.

RESTORATION EFFORTS

The essential aspect of planning and implementing restoration efforts is the proper identification of the problems affecting kelp habitats. The causes for deterioration of kelp habitat can differ among areas and regions. Once the causes (e.g., grazer impacts, human disturbances) are identified, appropriate restoration strategies can be developed. Larger ecosystem consequences of restoration activities should also be considered during the planning process.

Various researchers, agencies, and organizations, such as the Scripps Institution of Oceanography, Kelco Company, California Department of Fish and Game, and National Oceanic and Atmospheric

Administration (NOAA), have restored kelp habitats in the United States. These activities are aimed to increase kelp forest acreage and maintain habitat functions in support of coastal ecosystems which provide biodiversity, biomass, and economic opportunities. In the early 1960s, the Scripps Institution of Oceanography and Kelco Company began a cooperative program to develop techniques to protect and restore kelp forests off Southern California in order to keep the harvest industry viable. These efforts focused on predation control (i.e., sea urchin removal). Between 1967 and 1980, kelp restoration was then conducted along the Palos Verdes Peninsula in California by the Institute of Marine Resources and California Department of Fish and Game. This work combined sea urchin control and kelp transplanting with structural monitoring.

By the early 1990s, the California Department of Fish and Game's Artificial Reef Program and the Southern California Edison Company built artificial reefs in Mission Bay within San Diego County and San Clemente that supported the growth of kelp plants. Such reef-building efforts proved that if limited substrate is a factor in kelp forest restoration, then creating new reef substrate could increase the capacity for kelp forest expansion.

Recently, the NOAA Restoration Center funded the California Coastkeeper Alliance to develop facilities, training, and transplanting implementation methods for kelp forest development along the Southern California coast. These activities include the culture of kelp plants from field plants and attaching the holdfasts to natural and artificial reefs in Southern California. Recent research has studied the use of artificial kelp plants to reduce grazer impact in Southern California. Artificial (plastic) kelp plants are site-specifically designed and located on the perimeter of the transplant area to sweep the substrate and create a whiplash effect, moving the sea urchins away from the transplanted kelp (Vasquez and McPeak, 1998). While these efforts have had some success to date, there is a need for long-term monitoring as well as development of new restoration techniques.

Restoration practitioners can learn more about specific kelp and macroalgae restoration activities through NOAA's Restoration Center database of restoration projects. This web-based database can help in planning a restoration project, contacting restoration practitioners, and sharing information. The restoration project database can be found at: http://restoration.nos.noaa.gov/htmls/rpi_query/rpi_query.html. California kelp restoration activities may be found at: http://www.dfg.ca.gov/habitats. Bedford (2001) presents an excellent overview of the kelp forest restoration activities in California. More information from NOAA on laboratory procedures is available at: http//www.seagrant.noaa.gov/index.html and http//www.nmfs.noaa.gov/aquaculture.htm. Information on culturing macroalgae may also be obtained at: http://www.seacare.org.au/html/articles.htm.

Monitoring Kelp and Other Macroalgae

Most emphasis in macroalgal habitat restoration has been placed on kelp forests and intertidal rockweed (e.g., *Fucus* spp.) habitats. Kelp restoration projects are designed to accelerate the regeneration of existing or historical kelp forests, stabilize the community to support new plant recruitment, and remove or reduce human-induced disturbances. After identifying the need for a potential restoration effort, a detailed restoration plan must be developed. This plan has to address the specific impacts in the region, goals and objectives of the restoration project, and the conceptual model to measure progress toward meeting those goals and objectives. Consideration must be given to site selection, methods to be used, proper care and handling of samples, the benefits of cultured algae, chemical and physical conditions of the habitat, and any short- and long-term maintenance requirements. In addition, coordination and collaboration needs, regulatory requirements, parameters to be monitored to track progress, and monitoring time frame must be established. Monitoring should be performed before, during, and after the restoration effort to measure progress and success. Modifications may have to be made in design, implementation, and techniques to help ensure the potential for the project to obtain the pre-defined goals and objectives. This is referred to as adaptive management.

Parameters frequently monitored in kelp and other macroalgal habitats include (Foster and Schiel 1992):

- Abundance and growth rates of kelp and macroalgae
- Species composition
- Plant characteristics (e.g., length, holdfast size, stem density, plant density, rate of canopy closure, and aerial extent)
- Kelp recruitment
- Presence and abundance of kelp-associated species with known key effects on habitat health (e.g., otters, sea urchins, other grazers)
- Diversity of the habitat
- Tides and hydrographical conditions
- Temperature
- Sediment texture
- Salinity, and
- Water quality

Parameters monitored should be specific to the proposed restoration plan and design goals, and may vary depending on the project location and ecological situation. Where practicable, plans should consider transfer metrics to relate an individual project to others in order to increase the knowledge base of restoration techniques.

Species selection for monitoring is most important in assessing whether the kelp restoration project is appropriate to improve the structural and functional characteristics of the kelp forest. Ecologically important kelp and other algal species, invertebrates, and vertebrates need to be selected for monitoring. The primary objective in selecting taxa for monitoring is to provide a representative cross-section of structural and functional elements so that these taxa may serve as indicators of system status.

If the primary goal is to restore the faunal community, general criteria to select species include consideration of:

- Specific legal mandate(s) (e.g., protection of certain species)
- Species targeted by commercial or recreational harvest
- Exceptionally common species or characteristic of entire communities
- Species with known impacts on kelp (e.g., grazers, non-native invasive species)
- Species endemic to the study area, and
- Species with an extremely limited distribution

The selected species should prey on a variety of food types, including detritivores, primary producers, obligate herbivores, and higher level predators. In addition, the species should span mobility ranges from sessile filter feeders and sedentary grazers to highly mobile planktivorous fishes and wide ranging benthic foragers. Reproductive strategies of these species should be diverse, from live births as seen in surfperches (e.g., *Hyperprosopon argenteum*) to precarious release of gametes into the sea by many invertebrates (e.g., abalone and sea urchins) to those with long-lived pelagic larvae (e.g., the spiny lobster, *Panulirus interruptus)*. The selection of species should provide opportunities to detect ecosystem benefits and many facets of human impacts, from pollution to habitat disturbance and direct removal.

Standardization of monitoring methods and locations should be considered. Standardized techniques, while not optimum for a particular site or study, often provide a higher level of scientific value as part of a regional database or comparable temporal series. Monitoring stations should consider prevailing winds, water currents, bathymetry of adjacent areas, and terrestrial inputs, as these all greatly influence marine communities. Upwelling nutrients from deep basins produce exceptionally productive food webs and different temperature regimes than those present at the shallow sides of islands, headlands, or mainlands. Standardized protocols can also facilitate long-term monitoring of transition areas from one marine province to another (e.g., Californian to Oregonian provinces) which are especially susceptible to impacts with changing environmental conditions.

Selecting adequate monitoring techniques for the specific metrics of a restoration project are critical to obtaining useful data. The array of organisms and physical settings associated with kelp forests and macroalgal environments require equally diverse monitoring approaches to assess their population dynamics. Accuracy (i.e., the closeness of a measured value to its true value) is an important attribute of a monitoring technique, but precision (i.e., the closeness of repeated measurements of the same entity) and the ability to sample several target species at once are also required for the efficient sampling of an underwater habitat. Accuracy and precision of monitoring techniques used in long-term assessment programs must also be maintained by many generations of field samplers. Considerable biological and technical training - including biota identification, laboratory and field biological techniques, advanced technical scuba, boat handling, and self-rescue - must be provided for all personnel engaged in restoration monitoring activities. Finally, the selected monitoring techniques must provide values that do not vary among observers. The techniques must not significantly reduce populations of organisms being monitored, alter their environment, or introduce non-native species. Current technology for remote sensing or monitoring of kelp forest organisms from the sea surface is neither accurate nor precise enough to record population dynamics of key species. Development of diving equipment has generated various monitoring techniques that have potential for providing accurate and precise measures of population abundance, distribution, age structure, reproduction, recruitment, growth rate, mortality rate, sex composition, and phenology[4] of kelp forest organisms, but the measurements must be taken in close proximity to the organisms.

In summary, the selection of monitoring techniques for restoration should be evaluated using their ability to meet the following criteria:

- Accurately assess the structure and/or functional characteristics of canopy, understory, benthos, and water column,
- Sample targeted ecosystem-significant algae, fish, and invertebrate species accurately and precisely
- Identify potential impacts (e.g., pollution, disease, predation, competition, introduction of non-native invasive species) to target species and other biota
- Ensure efficiency, effectiveness, and repeatability of all monitoring methods and stations (e.g., by using global positioning systems (GPS), mapping coordinates)
- Create accurate permanent records for quality assurances and control and future analyses
- Address requirements and training necessary for observers, complexity of monitoring methods, and need for specialized equipment

[4] The study of plant growth and development related to the timing of different growth stages.

- Establish permanent stations and transects to give appropriate level of precision
- Develop a conceptual model of the questions to be answered by each monitoring technique
- Monitor all aspects of culturing techniques with accuracy and precision, and
- Develop and implement a plan for estimating risks of the potential for the introduction of non-indigenous marine organisms and methods to minimize these potential risks

STRUCTURAL CHARACTERISTICS OF KELP AND OTHER MACROALGAE

The primary structural components of kelp and other macroalgae relevant to restoration monitoring include biological, physical, hydrological, and chemical characteristics. The identified structural characteristics will help restoration practitioners determine whether kelp and/or other macroalgae can survive and grow in a potential restoration area and whether the habitat is functioning efficiently following restoration efforts. With the proper set of structural parameters in place, functional parameters (discussed in next section) may be more easily identified to create a sound science-based monitoring program. Two matrices at the end of this chapter (also found in *Volume One* for all habitats) show the connection between the habitat's structural and functional characteristics and the parameters that should be considered for monitoring.

The major structural characteristics, factors influencing them, and methods to monitor them are discussed in this section. Project goals, costs, and types of data to be collected must be considered when selecting these parameters. Experts in the field should also be consulted to determine the best method for a specific area.

The basic structural components of kelp forests include:

Biological
- Habitat created by plants (i.e., kelp and other macroalgae)

Physical
- Sediment (grain size and sedimentation)
- Light availability
- Turbidity
- Water temperature

Hydrological
- Current velocity and tides
- Wave energy and protection
- Water sources (i.e., nutrients and water quality)

Chemical
- Salinity

These characteristics dictate where kelp forests can grow and how well they perform certain functions (e.g., providing fish and invertebrate habitat, improving water quality) and therefore, should be among the first things measured during a monitoring effort. The hydrology and geomorphology of a potential restoration area are not characteristics that will be monitored for change over time but should be established for the basic understanding of a selected site. In kelp and macroalgal restoration projects requiring rock or sediment placement, however, practitioners will need to monitor substrate placement, stability, elevations, and topographic diversity for a period before transplant attachment to determine if the planned substrate conditions have been achieved.

BIOLOGICAL

Habitat Created by Plants (i.e., kelp and other macroalgae)

Among macroalgae, kelp species obtain the largest size and have the highest structural complexity (Figure 4). They are attached to the substrate with a holdfast from which a stipe extends. Continuous growth of a frond occurs from its tip or apical meristem (forming one or more blades).

Kelp holdfasts often have finger-like extensions (haptera) that take advantage of small-scale

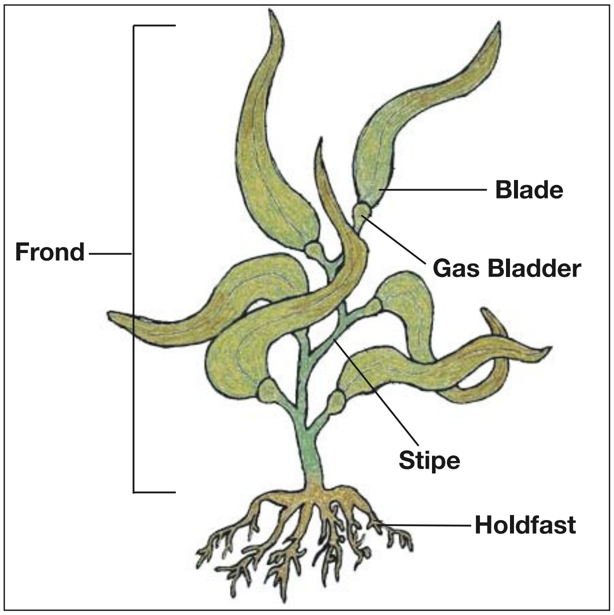

Figure 4. Parts of the kelp plant. Photo courtesy of Andrew Mason, NOAA, Center for Coastal Monitoring and Assessment, Silver Spring, MD.

Figure 5. The stipe of a kelp plant attached to hard bottom. Photo courtesy of Russell Bellmer, United States Fish and Wildlife Service.

structures of the substrate for attachment (Figure 5). They create a microhabitat for many specially adapted organisms such as polychaete worms, brittle stars, and small crustaceans. New haptera are added every year in perennial kelp species.

Stipes can be absent (e.g., stipe-less kelp, *Hedophyllum sessile*) or can extend several meters (e.g., bull kelp, *Nereocystis luetkeana)*. In the latter case, the stipe retains actively growing (meristematic) tissue. The number of stipes arising from a single holdfast varies from one to more than 50. One or more blades arise from the stipes. The blades continue to grow from the meristematic tissue at their basal portion while they deteriorate from the tip. Some kelp blades have a rippled surface which creates turbulent flow of the surrounding water across the blades to increase nutrient uptake. In canopy-forming kelp species, gas-filled floats (pneumatocysts) are located between the stipe and the blade. The pneumatocysts allow the blades to stay near the surface in the sunlight for photosynthesis.

Kelp life history includes the alternation of two generations: a large sporophyte commonly known as the kelp and a small gametophyte consisting of only several cells (Figure 6). In late summer, the sporophyte produces spores in certain sections of the blades (sori) or on specialized blades (sporophylls). These spores are the major dispersal stage in kelps. They undergo meiosis (i.e, the reduction of the DNA to a single set), and then settle and grow into a haploid gametophyte just a few cells in

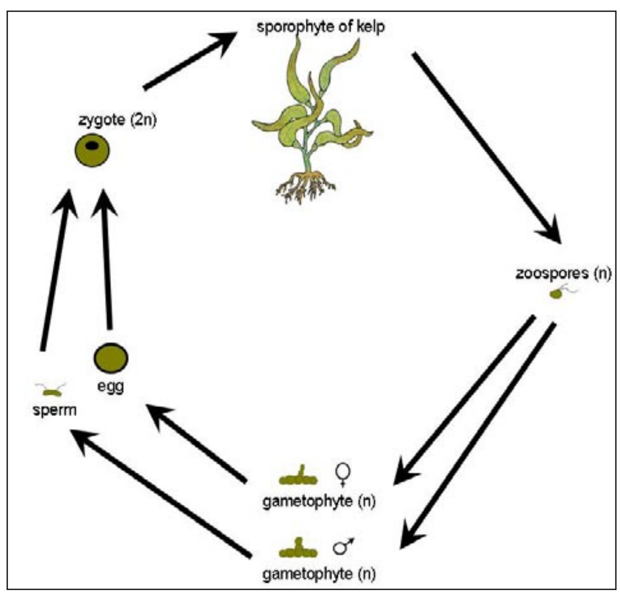

Figure 6. Kelp life cycle. Diagram courtesy of Andrew Mason, NOAA Center for Coastal Monitoring and Assessment.

size. In annual kelp species, the gametophyte is the overwintering stage. Male and female gametophytes then produce sperm and eggs, respectively, which fuse into zygotes from which new diploid sporophytes grow out.

It is important to understand this principle alternation of two physically different generations for the purpose of kelp monitoring and restoration because both generations have different requirements and weaknesses with regard to their physical and biological environment. Potential restoration sites must be screened for environmental requirements pertaining to both sporophytic and gemetophytic life stages if re-establishment is to be successful.

Canopy-forming kelp species, such as *Macrocystis* spp. and *Nereocystis luetkeana,* extend to the surface and thus, effectively block light penetration to the substrate below. This gives a forest-like appearance to scuba divers (as shown in Figure 7) and hence the term kelp forests. Certain animals associated with the kelp forests, especially fishes, are specialized to live among the top floating part of the canopy, while others are specialized to live in the midwater section. The holdfasts host their own specialized community of associated invertebrates. Many benthic invertebrates are also associated with the smaller understory kelp species, which provide efficient shelter and three-dimensional habitat. A diverse community of red algae (e.g., *Gigartina* spp.) also thrives in the smaller understory. The presence and physical structure also influence hydrological properties, such as the slowing of currents. Resulting effects include increased sedimentation and accumulation of finer sediment in the low current areas within the kelp forests. The three-dimensional structure of kelp forests and the influenced physical oceanographic processes are noticeably different than adjacent non-forested areas.

Some of the more common species of kelp include:

Figure 7. Diver observing kelp growth. Photo courtesy of Russell Bellmer, United States Fish and Wildlife Service.

Giant kelp (*Macrocystis* spp.)
Bull kelp (*Nereocystis luetkeana, Pterygophora californica)*
Forest kelp (*Laminaria* spp.*)*
Winged kelp (*Alaria* spp.*)*
Colander weed (*Agarum* spp.*)*
Southern sea palm (*Eisenia arborea)*
Stipe-less kelp (*Hedophyllum sessile*)
Chain bladder kelp (*Cystoseira osmundacea)*
Furbelows (*Saccorhiza polyschides)*
Feather boa kelp (*Egregia menziesii*), and
Strap kelp (*Lessoniopsis littoralis)*

However, there are many more species of kelp and large macroalgae distributed along the U.S. coasts. Another noteworthy macroalgal group that provides important habitat in intertidal regions is rockweeds such as *Fucus* spp. They also provide habitat structure, as well as shelter from predation and desiccation (i.e., loss of water or moisture) in the intertidal zone.

Another structural component of kelp forests of interest to restoration practitioners is the spatial extent, which can range from a few square meters to thousands of square kilometers. Spatial extent is variable on seasonal and interannual scales and needs to be monitored to understand the dynamics influencing a specific kelp habitat. Causes of kelp forest extent changes should be identified before site-selection of restoration and monitoring sites.

Measuring and Monitoring Methods

Various methods can be used to monitor and track the progress of kelp growth throughout a restoration project toward the goal of a self-sustaining kelp habitat. Digital remote sensing combined with geographical information systems (GIS) is an efficient method to collect and analyze data on changes occurring in kelp forest size and location. Spot satellite imagery, which is a remote sensing method, can be used to map large kelp forests (greater than10 hectares) and has been used along the California coast (Deysher 1993). Images from an Airborne Data and Registration (ADAR) system, a multi-spectral video sensor mounted on an airplane (developed by Positive Systems), can provide a spatial resolution of 2.3 meters in four spectral bands to map aerial extent and condition (Deysher 1993).

Geographic information systems (GIS) may also be used to monitor and analyze *Macrocystis pyrifera* canopy cover at both spatial and temporal scales (Bushing 2000). GIS-based gap analyses can be performed repeatedly on the designated area in relation to the regional ecology, disturbance regime, and persistence of giant kelp (*M. pyrifera*). Analysis of these temporal maps can be used to develop a model representing spatial scales of kelp over time. The disturbance regime and prominent physical variables can also be determined. This method is considered a useful tool for evaluating large-scale kelp communities as part of restoration monitoring efforts (Bushing 2000.)

Direct observation - Trained scuba diving marine biologists provide the most complete and reproducible survey method of kelp and other macroalgal communities. This technique is usually performed by repeated observations of a set of metrics on fixed transects over day and night as well as throughout the year. These efforts may be supplemented with remote sensing (e.g., aerial photography, space mounted sensors), video, and still photography. Surveys are performed to collect sound scientific data on the habitat structure of kelp and other macroalgae, such as:

- Abundance and distribution of individual plants
- Diversity of kelp species
- Reproductive state
- Plant recruitment
- Growth rates
- Canopy closure
- Size of plants
- Animal-induced changes to kelp and other macroalgae and/or substrate, and
- Changes in top predators, especially sea otters

Quadrats - Sample areas that are fixed or randomly placed along transects and commonly used to collect quantifiable data are called quadrats (Figure 8). Quantitative information can include percent cover of the understory kelp species in the quadrat compared to open substrate, red algae and sessile animal cover, stipe counts of kelp, and counts of kelp recruitment on the level of juvenile sporophytes. Canopy-forming kelp is often distributed in patches and cannot be estimated reliably from quadrat counts. For these, a swath of defined width along each side of the transect is counted for canopy kelp. When kelp size is measured, attention should be paid to growth patterns of kelp species which can include growth in length and width. If the kelp forest extends over a significant depth range, each sampling procedure must be performed at multiple depth intervals to account for this factor.

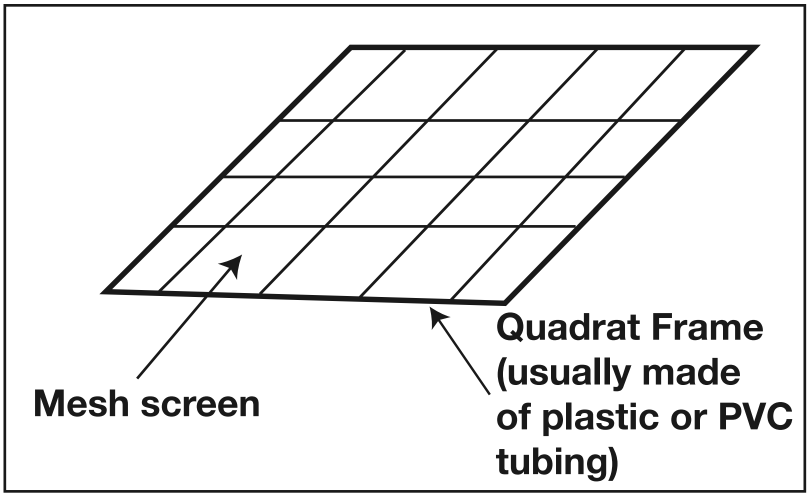

Figure 8. A quadrat, used to make visual assessments within the perimeter of the frame. Diagram courtesy of Felicity Burrows, NOAA National Centers for Coastal and Ocean Science.

Growth markers - Kelp growth can also be monitored by inserting growth markers into the blades or stipes. A growth marker can be as simple as a hole punched just above the meristematic tissue of a kelp blade. They can also be metal buttons that are inserted just above the meristematic tissue. The distance from the growth marker to the base of blade or holdfast is then measured repeatedly over time. The increase in distance per time frame can be expressed as the growth rate.

Both of these transect surveys can be combined with metrics of the functional characteristics of kelp, such as counts of large mobile animals (e.g., seastars, abalone). Swaths are the most common approach to quantify fish, as swaths can be done at various levels (bottom, midwater, top canopy) and encounter fish species enumerated (discussed further in the "Functional Characteristics of Kelp and Other Macroalgae" section).

PHYSICAL

Sediment

Grain size and sedimentation

The sediment composition in kelp forests ranges from bedrock and boulders to cobbles dispersed in sand (*see Geomorphology box*). Some *Laminaria* species are even able to attach their holdfasts to small pebbles buried in sand. The complex surface, crevices, and three-dimensional structures of areas with hard substrates support a variety of other plant and animal species. Adjacent to these hard substrates are often unconsolidated sediment, which is commonly transported back and forth by wave forces throughout the kelp forests. The kelp plant structure slows water movement, thereby allowing suspended sediment to settle to the bottom. More importantly, sediment movements may also affect kelp by covering the thallus and/or smothering the entire plant (Foster and Schiel 1992). Increased sedimentation rates may also reduce the recruitment rate and survival of gametophytes (Devinny and Volse 1978; Foster and Schiel 1992).

Geomorphology

In the matrix, at the end of this chapter, geomorphology is listed as a physical parameter that at a bare minimum should be assessed during restoration however this is in relation to the geomorphology of rocky substrates that support kelp and other macroalgae. A detail discussion on the geomorphology of rocky substrates is discussed in chapter 6: Restoration Monitoring of Rocky Habitats" of this document.

Sampling and Monitoring Methods

Sediment traps - Sediment that drops out of suspension over time (i.e., sedimentation rate) can be collected in sediment traps. The traps can be fixed for extended periods to determine total sediment input, or more importantly over predetermined shorter intervals to allow differentiation of acute sedimentation rates from long-term or seasonal patterns of sedimentation (Hargrave and Burns 1979; Hawley 1988; Rogers et al. 2001). Sediment traps are mainly constructed of several PVC pipes or jars attached to a steel rod and positioned at varying distances above the substrate. Each jar has a lid to seal it before it is removed from the water. Baffles or cones are placed at the top of the jar to prevent mobile organisms that may consume material in the trap from entering. Samples are then filtered, dried, weighed and analyzed in the lab (Hargrave and Burns 1979; Hawley 1988; Rogers et al. 2001).

Light Availability and Turbidity

Light availability

Kelp depends on sufficient light availability for photosynthesis. Wave action keeps the fronds in constant motion, allowing maximum exposure to sunlight and enhancing uptake of nutrients (Barnes and Hughes 1993). Kelp plants have a minimum light availability necessary to perform net photosynthesis. The energy produced during photosynthesis is stored as the carbohydrate laminarin that can be used for growth if sufficient nutrients are available. A study was performed to view the response of the Arctic kelp *Laminaria solidungula* to ambient light and nutrient levels in extreme conditions, when sufficient light is only available in the summer and nutrients are low (Henley and Dunton 1997). The Arctic kelp produces laminarin during summer but does not grow. When nutrient levels increase in the winter, the stored laminarin is used to fuel growth. Results showed that total annual growth was due mainly to light limitations. The minimum light requirements differ for different kelp species; canopy-forming species often need more light, while understory species are often more low-light adapted.

Recruitment of giant kelp (*Macrocystis pyrifera*) gametophytes and embryonic sporophytes in response to reduced light and nutrient availability has also been investigated (Kinlan et al. 2003). Laboratory cultures were provided with either limited light or nutrients for one month and then exposed to non-limiting conditions for ten days. Results showed that gametophytes failed to recruit to sporophytes. Light or nutrient-limited sporophytes survived but experienced slower growth than controls (Kinlan et al. 2003). These results show that limiting light and nutrient resources can inhibit recruitment of embryonic giant kelp sporophytes.

Photosynthetically active radiation (PAR)
PAR is the range of light wavelengths that is absorbed and used by plants for photosynthesis. In California, the effects of PAR on *Macrocystis pyrifera* in shallow waters were monitored (Graham 1996). At shallow depths and high PAR levels, *M. pyrifera* did not recruit or grow to macroscopic size, but rather survived at greater depths where PAR levels were decreased. This corresponded with natural recruitment and sporophyte distributions. Obviously, high PAR inhibited *M. pyrifera* recruitment to shallow water by destroying the post-settlement stages (gametophytes and embryonic sporophytes), which survived only when shaded.

Turbidity
Turbidity is also an important factor affecting the growth of kelp, as greater turbidity leads to reduced light penetration that in turn, affects photosynthesis. Water quality deterioration related to turbidity from coastal development, municipal and industrial discharges, and non-point source runoff has caused reductions in the spatial extent of kelp.

Sampling and Monitoring Methods

Photosynthetically active radiation (PAR) is measured using a quantum sensor at the water surface, throughout the water column, and at the substrate. There are two types of quantum sensors: flat sensors that measure light projecting downward, and spherical sensors that measure light from multiple directions. A spherical sensor should be used for underwater measurements. Quantum sensors can be used along with data loggers to record measurements of PAR at various locations and intervals over time (discussed further in Chapter 9: "Restoration Monitoring of Submerged Aquatic Vegetation (SAV)").

A common method used to estimate turbidity by the depth of light penetration is the use of a secchi disc (Figure 9) which measures water clarity. It is a standard sized (quartered black and white, weighted) plastic disc that is attached to a line and lowered through the water column from the shore, pier, or boat until the disc is no longer visible. This depth is then recorded as the secchi disc depth. Usually, three measurements from the same point are recorded so that the mean of these recordings can be used to establish the relative limit of visibility or turbidity.

Turbidity can also be measured using electronic light extinction sensors. Typically, the reduction in light transmission over a set distance is measured photoelectrically. Alternately, back-scatter or side-scatter may be measured to provide a separate measurement of light extinction due to particles in suspension.

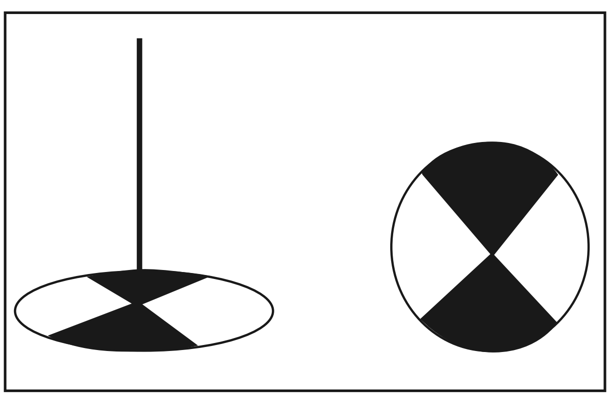

Figure 9. Secchi disc. Diagram courtesy of Felicity Burrows, NOAA National Centers for Coastal and Ocean Science.

A turbidimeter can also measure turbidity in a water sample by passing a beam of light through the water sample and measuring the quantity of light scattered by particulate matter (Rogers et al. 2001).

Water Temperature

Kelp grows best in cooler temperatures below 20ºC and cannot successfully reproduce in warmer temperatures. Increased water temperatures due to terrestrial runoff (including modified river flow regimes), human-induced pressures, and natural events may alter kelp communities. El Niño events are usually accompanied by warmer water temperatures, which reduce kelp growth or even eliminate kelp forests. In California, El Niño disturbances resulted in long-term negative changes in kelp standing stock due to change in the temperature gradient (Tegner et al. 2001). Massive mortality of the intertidal kelp species *Lessonia nigrescens* was seen in northern Chile where very few representatives survived the El Niño event of 1982-83 (Martinez et al. 2003). Recovery after an El Niño event can be very slow, but kelp forests have the ability to completely recover over time. Declines in kelp populations were also noted in relation to warm anomalies after the 1976-1977 regime shift (Wright et al. 2000). Increases in ocean temperatures as a result of global warming may shift the range of kelp populations northward towards currently cooler waters, thereby eliminating them from southern locations where kelp is currently growing at its upper temperature limit.

Sampling and Monitoring Methods

Water temperature can be measured using a thermometer. Scuba divers use thermometers that resemble wrist watches and record temperatures as they descend or ascend through the water column. Various other hand-held commercial instruments can also be used to measure water temperature. A maximum/

minimum thermometer can be left at the study site to record the warmest and coldest water temperatures since the last readings were recorded at the site (Rogers et al. 2001). Small temperature data loggers (developed by HOBO) that record temperature at set intervals for up to several years can also be deployed. Remote thermo-sensors collecting data continuously provide a comprehensive data set that can be used to typify the thermal regime over a long period of time, whereas thermometers used by divers or lowered from a boat gather comparatively less information.

HYDROLOGICAL

Natural stochastic occurrences, such as storms which are accompanied by intense current velocity, tidal fluctuations, and wave energy can influence kelp communities. For example, in addition to the associated temperature changes of the 1997-1998 El Niño in California, the event caused heavy storms along the West coast of North America which in turn, caused almost complete eradication of giant kelp forests in some areas (Edwards and Hernandez-Carmona 2000). Changes in climate will likely be connected to similar changes in hydrological characteristics. In addition to the direct effects on kelp, there are also indirect cascading effects on the associated animal community, food-web production, and trophic structure (Lehman 2004). Physical hydrological factors, such as current velocity, wave energy, and tidal fluctuations, should therefore be monitored because they can affect the success of kelp restoration projects.

Current Velocity and Tides

Current velocity and tides plays a significant role in the dispersal of kelp spores after they are released. Spore dispersal is important because it contributes to the colonization process and to genetic exchange among populations. High vertical currents may transport spores rapidly to the substratum where they settle before being dispersed (Denny and Shibata 1989). While this increases the probability of spore settlement in densities suitable for successful fertilization (Vogel 1991), it limits re-colonization of new areas. Vertical currents disperse spores into new locations, but very strong currents may also advect spores into unfavorable locations. In addition to currents and tides dispersing spores, many organisms, particularly those that attach to blades of kelp such as barnacles and tunicates, rely on tides and currents to help distribute nutrients throughout the water column so they can feed on these materials. Current velocity and direction, tides and other hydrodynamic variables should be measured to determine spore dispersal potential and nutrient transportation patterns.

Current velocity and fluctuating tides also influence the abundance of adult kelp and other macroalgae. Changes in the abundance of these plant species as a result of fluctuations in ocean conditions make it difficult to isolate and fully assess the impacts of potentially damaging human activities. The patchy geographic distribution also makes it difficult to detect adverse impacts to individual specimens at early stages.

Sampling and Monitoring Methods

There are various commercial instruments that can be used to measure currents and tides. For example, current velocity can be measured using current meters. The current meter is lowered into the water from a boat, dock, or pier using a wading rod or cable. Current velocity is measured by counting the number of revolutions of the bucket wheel over a certain time frame, then converting revolutions into water velocity using a rating chart (Anderson et al. 1996). Other technologies to measure current velocity exist and are discussed in chapter 9: Restoration Monitoring of SAV.

Tide gauges, which are mechanical devices that are usually placed on piers or pilings, can be used to record water levels (IOC 1985). The tide gauge consists of a data logger that reads and stores data from different sensors and a modem that communicates with a computer (IOC 1985). The water level sensor should be calibrated at regular intervals to ensure accurate water level measurements.

Acoustic Doppler flow meters can also be used to keep tidal flow by measuring velocity and particles moving through the water. Acoustic signals are transmitted from the instrument, then reflected off of particles and collected by a receiver. The signals received are then analyzed for frequency changes. The mean value of the frequency changes can directly relate to the average velocity of the particles moving through the water.

Wave Energy

Similar to currents, wave energy influences kelp structural and functional components. When severe storms occur, kelps may be uprooted and destroyed (Dayton 1985), as demonstrated by the large quantities found drifting at sea and washed up on beaches in winter. Severe wave action may also overturn the hard substrates (e.g., dislodge boulders, remove consolidated sediment, bury kelp with sediment) and destroy kelp, other macroalgae, and faunal communities (Foster and Schiel 1992). Increased wave energy also stirs up sediments, which smothers the kelp and reduces the amount of sunlight entering the water, thus reducing photosynthesis and restricting kelp growth. By monitoring the wave energy on kelp forest communities at both the surface and sediment surface, restoration practitioners will be better able to select plant species that are tolerant of such conditions, determine the time frame for restoration, and understand and address the physical impacts to the restored area. In addition to wave energy, the wave's angle of attack and the height at which the waves break should also be measured to assist in the restoration planting and monitoring design. Kelp and other macroalgae need to be planted in deep enough water to support them at low tide. This theoretical line is the shoreward limit of planting. Individual plants placed in shallow water will not survive the wave forces or will desiccate from too much exposure. Water depth should therefore be considered when selecting a restoration site and should be monitored relative to tidal cycles. Tide tables for the United States and its territories are available from NOAA at: http://tidesonline.nos.noaa.gov.

Measuring and Monitoring Methods

Wave energy effects on intertidal kelp and other macroalgae can be assessed using synchronized video, pressure sensors, and resistance wave gauges (Stevens et al. 2002). Accelerometers as well as displacement and force transducers can be used to measure macroalgal response to waves. Field measurements can then estimate forces and bending occurrences at the holdfast. It should be noted, however, that water depth variations throughout the tidal cycle affect blade accelerations and occurrences at the holdfast (Stevens et al. 2002).

Wave energy, average wave height, and periodicity can also be measured using wave buoys (Figure 10). Wave or current buoys are fixed weather stations in the ocean and record information about current conditions. Wave buoys measure wave heights, wave direction, and periodicity between waves using electronic sensors (Davies 1996). The buoys measure vertical and horizontal acceleration using accelerometers. Vertical acceleration determines wave height and horizontal acceleration determines wave direction (Davies 1996). These types of data are useful in kelp forest restoration design and implementation.

Various commercial instruments can also be used to measure depth and/or velocity as they relate to wave energy. Some instruments may be easy to install, operate, and maintain and include an ultrasonic velocity sensor with data

Figure 10. Retrieval of a current meter buoy. Photo courtesy of Commander John Bortniak, NOAA Corps. Publication of NOAA Central Library http://www.photolib.noaa.gov/corps/corp1716.htm

recording capabilities designed for both low and high flows found in kelp forests. The main advantage of electronic monitoring gear is the accuracy, consistency, and capability for real time data analysis.

Water Sources

Kelp and macroalgal communities can be modified by water quality. In many instances water entering coastal areas via terrestrial and industrial sources is polluted by excess nitrogen and phosphorus-based elements (Paine 1993). Sources responsible for changes in kelp and macroalgal communities include:

- Upland construction sites
- Increased freshwater discharges from channels and creeks that have been diverted for construction purposes
- Industrial discharges
- Oil pollution, which affects the functioning of both plant and animals (Williams et al. 1988)
- Agricultural and storm water runoff, and
- Sewage outfalls, drains, and contaminated rivers (Paine 1993)

Furthermore, increases in nutrient loading from pollutants result in phytoplankton blooms, causing reductions in light availability for kelps negatively affecting their growth.

The United States Environmental Protection Agency (USEPA) has developed a method to estimate toxicity of sewage effluent and receiving waters to kelp germination and development (see http://www.epa.gov/EERD/FB17_meth_905.pdf). Consideration should be given to the application of this method or a similar one before undertaking kelp reforestation. The *American Public Health Association's Standard Methods for the Examination of Water and Wastewater* also provides detailed field and laboratory procedures for analyzing water quality parameters such as nutrient concentrations, salinity, pH and dissolved oxygen that may be selected for use in restoration monitoring (Clesceri et al. 1998). Additional methods for assessing nutrient content in water samples are discussed further in chapters 9: SAV and 2: Water Column of this document.

CHEMICAL

Dissolved Oxygen

Most aquatic lifeforms need dissolved oxygen (DO) to survive. Factors responsible for dissolved oxygen in the water include the process of gas exchange with the atmosphere and the photosynthetic activity of plants such as macroalgae. Oxygen is then removed through respiration of living organisms and the decay of dead plants and animals. If the DO concentrations fall below the optimum level (hypoxia) needed to support plants and kelp associated organisms, then these plants and organisms may undergo stress. In some cases, excess nutrients may cause eutrophication which reduces oxygen levels to anoxic conditions (no oxygen). As a result of hypoxic or anoxic conditions, plant photosynthetic activity may be reduced affecting growth (Jackson 1977) and organisms, particularly fish that inhabit kelp forests and other macroalgae communities (see Chapter 2: titled "Restoration Monitoring of the Water Column" for a detailed discussion on low dissolved oxygen and its effects on fish).

Measuring and Monitoring Methods

There are various chemical and electronic methods that can be used to measure dissolved oxygen. Some of these methods are discussed in Chapter 2: Water Column, Chapter 4: Oyster Reefs, and Chapter 7: Soft Bottom Habitats of this document.

Salinity

Salinity plays a role in kelp and other macroalgal distribution and abundance. Salinity changes may occur due to freshwater inputs from industrial discharges, agricultural runoff, sewage discharges, and channel diversions. Construction activities may divert freshwater to areas occupied by kelp or discharge freshwater into kelp communities. As a result, salinity levels suitable for kelp growth may be altered, causing a decline in kelp productivity. Some studies have monitored germination inhibition of kelp *Ecklonia radiata* zoospores when exposed to sewage effluents and accompanying changes in salinity conditions (Burridge et al. 1999). Germination of zoospores responded negatively to the reduced salinity conditions when exposed for longer time periods.

Measuring and Monitoring Methods

Various hand-held commercial instruments can be used to measure salinity. Some electronic instruments calculate salinity in parts per thousand (ppt) based on temperature and conductivity readings. Hand-held refractometers on the other hand, measure salinity based on the salinity-dependent refraction index of light.

A conductivity, temperature, and depth (CTD) instrument (Figure 11) can also be used to measure salinity. The CTD instrument is lowered through the water column during which conductivity, temperature, and depth are continuously recorded. Salinity is then calculated based on conductivity because electric current passes readily through waters that have higher salinity levels. Salinity is usually given in practical salinity units (PSU), which is the same numerical value as parts per thousand.

Figure 11. CTD instrument. Photo courtesy of NOAA National Marine Fisheries Service, Southwest Fisheries Science Center.

FUNCTIONAL CHARACTERISTICS OF KELP AND OTHER MACROALGAE

Kelp forests fulfill important ecosystem functions, including:

Biological

- Provides habitat and shelter/refuge for many plants and animals
- Provides nursery and adult habitats that support species abundance and diversity
- Provides breeding grounds for fishes and marine mammals
- Provides feeding grounds for birds, fishes, invertebrates, and other marine organisms (Holbrook et al. 1990)
- Provides substrate for attachment

Physical

- Filters water and stabilizes sediment

By performing these functions, kelp forests are able to maintain plant and animal species diversity and abundance as well as support important recreational and commercial fisheries. If the algae are degraded in any way, the functioning of this habitat can be affected, such as its ability to support juveniles of marine organisms. Understanding how this habitat functions can help the practitioner select suitable parameters to track restoration efforts and achieve a naturally sustainable habitat. Monitoring should be performed to determine whether the habitat is functioning effectively and to track progress of the restoration project.

Methods to sample, measure, and monitor parameters affiliated with these functional characteristics are described below. This information is a limited account of the more important functions, as others exist and could also be valuable in monitoring certain restoration projects.

BIOLOGICAL

Provides Habitat and Shelter

Kelp forests and macroalgal habitats support diverse communities that contribute to primary productivity, as well as support biomass production, biodiversity, and a complex trophic structure (discussed in various sections throughout this chapter). These communities and their rocky substrate provide habitat for many different marine organisms. The three-dimensional structure of kelp forests can be divided into functional sub-habitats used by various organisms: The canopy is the region where the blades of the canopy-forming kelp species reach the surface. The midwater area is dominated by the stipes and lower blades of the canopy-forming algae. The complex structure of the benthic layer is comprised of the understory kelp, other algae, and the substrate. Some organisms associated with kelp forests can utilize all of these sub-habitats, but others are specialized in using certain areas. As species associated with kelp habitats vary among regions, practitioners should refer to the published literature to obtain species lists for the region in which restoration is being considered. The following will provide an overview of the general organism types associated with kelp beds as well as selected examples from various regions.

The canopy is mainly used by a variety of fish species which find shelter there from currents and predators that open water cannot provide. Adult fishes that utilize the canopy as habitat include:

Topsmelt (e.g., *Atherinops affinis)*
Kelp surfperch (e.g., *Brachyistius frenatus*)
Kelp pipefish (e.g., *Syngnathus californiensis*)

Kelp clingfish (e.g., *Rimicola muscarum*)
Rockfish (e.g., *Sebastes melanops)* (Figure 12)
Wrasses (e.g., *Semicossyphus pulcher, Oxyjulis californica*)
Damselfish (e.g., *Chromis punctipinnis)*, and
Bass (e.g.*, Paralabrax clathratus)*

(Note: species associated with each common name may vary by region or location.)

Many juveniles of these fish groups also utilize the canopy as habitat. In California, the giant sea bass (*Stereolepis gigas*) and pile surfperch (*Damalichthys vacca*) tend to be gregarious, swimming just under the canopy. A number of schooling fish, such as sardines, sometimes use the canopy. Invertebrates are less commonly seen in this upper level of the kelp forest, probably because the water motion prevents a good grasp to hold on to the kelp. Exceptions are pelagic species, such as jellies and shrimp, as well as some sessile organisms, such as diatoms, hydroids and bryozoans which can settle on the blades or stipes. Small gastropods (snails) can also be found on the blades of the canopy where they can remain aided by the strong suction adhesion of their foot. The canopy is also used as habitat by some marine mammals, especially sea otters which wrap themselves in kelp blades during resting periods to avoid drifting away or to protect themselves against predators such as white sharks (*Carcharodon carcharias),* killer whales (*Orcinus orca*), and bald eagles (*Haliaetus leucocephalus)* (Waite et al. 2002).

Fishes also dominate the organisms inhabiting the midwater zone of a kelp forest. Fish commonly found in the *Macrocystis pyrifera* beds of California are:

Kelp bass (e.g., *Paralabrax clathratus*)
Kelp surfperch (e.g., *Brachyistius frenatus*)
Rubberlip surfperch (e.g., *Rhacochilus toxoles*)
Blacksmith (e.g., *Chromis punctipinnis*)
Senorita (e.g., *Oxyjulis californica*) (Figure 13)
Halfmoon (e.g., *Medialuna californiensis)*
Giant kelpfish (e.g., *Heterostichus rostratus*)
Opaleye (e.g., *Girella nigricans), and*
Kelp clingfish (e.g., *Rimicola muscarum*)

Figure 12. Black rockfish. Photo courtesy of Kip Evans. Publication of NOAA Central Library. http://www.photolib.noaa.gov/sanctuary/sanc0805.htm

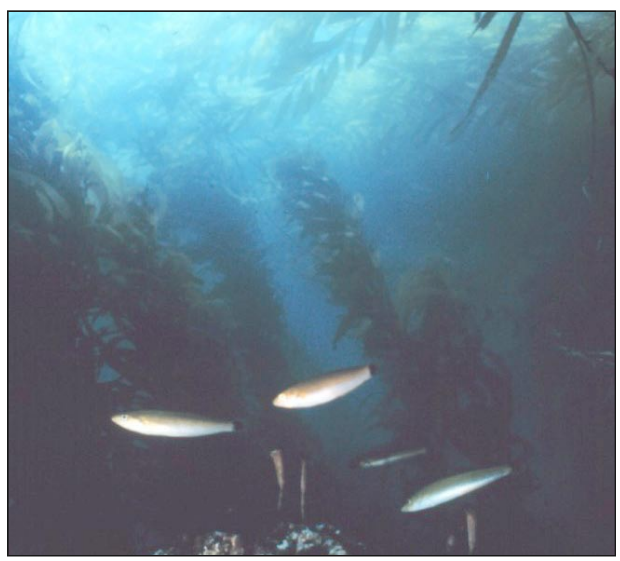

Figure 13. Senorita fish (*Oxyjulis californica*) in a giant kelp forest. Photo courtesy of Kip Evans. Publication of NOAA Central Library. http://www.photolib.noaa.gov/sanctuary/sanc0804.htm

(Note: species associated with each common name may vary by region or location.)

The halfmoon swims at midwater depth, occasionally feeding on sponges and bryozoans on the kelp stipes. The Rubberlip surfperch is also found at this midwater depth between the stipes. The clingfish attaches to kelp stipes using a suction cup and camouflages itself against predators. The most noticeable species associated with Southern California kelp forests is garibaldi (e.g., *Hypsypops rubicaunda*), with its bright orange adult color and high iridescent blue spots as juveniles. These individuals can be seen biting off pieces of kelp plants to feed on the bryozoa attached to the plant. The ocean whitefish (e.g., *Caulolatilus princeps*) wanders between the stipes several meters above the bottom and dives to the benthos to feed on the numerous crustaceans found there. Similar to the canopy, several invertebrates are able to utilize the structures provided by stipes and lower blades. These include hydroids, erect and encrusting bryozoans, and amphipods and other small crustaceans. Even larger gastropods and limpets can be found crawling up the stipes to graze. Some older stipes can also be heavily fouled (overgrown) by red algae.

At the bottom, kelp holdfasts, red algae, and the rock surface provide habitat for numerous mobile and sessile invertebrates and fishes. Sessile organisms found in this sub-habitat include:

Sponges
Hydroids
Tube dwelling polychaetes
Anemones (Figure 14)
Encrusting and erect bryozoans, and
Tunicates

Several polychaete worms and brittle stars make the interstitial spaces within kelp holdfast their protected home against predators. Such mobile invertebrates include:

Sea stars
Sea urchins
Sea cucumbers
Crabs and shrimp
Scallops
Gastropods
Nudibranchs, and
Limpets and abalone

Rockfish (*Sebastes* spp.) can be found in aggregations in the lower water depths around holdfast and between large rocks on the bottom. Gunnels, greenlings, sculpins, and ling cod also are common inhabitants of the benthos in kelp forests. Skates (Family Rajidae) and rays (Family Dasyatidae**)** can be seen moving along the bottom, and sanddabs (*Citharichthys* spp.) and halibut (e.g., *Paralichthys californicus*) are also common in this sub-habitat.

Provides Breeding and Nursery Grounds

Kelp and other macroalgae serve as breeding grounds for fishes, marine mammals, and sometimes birds. Several commercially important fish species (e.g., herring and rockfish)

Figure 14. Sea anemone (*Aiptasiidae*). Photo courtesy of Russel Bellmer, United States Fish and Wildlife Service.

use kelp forests as breeding grounds. Herring attach their eggs directly on the stipes of kelp. Sea otters have their young in kelp forest canopies, which provide shelter from strong currents and predators such as bald eagles and sharks. Birds usually do not use the subtidal kelp forest itself as breeding grounds, but intertidal kelp and other macroalgae can be important to some shorebirds and sea birds. Oystercatchers for instance, lay their eggs in macroalgal-dominated areas and sometimes shelter the eggs with algae. Kelp forests are also good nursery grounds because food is readily available for juveniles and the plants provide cover against predation. Some organisms such as fish, shrimps (Marliave and Roth 1995), and female otters with pups (Foster and Schiel 1985) commonly use kelp forests as nursery habitats.

Provides Feeding Grounds

Nutrients such as nitrate, nitrite, ammonia and phosphate are important for plant growth. Plants such as kelp and other macroalgal species absorb dissolved nutrients directly from the water through their blades which are then transported to other parts of the plant (e.g., stipe and holdfast).[5] Kelp and other macroalgae contribute substantial primary productivity and habitat complexity to the marine ecosystem (Dames and Moore 1977). Kelp plants, for example convert carbon dioxide (CO_2) and inorganic nutrients into organic matter that can be used as food by animals. When biological wastes and decayed plants and animals fall from the kelp forest into deep water, they form dissolved chemicals in the water. As water rises from deeper levels to the surface, they carry the dissolved chemical nutrients that are then used to nourish plants and animals amongst kelp. Thus, kelp form the base of the marine and estuarine food webs in the nearshore area where kelp dominates.

A variety of organisms uses kelp beds as feeding grounds on a number of different trophic levels. At the lowest trophic levels are the grazers, which utilize kelp directly by removing tissue from the algae. Grazers in kelp forests for example, include sea urchins, snails, and limpets. Although grazers usually are small in size compared to kelp, their feeding activities can have devastating effects. Urchins can graze at the stipes, causing dislodgement of entire kelp plants. Highly productive kelp forests were lost as a result of overgrazing by sea urchins in Nova Scotia (Johnson and Mann 1993) and the Aleutian Islands (Estes and Duggins 1995). Snails can occur in such large numbers that their grazing on the blades severely diminishes the photosynthetic capacity of kelp.

A large number of higher trophic level predators rely on these grazers and other omnivore invertebrates. Sea otters (Figures 15 and 16), lobsters, crabs, anemones, and fishes feed on sea urchins, snails, abalones, and limpets and play important roles in controlling these grazer populations (Barnes and Hughes 1993). Fish (e.g., lingcod, sculpins, and rockfish) commonly feed on small invertebrates and other fish that are present (Hogan and Enticknap 2003). Sea lions prey on fishes that live associated with kelp forests, and many diving birds, such as ducks and murres that feed in kelp forests.

Kelp is also the base of a second, detritus-based food web. A large portion of kelp biomass erodes through physical and bacterial actions and is supplied to the water column as detritus. This detritus is part of the diet of a large number of filter and deposit feeders, such as sponges, sea cucumbers, crustaceans, bryozoans, and ascidians, which in turn are food for predators such as nudibranchs, fishes, and crabs.

Provides Substrate for Attachment

Kelp provides attachment surfaces for many sessile and drifting life forms of various sizes. By attaching to kelp, species are able to obtain nutrients that are filtered by the blades. Some

[5] In the matrix at the end of this chapter, kelp's ability to "support nutrient cycling" is listed as a chemical function however the cycle of nutrients and, organisms that consume these nutrients relates to the biological functions of kelp and is discussed briefly under this section.

Figure 15. Sea otter wrapping in kelp blades. Photo courtesy of Russell Bellmer, Project Leader, United States Fish and Wildlife Service.

species such as barnacles (e.g., *Balanus* spp.), bryozoa (e.g., *Bugula* spp.), and foraminifera attach themselves to blades of kelp for support against currents. Some gastropods (e.g., turban snails) graze the fronds for epiphytic microalgae. The most common sessile organisms found in kelp forests include bryozoans, sponges (e.g., *Haliclona* spp.), tunicates (e.g., *Metandrocarpa* spp.), cup corals (e.g., *Balanophyllia* spp.), and anemones (e.g., *Epiactis* spp.).

Measuring and Monitoring Methods

Plant tissue analysis - Plant tissue analysis shows the nutrient status of plants at the time of sampling, i.e. whether there is adequate supply or deficiency of nutrients such as nitrogen and phosphorus that may affect kelp growth (Lyngby 1990). Kelp and other macroalgae wet samples are first collected and wet weight measured. The samples are then dried and grounded so that carbon and nitrogen concentrations in the plant tissues may be analyzed using a Carbon-Hydrogen-Nitrogen (CHN) elemental analyzer. Following acid digestion of the sample, phosphorus content can then be determined using spectrophotometric methods (Hernandez et al. 2001; Menendez et al. 2002).

Birds and marine mammals - Aerial surveys and direct counts along coastal and estuarine habitats can be used to monitor birds. Aerial

Figure 16. A sea otter feeding on a sea urchin. Photo courtesy of NOAA National Estuarine Research Reserve Collection. Publication of NOAA Central Library. http://www.photolib.noaa.gov/nerr/nerr0875.htm

surveys may be used to inventory shorebirds (Erwin et al. 1991) and monitor wintering populations (Morrison and Ross 1989). In addition, surveys are used to estimate relative abundance of migratory and wintering populations, as well as to assess population trends of migratory shorebirds. Direct counts are also used to estimate the number of shorebirds. In some cases, video cameras and aerial photography are used along with aerial surveys (Dolbeer et al. 1997). Photographs and other forms of data collected can be compared

Figure 17. Kelp attached to rocks on shore at low tide. Photo courtesy of Captain Albert E. Theberge, NOAA Corps (ret.). Publication of NOAA Central Library. http://www.photolib.noaa.gov/coastline/line2878.htm

to assess whether changes occurred in species numbers and distribution over time. In some cases, photographs may capture activities that may have occurred causing the reduction of one animal species and making conditions favorable for another. This can help the practitioner determine whether modifications can be made to the restoration project so that progress towards achieving a naturally sustainable habitat can be continued or whether the threat to the project is continuous and will continue to affect restoration progress.

Aerial surveys can also be used to count marine mammals. However, shore-based and boat-based surveys are usually more precise and allow for counting animals that spend considerable time underwater.

Fish and other species - Permanent transects and stations should be used to account for site variability and provide precise measurements of population dynamics where the major variable is time. Colored or otherwise marked transect lines are permanently attached to the seabed. Transect ends may be marked with a buoy to reduce search time. Permanent transects can be supplemented with random stations or transects. Transects and stations should also be located with Loran-C and GPS. The Loran-C system is a radio-navigation system that allows the user to accurately navigate and locate a position on the coastal waters and return to their starting position if needed. A global positioning system (GPS) is a satellite navigation system used to show an individual's exact position on Earth at anytime.

While there are numerous monitoring protocols, the following discussion focuses on those techniques most commonly used to gather data on population dynamics of selected kelp forest and other macroalgal associated organisms. Data collection should be replicated, and practitioners should consult a local biostatistician to ensure that the sampling design is not pseudoreplicated (i.e., replicate transects have to be spatially separated). Sampling and monitoring should also be replicated within a year to account for seasonal changes.

Typical sampling and monitoring methods for kelp-associated organisms include:

- Plankton nets (to sample larval fish) (Figure 18)
- Quadrat counts and percent cover estimates
- Swath transect counts
- Random point observations
- Roving diver fish counts, and
- Video fish transects (50 meters) in the kelp canopy, water column, and benthos

Described below are just a few of the many methods that can be used to sample and monitor fish and other mobile macroalgae associated species.

Plankton[6] nets - Plankton nets are used to capture plankton floating in the water column. These nets have a long funnel shape net that is used to capture different plankton sizes by changing the mesh size of the net and yet allowing water to filter through. These nets can

Figure 18. A diver deploys a plankton net in a kelp forest to collect larval fish. Photo courtesy of NOAA Office of Oceanic and Atmospheric Research, National Undersea Research Program. Publication of NOAA Central Library. http://www.photolib.noaa.gov/nurp/nur05519.htm

[6] The passively floating or weakly motile aquatic plants (phytoplankton) and animals (zooplankton).

be deployed by hand over the side of a boat or attached by hinges behind the boat and towed to collect plankton samples.

Quadrat counts and percent cover estimates - These measures can be used to efficiently and reliably assess the diversity and abundance of sedentary species and to record changes over time. An established set of species and other metrics can be assessed by divers in quadrats that are placed in fixed or random points along the transects. White plastic slates or clipboards with underwater paper are useful for notes. These measurements can be combined with the quantitative data obtained about kelp abundance (e.g., stipe counts, percent cover) and substrate. The size of the quadrat depends on the location and density of organisms. Usually, 50x50 centimeter or 1x1 meter quadrats provide sufficient area while still being manageable for a diver. It is also useful to work with three-sided quadrats, which can be easily placed on the bottom around tall kelp. Quadrats are commonly made out of PVC piping, but they should be weighted to avoid floating upward.

Swath transects - A certain width (one or two meters) on each side of the transect line is observed and fishes identified and counted. As different fish species may inhabit different sub-habitats of the kelp forest, these swaths can be repeated in midwater and under the canopy. If available, size frequency distributions can be used to estimate population age structure and to identify and monitor recruitment cohorts. Direct diver observations have often proven to be more reliable than video transects, but video can provide valuable support for fish observations if water clarity is good.

PHYSICAL

Filters Water and Stabilizes Sediments

Kelp and other macroalgae assist in filtering the water column by reducing wave energy and stabilizing sediments (discussed in various sections throughout this chapter). The kelp blades, as well as the holdfast (thallus), have the ability to slow water movement allowing sediments to accumulate on the benthic surface. This process helps to reduce the potential for erosion of shorelines by reducing wave energy.

CHEMICAL

The chemical characteristics of kelp and other macroalgae that are presented within the matrices, have been discussed within the structural and functional characteristics discussed above, particularly under sections titled “Physical” and “Dissolved Oxygen”.

PARAMETERS FOR MONITORING STRUCTURAL/FUNCTIONAL CHARACTERISTICS

The following matrices present parameters for restoration monitoring of the structural and functional characteristics of kelp and other macroalgae. These matrices are not exhaustive, but represent those elements most commonly used in such restoration monitoring strategies.

These parameters have been recommended by experts in kelp restoration as well as in the literature on kelp and other macroalgae restoration and ecological monitoring. Parameters with a closed circle (●) should be considered in monitoring restoration performance. Parameters with an open circle (❍) may also be measured, depending on specific restoration goals.

Parameters to Monitor the Structural Characteristics of Kelp and Other Macroalgae

Parameters to Monitor	Structural Characteristics: **Biological**	Habitat created by animals	Habitat created by plants	**Physical**	Sediment grain size	Light availability/Turbidity	**Hydrological**	Current velocity	Tides/Hydroperiod	Water sources	Wave energy	**Chemical**	pH, salinity, toxics, redox, Dissolved oxygen
Geographical													
Acreage of habitat types		❍	●										
Biological													
Plants													
Species, composition, and % cover of:													
Algae			●										
Epiphytes			❍										
Canopy aerial extent and structure			❍										
Interspersion of habitat types		●	●										
Plant height			❍										
Seedling survival			❍										
Hydrological													
Physical													
Photosynthetically active radiation (PAR)[7]						●							
Secchi disc depth						●							
Shear force at sediment surface								❍			❍		
Water column current velocity								●					
Water level fluctuation over time									❍				
Water temperature													●
Chemical													
Dissolved oxygen													❍
pH													❍
Salinity									❍				●
Toxics													❍
Soil/Sediment													
Physical													
Geomorphology (slope, basin cross section)									●				
Organic content					❍				❍				
Percent sand, silt, and clay					❍								
Chemical													
Pore water nitrogen and phosphorus										❍			

[7] Measured at canopy height and substrate surface.

Parameters to Monitor the Functional Characteristics of Kelp and Other Macroalgae

Parameters to Monitor	Biological	Contributes to primary production	Provides breeding grounds	Provides feeding grounds	Provides nursery areas	Provides habitat	Provides substrate for attachment	Supports complex trophic structure	Supports biomass production	Supports biodiversity	Physical	Reduces erosion potential	Reduces wave energy	Chemical	Modifies chemical water quality	Modifies dissolved oxygen	Supports nutrient cycling
Geographical																	
Acreage of habitat types		●	●	●	●	●	●	●	●	●		●	●		●	●	●
Biological																	
Plants																	
Species, composition, and % cover of:																	
Algae		●	●	●	●	●	●	●	●	●		●	●		●	●	●
Epiphytes		❍		❍				❍	❍	❍						❍	❍
Canopy aerial extent and structure			❍	❍	❍	❍	❍		❍	❍			❍				
Interspersion of habitat types			❍	❍	❍	❍		❍	❍	❍		❍	❍		❍		❍
Plant health (herbivory damage, disease[8])																	
Plant weight (above and/or below ground parts)		❍							❍								
Nutrient levels in algal tissues (nitrogen, phosphorus)		❍		❍					❍								
Rate of canopy closure															❍		❍
Seedling survival[8]		❍							❍								
Stem density					❍	❍	❍❍	❍				❍	❍				
Biological																	
Animals																	
Species, composition, and abundance of:																	
Birds																	
Fish			❍	❍	❍	●		❍	❍	❍							
Invertebrates			❍	❍	❍	●		❍	❍	❍							

[8] If the whole community is destroyed by disease or lack of seedling survival, all vegetation-related functions will be impaired.

Parameters to Monitor the Functional Characteristics of Kelp and Other Macroalgae (cont.)

Parameters to Monitor	Biological: Contributes to primary production	Provides breeding grounds	Provides feeding grounds	Provides nursery areas	Provides habitat	Provides substrate for attachment	Supports complex trophic structure	Supports biomass production	Supports biodiversity	Physical: Reduces erosion potential	Reduces wave energy	Chemical: Modifies chemical water quality	Modifies dissolved oxygen	Supports nutrient cycling
Hydrological														
Physical														
Photosynthetically active radiation (PAR)	●							●						
Secchi disc depth	●							●						
Trash			❍											
Water column current velocity										❍				
Water level fluctuation over time		❍	❍	❍	❍					❍			❍	❍
Chemical														
Dissolved oxygen		❍		❍			❍		❍			❍	❍	❍
Toxics		❍	❍	❍								❍		
Soil/Sediment														
Physical														
Geomorphology (slope, basin cross section)		●	●	●	●	●			●	●		●	●	
Sediment grain size (OM[9]/sand/silt/clay/gravel/cobble)						❍		❍		❍	❍	❍	❍	❍

[9] Organic matter.

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APPENDIX I: KELP AND OTHER MACROALGAE ANNOTATED BIBLIOGRAPHY

This annotated bibliography contains summaries of restoration case studies and basic ecological literature. It is designed to provide restoration practitioners with examples of previous restoration projects as well as overviews of papers from the ecological literature that offer more detail than that covered in the associated chapter. Entries are presented from both peer reviewed and grey literature. They were selected through extensive literature and Internet searches as well as input from reviewers. They are not, however, a complete listing of all of the available literature. Entries are arranged alphabetically. Wherever possible, web addresses or other contact information has been included in the reference to assist readers in easily obtaining the original resource. Summaries preceded by the terms '*Author Abstract'* or *'Publisher Introduction*' or similar descriptors were taken directly from their original source. Summaries without such descriptors were written by the author of the associated chapter.

Beissinger, S. R. 1995. Population trends of the marbled murrelet projected from demographic analyses, pp. 385-393. In Ralph, C. J., G. L. Hunt Jr., M. G. Raphael and J. F. Piatt (eds.), Ecology and Conservation of the Marbled Murrelet. Technical report - Pacific Southwest Research Station 152.

Author Abstract. This paper discusses monitoring of marbled murrelet populations amongst kelp beds. Researchers used a demographic model of the marbled murrelet to investigate possible population trends and factors that may influence them. The model included field data on juvenile ratios that were collected near the end of the breeding season and rectified for date of census, to estimate fecundity. See publication for additional information on techniques used. Murrelet survivorship estimates were based on comparative analyses of allometric relationships from 10 species of alcids. Results showed that the juvenile ratios were commonly low but were higher from shore or in kelp beds than conducted offshore (<5%). Annual survivorship was correlated to alcids body size. Marbled murrelet survivorship was predicted to be 0.845 and range to 0.90. The expected annual population growth rate was estimated based on combinations of fecundity and survival. This indicated that under all combinations murrelet populations were expected to decline. Based on data, rates of decline are predicted to be 4-6 percent per year, but the rate of decline could be twice as large. Results were based on factors affecting murrelet population growth, and the use of juvenile ratios for monitoring murrelet populations.

Burridge, T. R., M. Karistianos and J. Bidwell. 1999. The use of aquatic macrophyte ecotoxicological assays in monitoring coastal effluent discharges in southern Australia. *Marine Pollution Bulletin* 39: 89-96.

Author Abstract. Germination inhibition of zoospores of the aquatic, brown algal macrophyte *Ecklonia radiata* was employed to assess the toxicity of sewage effluents under short to long-term exposure and under modified salinity conditions. The rate of germination inhibition was determined for exposure times between 2 and 48 h in salinity modified and unmodified regimes and under reduced salinity conditions alone. The results indicated that rate of germination inhibition increased with duration of exposure to sewage effluents and to salinity reduction alone, and that response to the effluents may be enhanced under conditions of reduced salinity. Whilst the effect of primary treated effluent was primarily that of toxicity, secondary treated effluent effects appeared to be primarily that of reduced salinity although at a greater rate than would be expected for salinity reduction alone. The assay is suggested to provide a mechanism for monitoring sewage effluent quality and to monitor potential impacts of sewage effluent discharge on kelp communities in southern Australia.

Burridge, T., S. Campbell and J. Bidwell. 1999. Use of the kelp *Ecklonia radiata* (*Laminariales: Phaeophyta*) in routine toxicity testing of sewage effluents. *Australasian Journal of Ecotoxicology* 5: 133-140.

Author Abstract. This paper investigates the effect of primary and secondary treated sewage effluents on reproductive phases of the life cycle of the marine macrophyte (kelp) *Ecklonia radiata. Ecklonia radiata* is a major primary producer in near-shore medium to high energy habitats and as a benthic organism is subject to long-term chronic exposure to coastal effluent. See publication for additional information on methods used for toxicity testing with the use of kelp. Inhibition of germination and reduction in growth rate of gametophytes are used as end points in bioassays. For primary treated effluent, germination was significantly inhibited at 1% effluent while growth was significantly inhibited at 4% effluent. Responses to secondary treated effluent indicated that for both endpoints the principal effect was related to reduce salinity. For one of the secondary treated effluents and for both bioassays there was no significant difference in response from salinity reduction bioassays, and for the second effluent type toxicity was expressed at 40% to 60% effluent. The results indicate that both bioassays offer great potential for the routine screening of effluent quality. Both bioassays and especially the germination inhibition bioassay are simple to conduct, show high reproducibility and are ecologically relevant.

Bushing, W. W. 2000. Monitoring the persistence of Giant kelp around Santa Catalina island using a geographic information system. *Journal of Phycology* 36:9-10.

Author Abstract. Geographic information systems (GIS) facilitate monitoring and analysis of population distributions at spatial and temporal scales differing from those employed in conventional field monitoring. This study utilizes a GIS-based gap analysis of a network of marine reserves around Santa Catalina Island relative to the regional ecology, disturbance regime, and persistence of Giant kelp (*Macrocystis pyrifera*), a keystone species in the nearshore, marine environment. Catalina's orientation and greatly-dissected coastline create diverse microhabitats with respect to storm exposure, temperature, light regime and topographic factors. GIS overlay methods applied to multi-temporal kelp distribution maps generated a model representing the spatial "persistence" of kelp. Correlations between the kelp's geographic distribution and persistence, the disturbance regime and physical variables conferring resistance to or recovery from it were drawn. This analysis identified regions of persistent kelp under disturbance regimes markedly different from those in the existing reserves, suggesting the designation of additional reserves in unprotected areas is ecologically warranted.

Christie, H., S. Fredriksen and E. Rinde. 1998. Regrowth of kelp and colonization of epiphyte and fauna community after kelp trawling at the coast of Norway. *Hydrobiologia* 375-376:49-58.

Author Abstract. Off the Norwegian coast the kelp plants form dense forests, 1-2 m high, and house a large number of epiphytes and associated invertebrates. Researchers sampled kelp, epiphytes, and holdfast (thallus) (hapteron) fauna at two different regions in untrawled kelp forest and at sites trawled different number of years ago. Researchers examined the rate of kelp regrowth after trawling, and in what time scale the associated flora and fauna colonize the trawled areas. See publication for additional information on techniques used. Trawling removed adult kelp plants (the canopy plants), while small understory kelp plants were left undisturbed. Results showed that under improved light conditions recruits made the new generation of canopy-forming kelp plants that exceeded a height of 1 m within 2-3 y. Percent cover, abundance and number of epiphytic species increased with time following trawling, but epiphytic communities were not totally re-established before the next trawling episode. Colonization of most species of fauna inhabiting the kelp holdfast (thallus) was found as early as one year after trawling. However, increasing size of the habitat by age of kelp allowed both individuals and species numbers to increase. Slow colonization rate by some species might be due to low dispersal potential. Researchers concluded that due to a higher maximum age and size of kelp plants in the northernmost region studied, restoration of kelp and kelp forest community was slower there.

Cole, R. G. and C. Syms. 1999. Using spatial pattern analysis to distinguish causes of mortality: an example from kelp in north-eastern New Zealand. *Journal of Ecology* 87:963-972.

Author Abstract. Spatial analysis techniques were used to differentiate between climate-induced and pathogen-induced mass mortalities of the kelp *Ecklonia radiata* in north-eastern New Zealand. We predicted that climate-induced effects would generate broad-scale patterns, whereas pathogen-induced mortality would be traceable among neighbouring thalli. Spatial autocorrelation analysis was performed on the proportion of *E. radiata* affected by dieback in quadrats during an initial mortality event in 1991. The absence of any consistent spatial scale of affected thalli between 10 and 100 m suggested that small-scale spread of an agent might be occurring. Individual thalli were therefore mapped at two sites during a subsequent mortality event in 1992/93, and the degree of damage recorded. Spatial analyses found little evidence of aggregation of either intact or affected thalli at scales of 1-150 cm. The relative spatial patterns of healthy and affected plants in mapped quadrats during the 1992/93 mortality provided little evidence of spatial association or repulsion between these broad damage categories. The large-scale mortality of 1992/93 was consistent with a physiological response to broad-scale light deprivation, although other agents, perhaps both a virus and amphipod grazing, might also have been involved. Potentially complex interactions among the candidate agents render interpretation of the spatial patterns difficult.

Dayton, P. K. 1985. The structure and regulation of some South American kelp communities. *Ecological Monographs* 55:447-468.

The goal of the study was to assess how physical stress and herbivores influence giant kelp (*Macrocystis pyrifera)* distribution, abundance, size frequency, and mortality in the southeast Pacific. Data was collected by scuba diving and belt transects. Transects were placed beside isobaths in order to quantify depth effects. In some cases photographs were used to collect data. Results showed that *Loxechinus* was limited by larval recruitment in the far south, sedimentation, fresh water protected fjords, and by fishing in the northern areas. Significantly low *Loxechinus* densities were due to reduced kelp populations. Kelp mortality results from drifting *Macrocystis* plants. Based on studies, kelp populations seemed restricted by physical factors in the fjords and *Loxechinus* grazing in most areas.

Dean, T. A. and S. C. Jewett. 2001. Habitat-specific recovery of shallow subtidal communities following the *Exxon Valdez* oil spill. *Ecological Applications* 11:1456-1471.

Researchers compared *Exxon Valdez* oil spill impacts within kelp and eelgrass communities and examined recovery of these communities over a period of ten years after the spill. Methods used to assess oil spill impacts was an After Control Impact Pairs (ACI-P) design (Green 1979, Osenberg and Schmitt 1996). See publication for additional information on methods used. Observations revealed that impacts were mostly in sheltered bays that were exposed to heavy oiling. Results showed that within a year after the spill, total polycyclic aromatic hydrocarbons (TPAHs) concentrations were higher, negatively affecting organisms in both communities but eelgrass organisms were affected more severely than those in kelp beds. Overall recovery was slower in eelgrass than in kelp habitats. Within six years after the spill, approximately 80% of the groups in eelgrass beds showed little signs of recovery. However, kelp beds recovered within two years. Researchers stated that data supported previous findings that impacts due to large oil spills are persistent.

Dean, T. A. and D. Jung. 2001. Transplanting Giant Kelp (*Macrocystis pyrifera*) onto Artificial Reefs: The San Clemente Reef Mitigation Project, pp. 31-34. In Jewett, S. C. (ed.), Cold Water Diving for Science. University of Alaska Sea Grant, Fairbanks AK.

Author Abstract. Southern California Edison Co. (SCE) is required to build a 300 hectare (150 acre) artificial reef for the purpose of mitigating the impacts of the San Onofre Nuclear Generating Station on nearby kelp bed communities. One of the primary mitigation requirements is that the reef supports a stable population of moderate to high density of giant kelp (*Macrocystis pyrifera*). As an initial step in reef development, SCE constructed an experimental reef in fall 1999 to test several reef designs that are being considered for the larger mitigation effort (Deysher et al. 1998, in press). The experimental reef consists of fifty-six modules, each measuring approximately 40 x 40 m, which were placed on a sandy bottom at depths of 12 to 15 m off San Clemente, CA. Half the modules were constructed of quarry rock, the other half were constructed of waste concrete, and all were low relief (less than 1 m). In summer 2000, we transplanted juvenile giant kelp (*M. pyrifera*) onto 14 of these modules (seven quarry-rock and seven concrete) to test transplanting as a potential means of enhancing and maintaining moderate to high densities of kelp. In this paper we describe the diving techniques used in anchoring these plants onto concrete or rocks. The kelp used in transplanting were initially reared in the laboratory using methods described in Foster et al. (1985) and then transplanted onto the reefs. Divers collected sporophylls (spore-bearing blades) from the base of adult kelp and brought these back to the laboratory. There, we released spores from the blades and inoculated 0.6 cm diameter x 10 cm long nylon lines with the spore solution. The lines were cultured in the laboratory for about three to five weeks until a dense culture of small kelp plants (about 1 mm to 5 mm in height) was visible. The lines were then taken to reef sites and anchored onto rocks or concrete.

Dean T. A., J. L. Bodkin, S. C. Jewett, D. H. Monson and D. Jung. 2000. Changes in sea urchins and kelp following a reduction in sea otter density as a result of the *Exxon Valdez* oil spill. *Marine Ecology Progress Series* 199:281-291.

Author Abstract. Interactions between sea otters *Enhydra lutris*, sea urchins *Strongylocentrotus* *droebachiensis*, and kelp were investigated following the reduction in sea otter density in Prince William Sound, Alaska, after the *Exxon Valdez* oil spill in 1989. At northern Knight Island, a heavily oiled portion of the sound, sea otter abundance was reduced by a minimum of 50% by the oil spill, and from 1995 through 1998 remained at an estimated 66% lower than in 1973. Where sea otter densities were reduced, there were proportionally more large sea urchins. However, except in some widely scattered aggregations, both density and biomass of sea urchins were similar in an area of reduced sea otter density compared with an area where sea otters remained about 10 times more abundant. Furthermore, there was no change in kelp abundance in the area of reduced sea otter density. This is in contrast to greatly increased biomass of sea urchins and greatly reduced kelp density observed following an approximate 90% decline in sea otter abundance in the western Aleutian Islands. The variation in community response to a reduction in sea otters may be related to the magnitude of the reduction and the non-linear response by sea urchins to changes in predator abundance. The number of surviving sea otters may have been high enough to suppress sea urchin populations in Prince William Sound, but not in the Aleutians. Alternatively, differences in response may have been due to differences in the frequency or magnitude of sea urchin recruitment. Densities of small sea urchins were much higher in the Aleutian system even prior to the reduction in sea otters, suggesting a higher rate of recruitment.

Dean, T. A., K. Thies and S. Lagos. 1989. Survival of juvenile giant kelp: The effects of demographic factors, competitors, and grazers. *Ecology* 70:483-495.

Researchers examined survival patterns of juvenile giant kelp (*Macrocystis pyrifera*). Kelp was measured using quadrats and transects. Transects were marked permanently with steel bars that were forced into the bottom sediment. Juvenile kelp or larger were tagged along each transect. Researchers then mapped the location of each plant by recording the plant's distance from the center line. Surveys were performed to determine the presence and absence of each plant tagged, determined the bulk density of survivors, tagged and mapped newly recruited plants. Data collected showed survival was low in zones wherever white sea urchins (*Lytechinus anamesus*) were abundant or where there was an overlying canopy of adults. At other sites, the density of recruits that survived varied, and the amount of juveniles that survived negatively correlated with the number of recruits. In addition, algal competitors (*Pterygophora californica* and *Cystoseira osmundacea*), red sea urchins (*Strongylocentrotus franciscanus*) and substrate distributions had no significant effect on juvenile kelp survival.

Dean, T. A. and L. E. Deysher. 1994. Kelp restoration and establishment techniques. *Bulletin of Marine Science* 55:1333.

Author Abstract. This paper discusses the growth of Giant kelp on natural and artificial reefs for enhancing reef productivity and providing structure for fish and invertebrates. Researchers mention that transplanting of juvenile kelp appears most cost effective. The young plants can be collected after recruitment or can be reared in the laboratory. See publication for additional information on techniques used. Researchers "seed" kelp spores onto nylon lines, in the laboratory and grow plants to a small (1 mm) sporophyte stage. Sporophytes on lines however can be reared to a larger size (50 cm to 1 m in length) in the laboratory or in field "grow out" areas. Results showed that field "grow out" proved more successful and cost effective than laboratory grow out. Juvenile kelp (50 cm to 1 m) was transplanted on more than 20 occasions with success. Results also showed that approximately 90% of field "grow outs" provided large numbers of sporophytes for transplanting. Researchers concluded that in 3-5 months average height is about 50 cm and can then be transplanted to substrates. The survival rate is expected to be high (>80%) when planted in appropriate habitats.

Dean, T. A., M. S. Stekoll and R. O. Smith. 1996. Kelps and oil: The effects of the *Exxon Valdez* oil spill on subtidal algae, pp. 412-423. In Rice, S. D., R. B. Spies, D. A. Wolfe and B. A. Wright (eds.), Proceedings of the *Exxon Valdez* Oil Spill, American Fisheries Society Symposium 18. AFS Bethesda, MD.

Author Abstract. This study examined possible changes in the subtidal macroalgal populations as a result of the *Exxon Valdez* oil spill. The abundance and size distribution of dominant subtidal algae were measured in Prince William Sound one year after the spill. Population density, biomass, and cover were compared between oiled and control sites within each of three habitats: sheltered bays, moderately exposed points, and very exposed points with a surface canopy of *Nereocystis luetkeana*. Dominant macroalgae in these habitats were the kelps *Agarum cribrosum, Laminaria saccharina*, *L. groenlandica,* and *N. luetkeana.* There were no differences in the total density, biomass, or percentage cover of macroalgae between oiled and control sites. However, at least one of the dominant kelp species within each habitat was more abundant at the oiled sites. In addition, there were generally more small plants at oiled sites, suggesting recent recruitment or slower growth there. Recruitment at oiled sites may have been indicative of recovery from recent oil-related disturbance. Although these data suggest possible injury to kelps as a result of the spill, there were no apparent long-term impacts on subtidal populations of macroalgae.

De Vogelaere, A. P. and M. S. Foster. 1994. Damage and recovery in intertidal *Fucus gardneri* assemblages following the *Exxon Valdez* oil spill. *Marine Ecology Progress Series* 106:263-271.

Author Abstract. In March 1989, the *Exxon Valdez* spilled over 10 million gallons (ca 38 million l) of crude oil into Prince William Sound, Alaska, USA. The spill was followed by massive clean-up using hot seawater at high pressure as well as other mechanical and chemical techniques. Researchers studied initial damage and subsequent recovery in the upper margin of the *Fucus gardneri* assemblage on protected shores by comparing sites that were unoiled, oiled and cleaned with hot water at high pressure, and oiled but less intensely cleaned. See publication for additional information on method used. *F. gardneri* cover averaged 80 % on unoiled sites but <1 % on all oiled and cleaned sites 18 mo after the spill. The abundances of barnacles, littorine snails and limpets varied among sites and species, and this variation was associated in part with differences in their life histories. *F. gardneri* cover was still extremely low on oiled and cleaned sites 2.5 yr after the spill. Holdfasts (thallus) that persisted after cleaning did not re-sprout. *F. gardneri* recruitment was lowest at intensely cleaned sites, and most recruits occurred in cracks near adults. Recruits were less abundant under adult canopies but placing canopies over recruits did not decrease their survivorship over 5 mo. Natural weathering of tar was rapid, with most marked patches gone in less than 1 yr.

Ebeling, A. W., D. R. Laur and R. J. Rowley. 1985. Severe storm disturbances and reversal of community structure in a southern California kelp forest. *Marine Biology*. 84: 287-294.

Author Abstract. Regular observations made over a period of 5 yr in 4 permanent transects provided data on plant, sea urchin, and fish densities which indicate that 2 unusually severe winter storms in 1980 ("Storm I") and 1983 ("Storm II") had different effects on a southern California kelp-forest community. Storm I removed all canopies of the giant kelp *Macrocystis pyrifera*, but spared most understory kelps, mainly *Pterygophora californica*. Hence, the previously large accumulation of detached drift kelp, mostly *M. pyrifera,* disappeared. Denied their preferred diet of drift kelp, the sea urchins *Strongylocentrotus franciscanus* and *S. purpuratus* then emerged from shelters to find alternative food. Without effective predators, they consumed most living plants, including the surviving understory kelps. This weakened the important detritus-based food chain. In 1983, Storm II reversed the process by eliminating exposed urchins, while clearing rock surfaces for widespread kelp settlement and growth.

Edwards, M. S. and G. Hernandez-Carmona. 2000. Scale-dependent patterns of disturbance and recovery in Giant kelp forests. *Journal of Phycology* 36:540-544.

Author Abstract. We studied spatial variability in giant kelp (*Macrocystis pyrifera*) forests at 84 sites along the West coast of North America in order to assess the impacts of the 1997-98 El Niño. Our sites spanned the geographic range of giant kelp in the Northern Hemisphere and were surveyed just before, immediately following, several months after, more than one year after, and nearly two years after the El Niño. Interspersion of sample units allowed us to compare the effects of this disturbance among spatial scales ranging from a few meters to more than a thousand kilometers. Variance components analyses revealed that El Niño shifted the relative importance of factors that regulate giant kelp communities from factors acting at the scale of a few meters (local control) to factors operating at hundreds of kilometers (regional control). Moreover, El Niño resulted in a near-to-complete loss of giant kelp populations throughout nearly two-thirds of the species' range. Evaluation of these effects along with oceanographic data (at the "appropriate" spatial scales), along with closer examination of giant kelp populations in the most severely impacted region (Baja) suggested that the among-region differences in giant kelp survival was due, at least in part, to El Niño-induced differences in ocean climate. Giant kelp recovery following El Niño was also scale-dependent, but driven by factors different from those of the disturbance. Here, we present results for several species of macroalgae in an attempt to relate the importance of El Niño to that of other processes in creating scale-dependent patterns of variability.

Gerard, V. A. 1984. The light environment in a giant kelp forest: Influence of *Macrocystis pyrifera* on spatial and temporal variability. *Marine Biology* 84:189-195.

Practitioners measured quantum irradiance at numerous depths in giant kelp *M. pyrifera* (L.) C. Agardh forests in southern California throughout summer of 1983. Quantum irradiance measurements were made using two quantum scale profiling systems along with underwater sensors. The sensor was used to measure irradiance at the surface. Data were documented simultaneously from the sensors via IMS International computer and Biospherical Instruments interface hardware and software. Light transmission was also measured through each canopy blade using underwater sensors. Results showed that maximum irradiance reduction occurred in the top 1 m of the water column where the kelp fronds produced surface canopies. Average irradiances were documented at 1 m depth below kelp canopies beneath adequate sunlight levels at surface conditions. Light penetration correlated with canopy density, however, was greater than transmission through individual kelp blades.

Graham, M. H., C. Harrold, S. Lisin, K. Light, J. M. Watanabe and M. S. Foster. 1997. Population dynamics of Giant kelp *Macrocystis pyrifera* along a wave exposure gradient. *Marine Ecology Progress Series* 148:269-279.

Author Abstract. Sporophyte recruitment, holdfast (thallus) growth, and mortality of Giant kelp *Macrocystis pyrifera* were measured seasonally on permanent transects at three sites (protected, intermediate, and exposed) along a wave exposure gradient on the Monterey Peninsula, central California (USA) between 1988 and 1991. The constant presence of cold, nutrient-rich water and the relative absence of other kelps and large grazers allowed the dynamics of *M. pyrifera* populations to be examined under conditions in which wave exposure was highly variable and influences of other abiotic and biotic factors were minimized. Recovery of *M. pyrifera* populations from decreased adult density (presumably due to storm-induced mortality; adult density was negatively correlated with storm activity) was a two-stage process requiring the establishment of juvenile populations and conditions suitable for juvenile growth to adult size. Sporophyte recruitment was negatively correlated with *M. pyrifera* canopy cover, and thus appeared to be related to irradiance. Recruitment was low and continuous under a temporally stable *M. pyrifera* canopy at the protected site. At the intermediate and exposed sites, canopy cover was more variable, canopy loss was greater, and durations of low canopy cover were longer than at the protected site, resulting in episodic sporophyte recruitment.

Hernandez-Carmona, G., O. Garcia, D. Robledo and M. Foster. 2000. Restoration techniques for *Macrocystis pyrifera* (Phaeophyceae) populations at the southern limit of their distribution in Mexico. *Botanica Marina* 43:273-284.

Author Abstract. Following the 1982-83 El Niño, *Macrocystis pyrifera* (L.) C. Agardh, forests disappeared throughout their range in Baja California. The giant kelp forests subsequently recovered within this range except at their extreme southern limit, a region encompassing 50 km of coastline with a former giant kelp standing stock of 28,000 wet tons. Two techniques were tested to restore these forests: juvenile transplantation and seeding with sporophylls. For transplanting, juvenile *M. pyrifera* sporophytes were attached to *Eisenia arborea* stumps seasonally over a two-year period. Average survival of transplants ranged from 7% in spring to 41% in winter. After two years, the average number of basal fronds per plant increased from 2 to 64 per plant and surface fronds from 0 to 34 per plant. Average frond growth rate of the transplants ranged from 8.1 cm day^{-1} in summer to 10.8 cm day^{-1} in winter. No significant differences in growth rate were found among treatments (seasons) for the transplants, but control plants showed a seasonal variation, with higher frond growth rates in winter (13.3 cm day^{-1} and spring (9.3 cm day^{-1} and lower in summer (4.4 cm day^{-1}). The seeding technique was tested in a fully orthogonal-block design with three factors with two levels (factors: ± sporophylls addition, ± *Eisenia arborea* and ± understory algae). *Macrocystis pyrifera* recruitment occurred only in treatments with added sporophylls. The highest recruitment occurred where all algae were removed from the bottom, followed by the treatments without understory algae but with *Eisenia arborea*. Results suggest that a lack of spores and the presence of understory algae were the main factors inhibiting *Macrocystis pyrifera* recruitment in the area. Lower sea water temperatures and high nutrient concentrations occurred in spring and high temperatures and low nutrients in summer suggesting, as in southern California, an inverse relationship between these two factors. The results suggest a combined approach of transplanting juveniles and seeding during spring would be most effective for restoring the *M. pyrifera* forests.

Karsten, U., K. Bischof and C. Wiencke. 2001. Photosynthetic performance of Arctic macroalgae after transplantation from deep to shallow waters. *Oecologia* 127:11-20.

Author Abstract. Transplantation experiments conducted in the Arctic Kongsfjord (Spitsbergen) in summer 1997 investigated the effects of various types of filtered natural radiation (solar, solar without UV-B, solar without UV-A/B) on photosynthesis of various macroalgae. Two brown algal species (*Laminaria solidungula, Saccorhiza dermatodea*) and four red algal species (*Palmaria palmata, Phycodrys rubens*, *Phyllophora truncata, Ptilota plumosa*) were collected from deeper waters, kept in UV-transparent plexiglass tubes wrapped with different spectral cut-off filter foils and positioned at fixed depths in shallow waters for 7-9 days. At regular intervals, chlorophyll fluorescence of photosystem II (optimum quantum yield, Fv/ Fm) was determined, as an indicator of photosynthetic performance. The data demonstrate that shallow-water species such as *P. palmata* are much less affected by natural photosynthetically active radiation (PAR) and UV radiation near the surface than extremely sensitive deep-water species such as *Phyc. rubens* which exhibited strong decreases in photosynthetic performance, as well as photobleaching of part of the thallus. The other species showed intermediate response patterns. In most species investigated inhibition of photosynthesis was mainly caused by the UV-B wavelengths. Interpretation of the data clearly indicates species-specific tolerances of photosynthesis to ambient solar radiation which can be explained by broad physiological acclimation potentials and/or genetic adaptation to certain (low or high) irradiances. The species-specific photosynthetic performance under radiation stress is in good accordance with the vertical distribution of the macroalgae on the shore.

Leinaas, H. P. and H. Christie. 1996. Effects of removing sea urchins (*Strongylocentrotus droebachiensis*): Stability of the barren state and succession of kelp forest recovery in the east Atlantic. *Oecologia* 105:524-536.

Author Abstract. Stability properties of the barren state of a kelp forest-sea urchin system were studied in northern Norway. The ability of the sea urchin *Strongylocentrotus droebachiensis* to maintain high population densities and recover from perturbations, and the succession of kelp forest revegetation, were studied experimentally by reducing the sea urchin density on a barren skerry. Additional information was obtained from community changes following a natural, but patchy, sea urchin mortality that varied between sites. On the barren grounds, high sea urchin densities (30-50 per m^2) are maintained by annual recruitment. Severe reductions of sea urchin densities initiated luxuriant kelp growth, while more moderate reductions allowed establishment of opportunistic algae (during spring and early summer), but no kelps. Succession of algal growth, after the severe decline in sea urchin densities, followed a predictable pattern. At first the substrate was colonized by filamentous algae, but within a few weeks they were outcompeted by the fast growing kelp *Laminaria saccharina.* After 3-4 years of the removal experiment, the slower-growing, long-lived kelp *L. hyperborea* became increasingly dominant. Increased food availability after reduction in sea urchin density led to increased individual growth of the remaining sea urchins. However, the population density did not increase, neither from recruitment nor immigration from adjacent areas with high sea urchin densities. Possibly, early establishment of a dense kelp stand, may represent a breakpoint in the ability of sea urchins to reestablish a barren state. The ability of *L. saccharina* quickly to invade and monopolize an area may have both positive and negative effects on the succession towards the climax *L.*

hyperborea kelp forest. Competitive interactions may slow the process, but development of a dense stand of *L. saccharina* will also reduce grazing risk on scattered recruits of the more slowly growing *L. hyperborea.*

Lindstrom, S. C., J. P. Houghton and D. C. Lees. 1999. Intertidal macroalgal community structure in southwestern Prince William Sound, Alaska. *Botanica Marina* 42:265-280.

Researchers conducted long-term sampling of the intertidal zone in southwestern Prince William Sound after the *Exxon Valdez* oil spill. From 1989-1996 samples were taken in twenty-one intertidal locations which include mixed soft substrata, small boulder cobble and three rocky bedrock types. Oiling and treatments used include: unoiled, oiled, and unwashed; and oiled and washed with warm or hot water. Mixed gravel/sand/silt (mixed-soft) sites were characterized by *Fucus gardneri,* bivalves (*Mytilus spp*) and barnacles (*Balanus spp*.) in the mid-intertidal and by *Cladophora sericea, Fucus,* and *Pilayella littoralis* in the low intertidal zone. *Polysiphonia aff. tongatensis* was found only at mixed-soft sites. Boulder-cobble sites were characterized by *Acrosiphonia arcta, Fucus gardneri,* and 'Ralfsia' sp. in the low zone; in the mid-zone vegetation is minimal. Methods for evaluating impacts included the use of a 30-m horizontal transect line at three elevations at most sites. Points were located randomly along each transect line for placement of five or ten quadrats. Sampling points were marked permanently to ensure that quadrats are situated precisely each year (0.50m X 0.50m). Photographs were taken of each quadrat per year. Species were identified in each quadrat and categorized. Benthic macroalgae presence was confirmed using non-quantitative synoptic collapses. Species abundance was used in data analyses. Data analysis was then manipulated and analyzed using Microsoft excel and Principal Components Analysis (PCA). Results showed significant changes in annual species abundance over time, and interannual differences in species abundance and richness. See publication for additional information on techniques used for evaluating and analyzing macroalgae abundance.

Lyngby, J. E., S. M. Mortensen and M. Munawar (eds.). 1994. Assessment of nutrient availability and limitation using macroalgae. *Journal of Aquatic and Ecosystem Health* 3: 27-34.

Author Abstract. Researchers used macroalga as indictors for nutrient availability that also limits macroalga density. Macroalga, *Ulva lactuca* L., were transplanted around an ocean outfall and at a reference site in Koge Bay, Denmark, to assess the influence of outfall on the nutrient availability. Ten discs of *Ulva lactuca* were transplanted to perforated plexiglass cages and incubated at depths 0.5m, 2m and 3.5m. Samples were collected and analyzed for growth, nitrogen, and phosphorus content at 2-week intervals. Total nitrogen and total phosphorous was analyzed using the procedure by researcher Nordforsh (1975). Nitrogen was measured using titrimetrically and phosphorous colometrically. ANOVA Duncan multiple range test was performed on data collected. Results showed that the nitrogen and phosphorus tissue concentrations decreased away from the outfall. This indicated that tissue concentrations are apt for monitoring nutrient availability in coastal areas. The lowest tissue concentrations of nitrogen were recorded at the reference station, where the internal concentrations generally were below the critical concentration level, showing that nitrogen limited the growth. At the station located close to the outfall, the flux of nitrogen was sufficient to maintain the maximum growth rate. The tissue concentrations of phosphorus were only below the critical concentration level on one occasion, and the result showed a net uptake throughout the study period. Researchers concluded that nitrogen was the primary limiting factor for macroalgae growth during the summer. The applicability of tissue concentrations for assessment of nutrient availability is discussed and it is considered that the method, when evaluated against established critical concentrations, provides a valuable tool for assessing ecosystem health with regard to eutrophication.

McAlary, F. A. and W. N. McFarland. 1994. Catalina Island kelp forests: 1992-1993, pp. 35-44. In Halvorson, W. L. and G. J. Maender (eds.), Fourth California Islands Symposium*:* Update on the Status of Resources. Santa Barbara Museum of Natural History, Santa Barbara, CA.

Author Abstract. A monitoring project initiated in the spring of 1992 at the Catalina Marine Life Refuge focused on Giant kelp (*Macrocystis pyrifera*), sea urchins *(Strongylocentrotus* and *Centrostephanus*), and water temperatures along 60-m longshore transects at depths of 4, 10, and 20 m. Quarterly assessment of plant size and density tracked a continuing decline in kelp abundance at the site coincident with elevated sea temperatures. Frond elongation fell precipitously through the summer of 1992 and reached a low in the winter of 1993. Growth remained depressed through the spring and summer of 1993. This contrasts with previously measured temporal patterns of growth at this site when rates were highest in winter and spring. Population densities of sea urchins were relatively constant. Diminishment of the kelp forest together with the appearance of pelagic red crabs, a juvenile green turtle, and several species of tropical fish at Catalina portrays effects of lingering worldwide “El Niño” conditions.

McAlary, F. A., T. W. Turney, and J .L. Turney. 2000. Catalina Island kelp forests: 1992 to 1998, pp. 363-369. In Brown, D. R., K. L. Mitchell and H. W. Chaney (eds.), Proceedings of the fifth California islands symposium. United States Department of the Interior, Minerals Management Service, Pacific OCS Region, Camarillo, CA.

Author Abstract. To assess long-term changes in kelp forests at Santa Catalina Island, the Catalina Conservancy Divers recorded benthic water temperatures and conducted quarterly censuses of Giant kelp (*Macrocystis pyrifera*) and sea urchins along three permanent 120 m^2 transects at 4-m, 10-m, and 20-m depths since 1992. Catastrophic declines of *Macrocystis* occurred in 1992 and 1997 El Niño events. Rates of frond elongation (RFE) correlated with fluctuations in plant biomass and population density, but not plant size, which emphasized recruitment in maintaining Giant kelp at this site. Within seasons, RFE were highest at the lowest mean temperatures and declined significantly with exposure to water above 18 degree C. Data suggest that thermal anomalies such as El Niño led to the reduction of Giant kelp by intensifying stressful conditions in summer (high temperatures, low nutrients) and, also, by limiting production during winter and spring. Overgrazing of kelp by sea urchins was not observed. Depth distributions for three species of sea urchins remained stable from 1992 to 1998. Densities of *Strongylocentrotus purpuratus* and *S. franciscanus* declined, especially in 1992 and 1993, with the disappearance of Giant kelp and signs of echinoderm wasting disease. Increases in the density of *Centrostephanus coronatus*, a species with tropical affinities, exemplify the potential shift toward warm water species.

McClanahan, T. R., M. McField, M. Huitric, K. Bergman, E. Sala, M. Nystroem, I. Nordemar, T. Elfwing and N. A. Muthiga. 2001. Responses of algae, corals and fish to

the reduction of macroalgae in fished and unfished patch reefs of Glovers Reef Atoll, Belize. *Coral Reefs* 19:367-379.

Author Abstract. Macroalgae were experimentally reduced by approximately 2.5 kg/m^{-2} on eight similar-sized patch reefs of Glovers Reef Atoll, Belize, in September 1998. Four of these reefs were in a protected "no-take" zone and four were in "general use" fishing zone. Eight adjacent reefs (four in each management zone) were also studied as unmanipulated controls to determine the interactive effect of algal reduction and fisheries management on algae, coral, fish, and rates of herbivory. The 16 reefs were sampled five times for 1 year after the manipulation. We found that the no-fishing zone had greater population densities for 13 of 30 species of fish, including four herbivorous species, but lower herbivory levels by sea urchins. However, there was lower stony coral cover and higher macroalgal cover in the "no-take" zone, both prior to and after the experiment. There were no significant effects of management on the percent cover of fleshy macroalgae. The algal reduction resulted in an increase in six fish species, including four herbivores and two which feed on invertebrates. One species, *Lutjanus griseus*, declined in experimental reefs. Macroalgal biomass quickly recovered from the reduction in both management areas within a few months, and by species-level community measures within 1 year, while stony coral was reduced in all treatments. Coral bleaching and Hurricane Mitch disturbed the site at the beginning of the study period and may explain the loss of stony coral and rapid increase in erect algae. We suggest that reducing macroalgae, as a technique to restore turf and encrusting coralline algae and stony corals, may work best after reefs have been fully protected from fishing for a period long enough to allow herbivorous fish to recover (i.e., > 5 years). Further ecological studies on Glovers Reef are required to understand the shift from coral to algal dominance that has occurred on this reef in the last 25 years.

Mearns, A., G. Watabayashi and J. Lankford. 2001. Dispersing oil near shore in the California current region. *Reports of California Cooperative Oceanic Fisheries Investigations* 42:97-109.

AuthorAbstract. Mathematical models were used to develop scenarios for evaluating alternative nearshore responses to oil spills, including the use of chemical dispersants. The scenarios were used in ecological risk assessment (ERA) workshops designed to help fisheries, wildlife, and resource managers determine whether they would support pre-approving the use of dispersants. Resource managers proposed a worst-case spill scenario for the Gulf of the Farallones. Models were used to compare five options—no response, mechanical, burning, and two levels of dispersants--showing the trajectories, fate, and concentration of oil in surface slicks and dispersed oil plumes. Participating biologists used current data on dispersant and dispersed oil toxicity to develop consensus-based toxicity guidelines. During the first several hours following dispersal, the simulated dispersed oil concentrations exceeded guidelines for early life-history stages of fishes and zooplankton; adult fish and crustaceans were at risk for two hours. The benefits and risks to fishes, seabirds, cetaceans, pinnipeds, sea otters, and shoreline resources (marshes, kelp beds, and protected areas) were compared for the five response options. Dispersants substantially reduced the amount of both floating and stranded oil relative to the other options. Furthermore, the higher dispersant level (85%) removed more oil than the lower level (35%). Risk assessments so far indicate that chemical dispersion can reduce the overall ecological effects of a nearshore oil spill. The final decision to pre-approve dispersant use along the Pacific Coast will still require input from the political, social, and economic sectors.

Moore, P. G. 1973. The kelp fauna of northeast Britain 1.: Introduction and the physical

environment. *Journal of Experimental Marine Biology and Ecology* 13:97-125.

Author Abstract. As part of a multidisciplinary investigation of pollution in northeast Britain a study of the sublittoral kelp fauna is described. Sampling strategy is discussed and a program adopted involving the investigation of an instantaneous faunal pattern over a wide area and its environmental correlation. The kelp holdfast (thallus) as a sample unit is briefly evaluated. The total faunal content of the survey samples is described in gross terms. A review of the physical parameters which impinge upon the holdfast fauna is made and on this basis significant variables are resolved into turbidity, pollution, water movement, and holdfast morphology. Detailed treatment of these factors follows and their distribution over the northeast coast transect is described. Seasonal studies on suspended solids enable an approximate area north of the River Coquet in Northumberland to be considered as continually clear, whilst the area to the south is considered turbid. The region of turbid water is considered to be the consequence of erosion of superficial coastal deposits under the action of marine and atmospheric forces. The role of discharges in contributing to suspended solids is considered. Nutrient data are given; the amounts were spatially similar over the whole coastline. An area of 'pollution' is provisionally designated on the basis of published figures. The problems of assessment of wave exposure and present inadequate knowledge of local inshore current systems preclude other than crude separation of one site on considerations of water movement. Holdfast parameters are generally interdependent: however, the degree of holdfast branching is shown to be independent of age and to influence significantly (along with water movement external to the holdfast) the degree of holdfast silting.

Reed, D. C. and M. S. Foster. 1984. The effects of canopy shading on algal recruitment and growth in a giant kelp forest. *Ecology* 65: 937-948.

Author Abstract. The subtidal assemblage in the relatively sheltered giant kelp forest at Stillwater Cove in Carmel Bay, California, consists of perennial species forming three major vertical layers: a *Macrocytis purifera* surface canopy, a dense subsurface canopy of another kelp (*Pterygophora californica)* and an understory of articulated and encrusting coralline algae. The effects of light reduction by these vegetation layers on algal recruitment and subsequent growth were determined by removing various combinations of canopies over a 2-yr period, and following subsequent changes relative to appropriate controls. Removing both *M. pyrifera* and *P. californica* canopies resulted in moderate recruitment of these species as well as of the annual brown alga *Desmarestia ligulata* var. Relatively low levels of both physical and biological disturbance in Stillwater Cove allow the establishment of a few perennial algal species that inhibit their own recruitment, as well as invasion of other species, by shading.

Simms, E. L. and J. M. M. Dubois. 2001. Satellite remote sensing of submerged kelp beds on the Atlantic coast of Canada. *International Journal of Remote Sensing* 22:2083-2094.

Author Abstract. Underwater kelp seasonal variation is assessed through the comparative analysis of HRV and Thematic Mapper (TM) images of Baie des Chaleurs between Caps-Noirs and Pointe-Bonaventure, Quebec. The total biomass is estimated, based on the morphology of the dominant species *Laminaria longicruris*. Kelp-covered and kelp-free areas are differentiated from each other in water depth of 0-6 m and 0-7 m with the HRV and TM images, respectively. The median biomass estimated for the kelp-covered category of the classified image is (1500 ± 400) g/m^{-2}. The multidate image shows a spatial variation of

the kelp beds in 45% of the area. Areas where no change occurred occupy at least 70 ha, while growth and decay of kelp are observed in much smaller areas, in shallow water and at the boundary of kelp beds.

Singer, M. M., R. S. Tjeerdema and R. S. Smalheer. 1992. Evaluation of the toxicological effects of oil dispersants by modeled-exposure toxicity testing, pp. 175-182. In Niimi, A. J. and M. C. Taylor (eds.), Proceedings of the Eighteenth Annual Toxicity Workshop: September 30 – October 3, 1991, Ottawa, Ontario. Canadian Technical Report on Fish Aquatic Sciences 1863.

Author Abstract. By virtue of their nature and usage, the exposure potential of aquatic organisms to oil dispersants is highly ephemeral. To address this circumstance, in addition to traditional constant-concentration exposures, more realistic spiked-exposure, continuous-flow toxicity tests using the oil dispersant Corexit 9527 were performed using the early life stages of four California marine species: the Giant kelp (*Macrocystis pyrifera),* the red abalone (*Haliotis rufescens*), a kelp forest mysid (*Holmesimysis costata*), and the topsmelt (*Atherinops affinis*), were inoculated with concentrated dispersant, then allowed to flush with clean, filtered seawater. Spectrophotometric monitoring of tests showed dispersant levels diminishing to below detection limits within 5 to 6 h or less. Comparison of spiked-exposure results with previous data obtained using the same species and dispersant under constant-exposure conditions showed higher values for both EC/LC50s and NOECs under spiked conditions.

Stekoll M. S. and L. Deysher. 1996. Recolonization and restoration of upper intertidal *Fucus gardneri* (Fucales, Phaeophyta) following the *Exxon Valdez* oil spill. *Hydrobiologia* 327:311-316.

Author Abstract. The *Exxon Valdez* oil spill in March 1989 and subsequent cleanup caused injury to intertidal *Fucus gardneri* populations especially in the upper intertidal. A survey in 1994 in Prince William Sound, Alaska showed that the upper boundary of *Fucus* populations at oiled sites was still an average of 0.4 m lower than the upper boundary at unoiled sites. Restoration of severely damaged *Fucus* populations was started on a small-scale at a heavily oiled rocky site in Herring Bay, Prince William Sound. Experiments employed mats of biodegradable erosion control fabric to act as a substratum for *Fucus* germlings and to protect germlings from heat and desiccation stress. A series of plots was covered with mats made from a resilient coconut-fiber fabric in June 1993. Half of the mats were inoculated with *Fucus* zygotes. A series of uncovered control plots was also monitored. There was no enhancement of Fucus recruitment on the rock surfaces under the mats. Dense populations of *Fucus* developed on the surface of all of the mats by the summer of 1994. The natural rock surfaces in the control plots, both inoculated and not, were barren of macroscopic algal cover. By September 1994, the juvenile thalli on the mats were approximately 2 cm in length. Inoculating the mats had an effect only in the upper region of the intertidal. It is expected that the thalli will become fertile during the 1995 season. These thalli may serve as a source of embryos to enhance the recovery of new *Fucus* populations in this high intertidal area.

Steneck, R. S. and M. N. Dethier. 1994. A functional group approach to the structure of algal-dominated communities. *Oikos* 69: 476-498.

Author Abstract. We suggest that relatively few species attributes are of overriding importance to the structure of benthic marine algal

communities and that these are often shared among taxonomically distant species. Data from the western North Atlantic, eastern North Pacific and Caribbean suggest that patterns in algal biomass, diversity and dominance are strikingly convergent when examined at a functional group level relative to the productivity and herbivore-induced disturbance potentials of the environment. We present a simple graphical model that provides a way to predict algal community composition based on these two environmental axes. This predictability stems from algal functional groups having characteristic rates of mass-specific productivity, thallus longevity and canopy height that cause them to "behave" in similar ways. Further, herbivore-induced disturbances have functionally similar impacts on most morphologically and anatomically similar algae regardless of their taxonomic or geographic affinities. Strategies identified for marine algae parallel those of a terrestrial scheme with the addition of disturbance-tolerant plants that characteristically coexist with and even thrive under high levels of disturbance. Algal-dominated communities, when examined at the functional group level, appear to be much more temporally stable and predictable than when examined at the species level.

Tegner, M. J., P. L. Haaker, K. L. Riser and L. I. Vilchis. 2001. Climate variability, kelp forests, and the southern California red abalone fishery. *Journal of Shellfish Research* 20:755-763.

Author Abstract. Declines in landings of Southern California abalone fisheries and the eventual collapse of many stocks over the last two decades coincided with a period of greatly increased environmental variability. This included massive storms, an increase in the frequency of warm-water El Niño events after 1976, and an interdecadal-scale increase in sea surface temperatures. Kelp populations may be decimated by severe storms or warm water. Because of the strong inverse relationship between nitrate availability and water temperature, temperature is a good indicator of nitrate availability or stress since kelp growth ceases in warm nutrient-depleted water, tissue decays, and standing stocks may be greatly reduced. Abalones are affected by the availability of the drift kelp on which they feed. Anomalously warm temperatures may affect reproduction, and altered current patterns may affect larval dispersal. Because water temperature varies with location in southern California and each of the five exploited abalone species has its own thermal preferences, we chose to evaluate the role of environmental variability on populations of red abalone (*Haliotis rufescens*) on three northern Channel Islands spanning a temperature gradient. We compared water temperature regimes and anomalies, monthly aerial surveys of canopies of Giant kelp (*Macrocystis pyrifera*), and field evidence of poor abalone growth and reproduction during El Niño events. The severity of El Niño disturbances and long-term changes in kelp standing stocks both correlated with the temperature gradient. Declines of red abalone total landings and area-specific landings on the warmer Santa Cruz and Santa Rosa Island began a decade after the large 1957-1959 El Niño. The subsequent collapse of many populations appears related to warm anomalies after the 1976-1977 regime shift, kelp declines, and poor reproduction coupled with fishing-induced declines in adult abalone density. Red abalone populations have persisted on cooler San Miguel Island where thermal anomalies had less effect and kelp canopy biomass has been more stable. Southern California abalones evolved in this disturbance regime, but the combination of extended periods of increased environmental variability with intense fishing pressure may have led to the loss of local populations, especially in warmer areas.

Terawaki, T. and H. Goto. 1988. Preliminary study for creation of kelp forest, (Part 1).

Seasonal Changes of Lamina and Growth of Root of *Elsenia bicyclis* in Odawa Bay, Miura Peninsula, 24 p. Central Research Institute of Electric Power Industry (CRIE-U-87056), Tokyo, Japan.

Author Abstract. A preliminary study for the creation of a kelp forest has been carried out in Odawa Bay, Kanagawa Prefecture. In foreshore reclamation on an electric power plant siting, the restoration and substitution measures of kelp forest are important for the protection of living aquatic resources and marine environment. Observations on seasonal changes of lamina and growth of root of *Eisenia bicyclis* were carried out during July 1984 to October 1985. The maximum weight of a lamina reached about 600g during July to August, then decreased and reached a minimum weight of 120g in November. The maturation period was observed from September to March. Primary pinnae length reached maximum of 57cm a March to April and a minimum of 30cm in October. Its width reached a maximum of 9cm in July and the minimum of 6cm in November. New root growth occurred in October, reached rockbed exceeded old root growth by April. New root weight occupied 40% of the whole holdfast weight. The period from November to February, when maturation and root growth are active, is an important season for the preservation of the *E. bicyclis* population, and is suitable for seeding and transplanting.

Vasquez, J. A. and R. H. McPeak. 1998. A new tool for kelp restoration**.** *California Fish and Game* 84:149-158.

Researchers developed new techniques for restoring and protecting Giant kelp, *Macrocystis pyrifera*, forests in southern California. These techniques include the use of artificial kelp plants that are constructed of plastic. The blades of these artificial plants would sweep across the substrate similar to that reported in natural kelp populations in Chile and southern California. This sweeping movement helps with filtering of sediments, functioning of the ecosystem along with other functions. Based on results the artificial plants reduced purple sea urchins density, *Strongylocentrotus purpuratus*, by about 85% and red sea urchins, *S. franciscanu*s, by 75% in sea-urchin-dominated areas. The artificial plants successfully protected Giant kelp transplants that were present in sea-urchin-dominated areas. See publication for additional information on kelp restoration techniques.

Wilson, K. C. and W. J. North. 1983. A review of kelp bed management in southern California. *Journal of World Mariculture Society* 14: 347-359.

Author Abstract. Methods for maintaining and enhancing stands of Giant kelp (*Macrocystis spp*.) continue to evolve. This paper reviews the history of kelp management techniques and describes recent research, as well as new methodology that have come into general usage. The southern California kelp populations are basically wild crops, but survival and biomass production can be significantly affected by relatively moderate inputs of human effort. Methodologies discussed include urchin control techniques (hammering, suction dredging, quick-lime, and harvesting urchins as specialty foods), culturing and transplanting kelp, control of competitive weeds, and monitoring. New research areas include improved understanding of the kelp ecosystem, kelp nutrition (with possibilities for enhancing productivity by fertilizing), genetics and breeding, optimizing biomass density, and expanding beds by use of artificial substrates.

APPENDIX II: KELP AND OTHER MACROALGAE REVIEW OF TECHNICAL METHODS MANUALS

This Review of Technical Methods Manuals includes a variety of sampling manuals, Quality Assurance/Quality Control (QA/QC) documents, standardized protocols, or other technical resources that may provide practitioners with the level of detail needed when developing a monitoring plan for a coastal restoration project. Examples from both peer reviewed and grey literature are presented. Entries were selected through extensive literature and Internet searches as well as input from reviewers. As with the Annotated Bibliographies, these entries are not, however, a complete list. Entries are arranged alphabetically by author. Wherever possible, web addresses or other contact information is included in the reference to assist readers in easily obtaining the original resource. Summaries preceded by the terms '*Author Abstract'* or *'Publisher Introduction*' or similar descriptors were taken directly from their original source. Summaries without such descriptors were written by the authors of the associated chapters.

Bushing, W. W. 2000. Monitoring the persistence of giant kelp around Santa Catalina island using a geographic information system. *Journal of Phycology* 36: 9-10.

Author Abstract. Geographic information systems (GIS) facilitate monitoring and analysis of population distributions at spatial and temporal scales differing from those employed in conventional field monitoring. This study utilizes a GIS-based gap analysis of a network of marine reserves around Santa Catalina Island relative to the regional ecology, disturbance regime, and persistence of giant kelp (*Macrocystis pyrifera*), a keystone species in the nearshore, marine environment. Catalina's orientation and greatly-dissected coastline create diverse microhabitats with respect to storm exposure, temperature, light regime and topographic factors. GIS overlay methods applied to multi-temporal kelp distribution maps generated a model representing the spatial "persistence" of kelp. Correlations between the kelp's geographic distribution and persistence, the disturbance regime and physical variables conferring resistance to or recovery from it were drawn. This analysis identified regions of persistent kelp under disturbance regimes markedly different from those in the existing reserves, suggesting the designation of additional reserves in unprotected areas is ecologically warranted.

Davies, J., J. Baxter, M. Bradley, D. Connor, J. Khan, E. Murray, W. Sanderson, C. Turnbull and M. Vincent. 2001. Marine Monitoring Handbook. UK Marine Science Project, and Scottish Association of Marine Science. Joint Nature conservation Committee, English Nature, Scottish Natural Heritage, Environment and Heritage Services. http://www.jncc.gov.uk/marine/mmh/Introduction.pdf.

The UK Marine Science Project developed this hand book to provide guidelines for recording, monitoring and reporting characteristics and conditions of marine habitats. However, based on location and other environmental conditions methodologies will have to be modified to suit the structural characteristics of the habitat. This manual addresses the fundamentals and procedures for monitoring different parameters in marine habitats, management tools, and benefits and costs for developing a monitoring project. Topics presented in this document include establishing marine monitoring programs highlighting what needs to be measured and methods to use; provides guidance when developing a monitoring program; selecting proper monitoring techniques to attain precision and accuracy; and procedural guidelines for monitoring a specific marine habitat. Detailed information on the tools needed for monitoring marine habitats are described within the marine monitoring handbook.

Davis, G. E., K. R. Faulkner and W. L. Halvorson. 1994. Ecological monitoring in Channel Islands National Park, California, pp. 465-482. In Halvorson, W. L. and G. J. Maender (eds.), The 4th California Islands Symposium: Update on the Status of Resources.

Author Abstract. Natural resource managers need to understand the natural functioning of and threats to ecosystems under their management. They need a long-term monitoring program to gather information on ecosystem health, establish empirical limits of variation, diagnose abnormal conditions, and identify potential agents of change. The approach used to design such a program at Channel Islands National Park, California, may be applied to other ecosystems worldwide. The design of the monitoring program began with a conceptual model of the park ecosystem. Indicator species from each ecosystem component were selected using a Delphi approach. Scientists identified parameters of population dynamics to measure, such as abundance, distribution, age structure, reproductive effort, and growth rate. Short-term design studies were conducted to develop monitoring protocols for pinnipeds, seabirds, rocky intertidal communities, kelp forest communities, terrestrial vertebrates, land birds, terrestrial vegetation, fishery harvest, visitors, weather, sand beach and coastal lagoon, and terrestrial invertebrates (indicated in priority order set by park staff). Monitoring information provides park and natural resource managers with useful products for planning, program evaluation, and critical issue identification. It also provides the scientific community with an ecosystem-wide framework of population information.

Deysher, L. E. 1993. Evaluation of remote sensing techniques for monitoring giant kelp populations. *Hydrobiologia* 260-261:307-312.

Author Abstract. Photographs and maps of the floating canopy of the giant kelp, *Macrocystis pyrifera*, provide an important data source to monitor nearshore water quality in southern California. Declines in water quality related to turbidity from coastal development, ocean discharges, and non-point source runoff have caused reductions in the areal extent of these kelp beds. Historically the kelp beds have been monitored by a variety of methods including small format infrared and color photography. New digital remote sensing instruments combined with geographical information system (GIS) databases offer an efficient method for collecting and analyzing data on changes in kelp bed size and location. SPOT satellite imagery has been found to provide adequate resolution for mapping the larger beds of giant kelp along the California coast. Beds smaller than 10 ha are not resolved well with SPOT imagery and need to be mapped with a resolution greater than the 20 m pixel size provided by the SPOT multispectral imagery. Imagery from a prototype of the Positive Systems ADAR system, an airplane mounted multispectral video sensor, provided a spatial resolution of 2.3 m in 4 spectral bands. ADAR imagery taken on 2 October 1991 of the San Onofre Kelp Bed in northern San Diego County showed 39% more kelp than small format color infrared photography made during the same time period.

Halse, S. A., D. J. Cale, E. J. Jasinska and R. J. Shiel. 2002. Monitoring change in aquatic invertebrate biodiversity: sample size, faunal elements and analytical methods. *Aquatic Ecology* 36:395-410.

Author Abstract. Replication is usually regarded as an integral part of biological sampling, yet the cost of extensive within-wetland replication prohibits its use in broad-scale monitoring of trends in aquatic invertebrate biodiversity. In this paper, we report results of testing an alternative protocol, whereby only two samples are collected from a wetland per monitoring event and then analyzed using ordination to detect any changes in invertebrate biodiversity over time. Simulated data suggested ordination of combined data from the two samples would detect 20% species turnover and be a cost-effective method of monitoring changes in biodiversity, whereas power analyses showed about 10 samples were required to detect 20% change in species richness using ANOVA. Errors will be higher if years with extreme climatic events (e.g., drought), which often have dramatic short-term effects on invertebrate communities, are included in analyses. We also suggest that protocols for monitoring aquatic invertebrate biodiversity should include microinvertebrates. Almost half the species collected from the wetlands in this study were microinvertebrates and their biodiversity was poorly predicted by macroinvertebrate data.

McCobb, T. D. and P. K. Wieskel. 2003. Long-Term Hydrologic Monitoring Protocol for Coastal Ecosystems, 94 pp. United States Geological Survey Open-File Report 02-497. http://water.usgs.gov/pubs/of/2002/ofr02497/

The United States Geological Survey (USGS) and the National Park Service have designed and tested monitoring protocols implemented at Cape Cod National Seashore. The monitoring protocols are divided into two parts. Part one of the protocol discusses the objectives of the monitoring protocol and presents rationale for the recommended sampling program. The second part describes the field, data-analysis, and data-management, and variables that are to be taken into consideration when monitoring (e.g., sea level rise, climate change and urbanization). This protocol provides consistency when monitoring changes in ground-water levels, pond levels, and stream discharge. The monitoring protocol not only establishes a hydrologic sampling network but provides reasoning for measurement methods selected and spatial and temporal sampling frequency. Data collected during the first year of monitoring and hydrologic analyses for selected sites are presented. Long-term hydrologic monitoring procedures performed at the Cape Cod National Seashore may also assist set a template for deciphering findings of other monitoring programs.

Oregon Watershed Enhancement Board. 1999. Oregon Aquatic Habitat: Restoration and Enhancement Guide. Contact information: 775 Summer street, suite 360, Salem Oregon, 97301, Phone# (503) 986-0178. http://www.oweb.state.or.us/publications/habguide99.shtml

This guide was developed to provide guidance on restoration and enhancement measures that would assist in aquatic ecosystem recovery. The guide is divided into five sections: An overview of restoration activities, activity guidelines, overview of agency regulatory functions and sources of assistance, grants and assistance, and monitoring and reporting. The purpose of this document is to provide information that will assist in developing effective restoration projects; to define standards and priorities that will be approve by state and receive funding or authorized restoration projects; to identify state and federal regulatory requirements and receive assistance in restoration projects. Additional information on monitoring techniques for salmonid restoration and guidelines and considerations for reporting restoration progress over time are described within the document.

Reed, B., C. Collier, J. Altstatt, N. Caruso and K. Lewand. 2002. Regional Kelp Restoration Project: Restoration and Monitoring

Protocol. California CoastKeeper Alliance, Kelp Restoration Team, Santa Monica, CA.

The California CoastKeeper Alliance (CCKA) presents restoration techniques that are used in kelp habitats. Described in this document are protocols for kelp restoration and kelp monitoring. Methods used for kelp restoration include: outplanting of kelp in which kelp sporophytes are cultivated in the laboratory, transplanting of the drift kelp, sporophyll bags and how grazers are removed (e.g., sea urchins). The Coastal Resource Associates in Carlsbad stated however that outplanting of juvenile kelp seems the most cost effective for restoration work. Methods described in the kelp monitoring protocol include: quadrats, band transects, roving diver fish survey, sea urchin size frequency survey, Giant kelp plant tagging survey, substrate survey and temperature monitoring. Detailed information on methods used for restoration and monitoring are described in the document.

Trippel, E. A. 2001. Marine Biodiversity Monitoring: Protocol for Monitoring of Fish Communities. A Report by the Marine Biodiversity Monitoring Committee (Atlantic Maritime Ecological Science Cooperative, Huntsman Marine Science Centre) to the Ecological Monitoring and Assessment Network of Environment Canada. http://www.eman-rese.ca/eman/ecotools/protocols/marine/fishes/intro.html#Rationale

This document presents a monitoring protocol for estimating species diversity of bottom dwelling or demersal fish species inhabiting the Canadian continental shelf regions. Monitoring protocols presented in this document can be used to monitor and evaluate fish communities in regions other than the Canadian continental shelf. Methods used to estimate the abundance of different demersal fish species include random stratified sampling and fixed station sampling. Using these standardized procedures helps to maintain precision. Some factors taken into consideration when monitoring fish communities include depth, temperature, salinity, seasonal shifts and diurnal behavior patterns. Additional information found in this document includes size of area and sampling intensity, sampling gear, sampling procedures, and treatment of data.

United States Environmental Protection Agency (USEPA). 1992. Monitoring Guidance for the National Estuary Program. United States Environmental Protection Agency, Office of Water, Office of Wetlands, Washington D.C. EPA Report 842-B-92-004.

This document provides guidance on the design, implementation, and evaluation of the required monitoring programs. It also identifies steps to be taken when developing and implementing estuarine monitoring programs and provides a technical basis for discussions on the development of monitoring program objectives, the selection of monitoring program components, and the allocation of sampling effort.

Some of the criteria listed for developing a monitoring program and described in this document include: monitoring program objectives, performance criteria, establish testable hypotheses, selection of statistical methods, alternative sampling designs, use of existing monitoring programs, and evaluate monitoring program performance. Additional information on guidelines for developing a monitoring program is described in this document.

United States Environmental Protection Agency (USEPA). 1993. Volunteer Estuary Monitoring, 176 pp. In Ohrel, R. L. Jr. and

K. M. Register (eds.), A Methods Manual. U.S. Environmental Protection Agency, Washington, D.C., Office of Water. EPA Report- 842-B-93-004. http://www.epa.gov/owow/estuaries/monitor/.

This document presents information and methods specific to measuring estuarine water quality. Information presented in the first eight chapters includes: understanding estuaries and what makes them unique, impacts to estuarine habitats and society's role in solving the problems; guidance on how to establish and maintain a volunteer monitoring program; guidance for working with volunteers and ensuring that they are well-positioned to collect water quality data safely and effectively; ensuring that the program consistently produces high quality data; and guidenace for managing the data and making it readily available to data users. Also presented are water quality measures that determine the condition of the estuary. These include physical (e.g., substrate texture), chemical (e.g., dissolved oxygen), and biological parameters (e.g., plant and animal presence and abundance). The importance of each parameter and methods used to monitor the conditions are described in a gradual process. Proper quality assurance and quality control techniques must also be described in detail to ensure that the data are beneficial to state agencies and other data users.

Wenner, E. L. and M. Geist. 2001. The national estuarine research reserves program to monitor and preserve estuarine waters. *Coastal Management* 29:1-17.

The National Estuarine Research Reserve (NERR) sites in 1992 coordinated a program that would attempt to identify and track short-term variability and long-term changes in representative estuarine ecosystems and coastal watersheds. Water quality parameters that were monitored include: pH, conductivity, temperature, dissolved oxygen, turbidity, and water level. Standardized protocols were also used at each site so that sampling, processing, and data management techniques were consistent among sites. Statistical techniques are being used to identify periodicity in water quality variables. Periodic regression analysis indicated that diel periodicity in dissolved oxygen is a larger source of variation than tidal periodicity at sites with less tidal amplitude. Authors of this document stress how understanding the functions of estuaries and how they change over time will help predict how these systems respond to change in climate and anthropogenic sources.

APPENDIX III: LIST OF KELP AND OTHER MACROALGAE EXPERTS

The expert listed below has provided his contact information so practitioners may contact him with questions pertaining to the restoration or restoration monitoring of this habitat. Contact information is up-to-date as of the printing of this volume. The list below includes only those experts who were 1) contacted by the authors and 2) agreed to submit their contact information. In addition to this resource, practitioners are encouraged to seek out the advice of local experts as well faculty members and researchers at colleges and universities. Engineering, planning, and landscape architecture firms also have experts on staff or contract out the services of botanists, biologists, ecologists, and other experts whose skills are needed in restoration monitoring. These people are in the business of providing assistance in restoration and restoration monitoring and are often extremely knowledgeable in local habitats and how to implement projects on the ground. Finally local, state, and Federal environmental agencies also house many experts who monitor and manage coastal habitats. In addition to the National Oceanic and Atmospheric Administration (NOAA), the Environmental Protection Agency (EPA), the Army Corps of Engineers (ACE), Fish and Wildlife Service (FWS), and the United States Geologic Survey (USGS) are important Federal agencies to contact for assistance in designing restoration and monitoring projects as well as potential sources of funding and permits to conduct work in coastal waterways.

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CHAPTER 6: RESTORATION MONITORING OF ROCKY HABITATS

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INTRODUCTION

Rocky habitats are found in freshwater, estuarine, and marine systems. In estuarine and marine systems, they include rocky shorelines, rock bottoms, and the substratum in kelp and other macroalgal habitats as defined and discussed in *Volume One* of the "*Science-Based Restoration Monitoring of Coastal Habitats*" document. Rocks in these habitats can vary from expanses of solid bedrock to large boulders to cobbles greater than seven centimeters in diameter, and often contain mixtures of these rock sizes. Habitats composed mostly of particles smaller than seven centimeters support very diverse communities, are affected by different environmental factors, and therefore, are best monitored using approaches and techniques for soft bottom habitats. Rocky habitats occur at all depths in the ocean, but because of accessibility and cost issues, it is unlikely, at least in the near future, that restoration or recovery after anthropogenic disturbance will be commonly monitored at depths greater than 30 meters. These habitats found at depths greater than 30 meters can be very important in freshwater systems, and are a critical component of restoring stream habitat for salmon and other fish (Koski 1992). In this document, in-stream monitoring and deeper rocky habitats will not be discussed, although many of the monitoring approaches for marine rocky habitats are applicable.

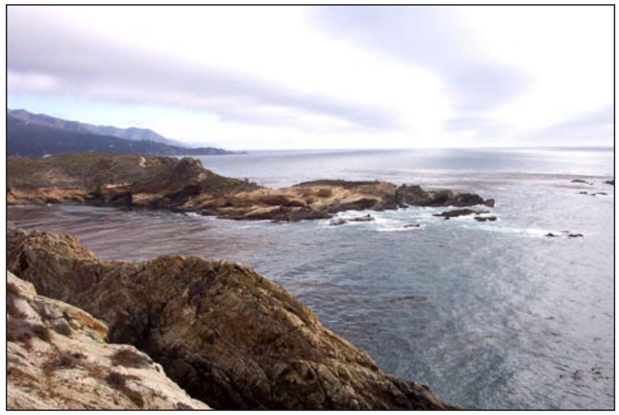

Figure 1. Big Sur rocky coastline towards Point Sur, California. Photo courtesy of Captain Albert E. Theberge, NOAA Corps. Publication of NOAA Central Library. http://www.photolib.noaa.gov/coastline/line3023.htm

Rocky habitats (see rocky shoreline, Figure 1) are generally high-energy habitats exposed to frequent wave action or strong currents (Lewis 1964; Stephenson and Stephenson 1972; Cowardin et al. 1979; Raffaelli and Hawkins 1996; Menge and Branch 2000). The rocky substrate provides a place of attachment and growth for sessile invertebrates and seaweeds which would otherwise be swept away or buried. In turn, the invertebrates and seaweeds provide sub-habitats and food for numerous other invertebrates, algae, and fishes. Vertical zonation of organisms is a consistent feature of rocky habitats, and is especially evident on intertidal shores subjected to steep gradients of tidal exposure and wave action (Stephenson and Stephenson 1972; Cowardin et al. 1979; Archambault and Bourget 1996; Menge and Branch 2000).

Rocky habitat types are inhabited by highly diverse assemblages of organisms from a variety of taxonomic groups (Figure 2). Organisms range from primary producers such as macroalgae to consumers such as fish, birds, seals, and sea otters (Lewis 1964; Cowardin et al. 1979; Menge and Branch 2000). For example, macroalgae on rocky shores in the high intertidal zone in central California harbor over 90 species of invertebrates (Glynn 1965). Rocky habitats can

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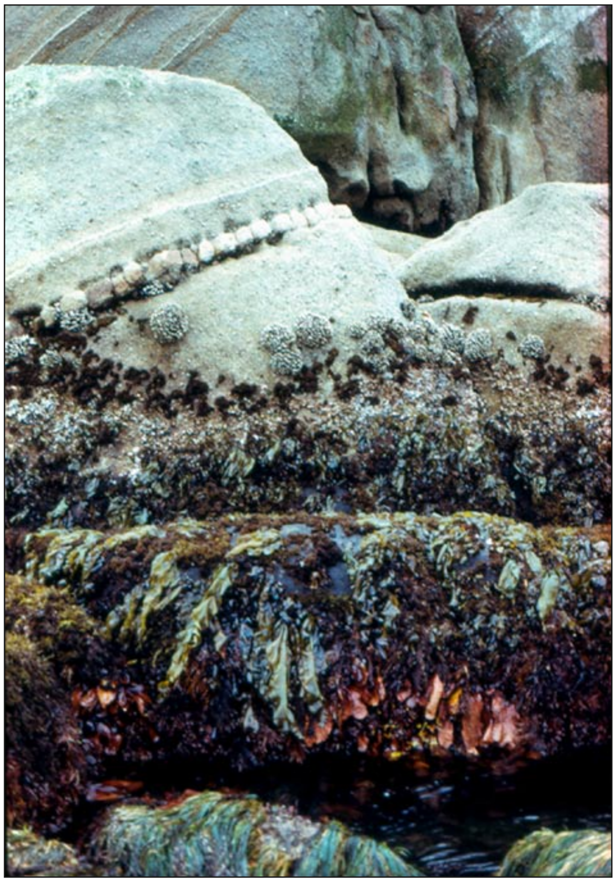

Figure 2. Semi-exposed rocky shore at low tide in central California. Note the considerable diversity and complex structure, with conspicuous organisms in zones from clumps of goose barnacles in the high intertidal zone to surf grass in the low tide. Photo courtesy of Michael Foster, Moss Landing Marine Laboratories, California.

support numerous filter feeding organisms such as mussels, barnacles, and oysters that contribute to habitat and water quality. Animals such as juvenile fishes, crustaceans, and polychaetes may also seek refuge within the matrices of rocky substrates and their attached organisms to prevent being swept away by strong currents and avoid predators. Additional descriptions of the natural history of rocky habitats are in *Volume One* of the "Science-Based Restoration Monitoring of Coastal Habitats" document.

Not only do these habitats play an important ecological role, but they also have very high economic value. Rocky habitats contribute to the economy by providing breeding, feeding, nursery, and adult habitat for commercially and recreationally fished species, including invertebrates such as abalone and lobster, and seaweeds that are harvested for food and chemicals. Rocky habitats also have increasingly important economic value as recreational resources for shore visitors, divers, boaters, and kayakers attracted to their diversity and aesthetic values. Finally, these habitats have high scientific value. Because of their accessibility, diversity, and structure, rocky habitats have been primary research sites for studies of land-sea interactions; morphological, physiological, and life history adaptations; as well as ecological interactions. Information from such studies has been critical to understanding the role of competition, predation, and physical gradients in structuring communities as well as assessing the causes of variation in biodiversity and the effects of this variation on community dynamics.

HUMAN IMPACTS TO ROCKY HABITATS

Various natural and human disturbances impact rocky habitats. Human impacts that may disrupt the natural ecological communities include:

- Agricultural and chemical runoff
- Sewage discharges
- Oil spills
- Heat from coastal power plant discharges
- Construction (i.e. increase sedimentation from coastal development), and
- Recreational activities (e.g., fishing and human trampling

Despite their ecological, economic, and aesthetic importance, impacted rocky habitats are rarely considered for restoration because they are usually spatially small or patchy, many of the organisms have the ability to disperse long distances via adult movement and dispersal of planktonic larvae and spores, and the rocks are rarely destroyed. Thus, recovery often readily occurs via natural processes once the impact is removed. This may be true even if the chemical impact remains in the environment for some time after the source has been eliminated. Some researchers suggest that removing residual oil from rocky shores after an oil spill may delay recovery more than if the oil was left to degrade naturally (DeVogelaere and Foster 1994). Recovery times from natural and human-induced disturbances are often on the order of one to ten years (Foster et al. 1988; Hawkins and Southward 1992; Schiel and Foster 1992; Foster et al. 2003). In most cases, the decision to restore or not to restore depends on whether researchers want to try and increase the rate of natural recovery. Increasing the rate of natural recovery has not been attempted in rocky habitats except in the context of trying to increase populations depleted by overfishing, or to speed the recovery of some algal populations and habitats (Schiel and Foster 1992; Walder and Foster 2000). There is little evidence that the former goal has ever worked well, and the latter is still experimental.

Cases where human impacts to rocky habitats have occurred and the results of these impacts include pollution and physical damage.

Pollution

Oil spills are considered a major threat to plant and animal communities of rocky habitats (Figure 3). A well-known oil spill event which affected marine life along the coast of Prince William Sound, Alaska is the *Exxon Valdez* oil spill (Andres 1998; Jewett et al. 2001). Following this spill event, the growth and survival of important economic fish species (e.g., juvenile

Figure 3. Oil-covered rocks on the shoreline of San Juan, Puerto Rico. Photo courtesy of Morris Berman. NOAA Office of Response and Restoration (ORR) photo gallery. http://photos.orr.noaa.gov//Photos/PCD4446/IMG0088.JPG.

Figure 4. Cleanup workers use vacuums to remove oil from rocky shores of San Juan, Puerto Rico. Photo courtesy of Morris Berman. NOAA Office of Response and Restoration (ORR) photo gallery.

salmon) were reduced significantly (Willette 1996), which in turn caused a decline in the fisheries industry.

Chemical dispersants used to remove oil may leave traces of chemicals in the environment that can cause additional harm to organisms occupying these habitats. Mechanical cleaning of oil may also disturb the physical structure of the environment (Figure 4) (Foster et al. 1988). Oil spill impacts vary significantly in amount, chemical composition, and degree of weathering before reaching the shore (Foster et al. 1988). Ongoing research in central California using completely cleared plots as indicators of recovery from oil spills showed that recovery can occur within a year in the upper intertidal zone, but in the mid intertidal zone where mussel beds exist, the recovery may take more than ten years (MMS 1992). Recovery rates may also be influenced by damage intensity and cleanup efforts (DeVogelaere 1991; DeVogelaere and Foster 1994).

Pollutants associated with stormwater runoff, sewage, and other point source discharges can also cause direct degradation to rocky habitat communities as a result of toxicity (Littler and Murray 1975). Excessive sedimentation and turbidity can negatively impact the growth of algae by smothering the algae or reducing light needed for photosynthesis (Devinny and Volse 1978). Pollutants discharged along rocky habitats may also affect the growth and survival of juvenile fish and crustaceans, particularly those species closest to the loading source (Smith et al. 1999; Guidetti et al. 2003).

Physical Damage

Various factors such as ship groundings and bottom fishing practices can physically damage rocky habitats. Bottom fishing activities, for example, may cause permanent habitat changes when rock substrata used as a place of attachment for sessile organisms is damaged or destroyed (Kaiser 1998). Trawling and dredging are two common fishing activities that can damage rocky habitats and disrupt animal communities. Bottom trawlers have wide nets consisting of extremely heavy rollers, chains, and doors that are dragged across rocky bottom habitats. Dredges contain rake structures at the end of their frames that also drag and scrape along the bottom (Freese et al. 1999; NAS 2002). As a result of rocky habitat destruction, the abundance of sessile organisms is reduced and mobile organisms (e.g., juvenile fish and shellfish) may migrate to areas that can provide adequate shelter. The removal of sessile epifauna through harvesting may also negatively alter habitat topography. In some cases, species that contribute to the topographic relief of rocky habitats tend to experience slow growth and require several years to recolonize.

RESTORATION EFFORTS

Restoration may be attempted in areas impacted by ship groundings that can destroy the rock or by sediment discharge that may bury the rocky substratum in calm water portions of an estuary. Restoration of ship grounding impacts may include replacing the destroyed rock, although in many wave-exposed coastal areas, it would be extremely expensive to transport and anchor rocks large enough to remain in place. Restoration of rocks that have been buried by human activity may include suction dredging to remove the deposited material. Guidance on restoration for sediment discharge may be provided by projects that have created rocky habitat to compensate or mitigate for a human impact. For example, an artificial reef was created to replace habitat loss due to a power plant discharging heated, turbid water into a kelp forest (Reed and Schroeter 2004)[4]. Mitigation projects for rocky bottom impacts are, however, still in the experimental stage and are likely to be very site-specific. Such projects require the creation of rocky habitat, followed by monitoring to compare the populations or communities in the newly created rocky habitat to those in comparable habitats unaffected by the discharge.

As part of restoring the value of rocky habitats, assessment of natural recovery after an impact has been removed should occur in most cases. Such assessment is the focus of the remaining chapter.

MONITORING ROCKY HABITATS

With the exception of creating rocky habitats to mitigate rocky habitats that were destroyed by ship groundings, the primary purpose of monitoring is to determine whether recovery is occurring after an impact has been removed, how fast it is occurring, and when the area has fully recovered. In addition to simply understanding how recovery is proceeding, the results of monitoring may also have regulatory consequences and may be of interest to the general public, particularly those who desire to use the formerly impacted area for recreational or commercial purposes. Assuming the impact has been removed and the substratum was not altered, there is generally no need to monitor the recovery of physical and/or chemical parameters as they should return to "natural", pre-impact conditions. For example, in areas where sediment runoff from coastal development is stopped, it takes some time for the sediment to be removed by natural re-suspension and transport. Thus, it would be necessary to monitor sediment cover to determine the time frame for natural removal and ensure the recovery of organisms.

[4] For an overview of a project to compensate for the effects of a power plant discharge, see Reed and Schroeter (2004).

Monitoring restoration after the removal of an impact can test the efficacy of restoration techniques and threats to rocky habitats, increase understanding of rocky habitat ecology in general, and reveal fundamental population and community patterns needing further investigation. Ultimately it is knowledge of the mechanisms producing observed patterns that will allow accurate predictions about the effects of particular impacts and how best to restore an area after impacts are removed. Well-designed monitoring programs have a great potential to contribute to that knowledge.

HOW TO MONITOR

There is an enormous amount of information about rocky habitats, sampling designs and methods, and data analyses and interpretation associated with monitoring. It is impossible to adequately review all of the available information in this chapter. The purpose of this section is to give an overview of what needs to be considered in any restoration monitoring project for rocky habitats. Developing a monitoring plan for a particular restoration site requires consulting technical references and experts as well as considering other factors such as selection of suitable sites, sampling and monitoring methods, and study time frame. Following are several recommended considerations when developing a restoration monitoring plan.

A detailed discussion on Consulting experts has been presented in Volume One of this document and should be applied to each habitat type discussed in Volume Two. Also, see Chapter 15 entitled the "Selection of Reference Sites or Conditions" for a discussion on the need for comparison sites.

Deciding What to Monitor

Organisms that cannot be easily seen with the unaided eye (i.e., those approximately less than 0.5 centimeters in size) are not generally monitored, but there is an enormous diversity of taxonomic groups (e.g., barnacles to sea lions), sizes, characteristics (e.g., attached seaweeds versus highly mobile fish), and abundances among the larger organisms found in rocky habitats. It is usually impossible to monitor enough to be able to test hypotheses concerning recovery for all of them. Therefore, one of the first tasks of any monitoring program is to decide what to monitor. If the impact was selective (e.g., intense fishing for species X that eliminated the species from the habitat), then a sampling program that only monitors the recovery of species X, its predators, and its competitors is appropriate. If the effect of the impact was more widespread among species, then a few species that are abundant and characteristic of the habitat may be selected and monitored with the assumption that if they recover, associated species that were not sampled have likely recovered as well (Foster et al. 2003). The most usual approach to this latter situation is to design a sampling program that samples characteristic and common species, and assesses the abundance of other species greater than 0.5 centimeters in size. For example, 0.5 meter by 0.5 meter quadrats might be used to sample common and characteristic limpets, but other snails are also counted in the same quadrats. While the other snails may not be abundant enough for powerful statistical analyses using this quadrat size, they might be used in community analyses that pool all species and examine changes in community similarity over time (Foster et al. 2003).

Monitoring Approaches

Restoration monitoring can be qualitative, quantitative, or a mixture of both. When quantitative sampling cannot be done, reports based on periodic visits to the restored site and comparison site(s) by experts familiar with unimpacted habitats may be sufficient. It may be that no suitable natural site is available for comparison. In this case, recovery trends based on sampling the restored sites might be qualitatively compared to what the literature and/

or experts suggest would be expected in a natural site. The most rigorous approach is quantitative sampling of the restored site and one or more natural areas to test hypotheses concerning the degree of recovery. This approach is discussed further in this chapter.

Monitoring Designs for Quantitative Hypothesis Testing

A fundamental problem with testing hypotheses about recovery after restoration is that there is usually only one restoration site. If the restoration is thought of as a "treatment" in the statistical sense, one site means there is only one replicate in space. Without an estimate of the treatment variance due to treatment replication, it is impossible to rigorously determine if any differences between the restoration and natural sites are due to the restoration activity or simply due to "location." Samples within a restoration site are not replicates of restoration; they are subsamples of one restoration replicate (Hurlbert 1984). To avoid this problem, one can repeatedly sample the restoration site and comparison site(s) before and after restoration occurs using Before After Control Impact (BACI) or Before After Control Impact Paired (BACIP) designs. The BACI designs use replication in time rather than space to estimate treatment effects. The resulting data can be used in various statistical tests to examine the efficacy of the restoration, including testing the differences in the mean abundances of a particular species between the restoration and comparison sites (Steward-Oaten et al. 1986). This approach has been used to examine the effects of a thermal discharge on rocky habitats in central California (Schiel et al. 2004). While this recent study considered what changes occurred as a result of the discharge, the same approach could be used to determine recovery after the impact is removed by comparing differences between the impacted and natural areas before and after the impact is removed. This approach obviously requires that monitoring starts before restoration begins.

In most cases, sufficient pre-restoration data from the relevant sites cannot be obtained. The best design in these cases is to sample the restored and comparison sites over time after restoration using an After Control Impact (ACI) design, and assess recovery relative to how similar the restored site is to the comparison site(s). This can be done by comparing the abundances of particular species in the two types of sites, or some measure of community structure such as similarity. This approach has been used to assess the recovery of cleared plots relative to control plots at six sites in California (Foster et al. 2003). The similarity of biological assemblages in the control plots - the equivalent of comparison sites in restoration monitoring - to each other over time was used to define a similarity envelope. As the cleared plots recovered, their similarity to the control plots was calculated, and when the similarity of the cleared plots to the control plots fell within the range of similarity of the control plots to each other, the cleared plots were considered recovered. Other multivariate techniques can also be used to assess community recovery (Clarke 1993; Clarke and Gorley 2001).

(*Note: This can only be done effectively if MANY species with various characteristics are monitored; otherwise multivariate analyses do not have enough species with which to work.*)

STRUCTURAL CHARACTERISTICS OF ROCKY HABITATS

As previously mentioned, rocky habitats are not typically restored and monitored. If practitioners decide to restore rocky habitats, they must first understand the structural characteristics of the habitat and how they relate to the project goals. The structural characteristics described in this section refer to some of the habitat's biological, physical, hydrological, and chemical features (potential parameters for baseline information and monitoring restoration) and abiotic factors that may influence each characteristic during the restoration process. These characteristics include:

Biological

- Habitat created by rocky substrates

Physical

- Geomorphology and topography

Hydrological

- Currents and Tides
- Wave energy
- Water source (associated with water quality)

Chemical

- Salinity

Not all structural characteristics described in this chapter, however, need to be measured. In most cases, it is not necessary to monitor the physical and chemical environment of rocky habitats during restoration unless the practitioner wants to determine the length of time it takes for the contaminant/pollutant to be naturally removed. The physical and chemical sections of this chapter simply provide some background information on the ecology of rocky habitats such as the role each characteristic plays in supporting the habitat's structure and plant and animal life, and whether any of these characteristics may be parameters for gathering baseline information and monitoring restoration progress. Parameters primarily monitored during rocky habitat restoration are those which relate to the habitat's biota, as discussed in the "Functional Characteristics of Rocky Habitats" section of this chapter.

Parameters selected for measurement will vary depending on the goals of the project. The methods mentioned in this chapter are just a few of many methods that can be used to sample, measure, and monitor the habitat's characteristics. Some methods mentioned may be high-tech and not typically used by laypersons. Thus, data using these methods may be available from various scientists and researchers from federal, state, and local government agencies and academia who have performed assessments prior to restoration efforts in the study area.

Described below are the structural characteristics previously listed, as well as their influence on rocky habitats and methods to monitor each characteristic, whenever possible, before, during, and after restoration.

BIOLOGICAL

Habitat Created by Rocky Substrates

Rocky habitats, as previously discussed, consist of both rocky bottoms and rocky shores. Rock bottoms (subtidal) consist of solid, consolidated substrate such as bedrock, as well as reefs and banks found on the seafloor. The solid seafloor provides an attachment surface for sessile organisms as well as a rough three-dimensional surface that encourages water mixing and nutrient cycling (Stephenson and Stephenson 1972; Cowardin et al. 1979; Bertness et al. 2001). In some cases, organisms such as polychaetes and fishes are found in or near finer sediments between crevices of the rocky substrates. Rocky shores (Figure 5) are distinguished from rocky bottoms by sharp environmental gradients from low rocky intertidal to upper intertidal zones. They include wetland environments that are distinguished by bedrock, stones, or boulders and located along marine and freshwater shorelines (Lewis 1964; Stephenson and Stephenson 1972; Cowardin et al. 1979; Bertness et al. 2001).

Figure 5. Rocky shoreline in Maine. Photo courtesy of William Folsom, NOAA National Marine Fisheries Service. Publication of the National Oceanic and Atmospheric Administration (NOAA), NOAA Central Library. http://www.photolib.noaa.gov/coastline/line1315.htm.

Rocky habitats have several functions, including high primary productivity, biomass export, wave energy reduction, spawning and nursery habitat for fish, invertebrate habitat, and bird and mammal feeding grounds. In many marine areas, rocky substrates are covered with kelp species such as *Laminaria* spp. and *Agarum cribrosum* (found in subtidal zones only), seaweeds, and many gastropods (Lewis 1964; Bertness et al. 2001; Murray et al. 2002). Predation, grazing, and physical factors are important in controlling the zonation of sessile species in these habitats.

Rocky habitats can be divided into three zones: the splash zone, intertidal zone, and subtidal zone (Figure 6). The splash zone acts as a boundary extending above the high water level. The width of this zone may vary depending on factors such as light and shade variations, exposure to waves, and tidal range. This zone is characterized by organisms that can tolerate extreme changes in desiccation, salinity, and temperature; therefore, very few species can thrive in this environment. Commonly seen in this zone are lichens and blue-green algae. Lichens are colonizers of bare rock and are slow growing yet long lived. Blue-

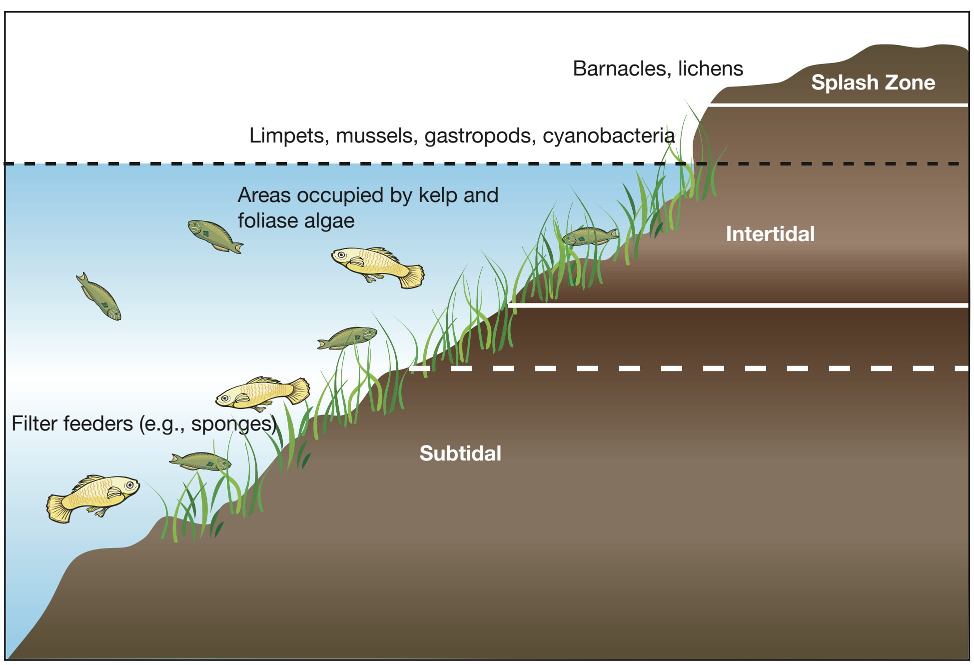

Figure 6. Zonation patterns within a rocky habitat from the shoreline to the ocean's bottom. Figure provided by Brenay Major, intern of NOAA National Centers for Coastal Ocean Science.

green algae, commonly known as cyanobacteria, are small, photosynthetic bacteria that form large colonies which can be seen by the naked eye. Both lichens and blue-green algae adapt to long periods of exposure to air, heat, cold, rain, and predation by land animals and seabirds (Stephenson and Stephenson 1972; Little and Kitching 1996; Bertness et al. 2001). Frequently, you may also see shorebirds such as pipers and wandering tattlers foraging this area for food such as crustaceans and small fish primarily seen in small pools of water on the surface called tide pools.

The high intertidal zone, which is found between the low and high water level, is biologically rich, supporting a diverse assemblage of plants and animals. Animal inhabitants (e.g., limpets, gastropods, mussels, etc.) and vegetation (e.g., algae) are able to attach themselves securely to the rocks during high tides or pulsating waves (Lewis 1964; Raffaelli and Hawkins 1996; Bertness et al. 2001; Murray et al. 2002). Waves also play a positive role in supporting small organisms by assisting in shaping and reforming cliffs, gaps, and caves within this zone that provide habitat for the organisms such as invertebrates and small fishes (such as sculpin and blennies). Organisms in this area are not only exposed to tides and waves, but also to light which can make rock surfaces very dry if waves are reduced. Mobile animals occupying this area (as well as the splash zone) avoid desiccation (drying out) by hiding under moist or completely wet algae, or in rock crevices or tidepools. The lower area of the intertidal zone is covered by water except for a short period of time during the lowest tides. Most plants and animals in the low intertidal area can only survive for short periods without water. Moss, red encrusting algae, sea anemones, and hermit crabs are examples of species inhabiting the lower area of the intertidal zone (Bertness et al. 2001).

Other organisms that occupy intertidal zones include:

- Nudibranchs
- Hydroids
- Sea stars (Figure 7)
- Sea urchins
- Mussels
- Brittle stars (Figure 8), and
- Sea cucumbers

Rocky subtidal zones are areas below the tides where light is reduced as it travels toward the ocean's floor. If water is relatively clear within subtidal zones to depths of around 30 meters, large kelp is often seen dominating this area, some of which can produce canopies that float

Figure 7. Starfish and anemones in a cold water rocky community. Photo courtesy of L. Stewart, OAR/National Undersea Research Program. Publication of the NOAA Central Library. http://www.photolib.noaa.gov/nurp/nur03503.htm

Figure 8. Brittle star on rocky substrates. Photo courtesy of Russell Bellmer, United States Fish and Wildlife Service.

on the surface (e.g., giant kelp, *Macrocystis*). These canopies also reduce light reaching the ocean's bottom, so organisms found below kelp canopies adapt to low light availability (Kennely 1989). Other species commonly found in subtidal zones include worms, sea stars, sea urchins, sea anemones, sponge, various gastropods, red algae (Rhodophyta), brown algae including kelp (Phaeophyta) and green algae (Chlorophyta) (Stephenson and Stephenson 1972; Sebens 1985; Little and Kitching 1996; Bertness et al. 2001). Subtidal foundation species perform important functions such as altering patterns of water movement (Jackson and Winant 1983; Eckman et al. 1989), which in turn influence food and larval supply, and provide refuge from predation similar to rocky intertidal areas (Bertness et al. 2001).

Sampling and Monitoring Methods

There are several methods to map rocky habitats which can also be used for pre-monitoring and post-monitoring of restoration and natural recovery efforts. For pre-monitoring purposes, these methods can be used to determine habitat characteristics, identify activities occurring near the habitat that may influence restoration progress, and verify whether the habitat is in a suitable location for restoration. These methods can also be used in post-monitoring efforts to determine if the habitat's structure changed over time.

Photography - may be used in the intertidal and subtidal zones to characterize benthic substrates and identify the type of substrates present (Lundalv 1971). Divers can use underwater cameras to conduct quantitative surveys of large rocky areas. Selected areas can be photographed at various intervals over time to show changes occuring within their biocoenoses[5]. Photographs can then be analyzed in a stereo comparator and stereo microscopes in connection with organism density, cover, size distribution, and biomass on the rocky substrates (Lundalv 1971).

PHYSICAL

Geomorphology and Topography

Geomorphology refers to the study of the nature, origin, and historical changes that have taken place, particularly those caused by erosion and deposition. The nature of rocky habitats consists of bedrock, stones, and boulders. The shape and structure of rocky habitats are influenced significantly by weathering, currents, waves, and tidal action (Pethick 1984; Bird 2000). These habitats are also formed as a result of faulting and earthquakes (Pethick 1984). Rocky bottom (subtidal) habitats are formed when rocky substrates are transported and laid down along the ocean's bottom by means of weathering and waves. The composition of the subtidal community is influenced significantly by slope of the rock and nature of the substrate. Horizontal and gently sloping substrates, for example, are normally dominated by macroalgae, whereas vertical rock structures may be dominated by epifaunal invertebrates (Lundalv 1971). This may be due partially to higher light levels on horizontal surfaces than vertical structures and therefore, flat and sloping rock surfaces provide a more suitable environment for macroalgae growth and survival (Bertness et al. 2001). If construction along the coast or destructive dredging on the ocean's bottom takes place during a restoration project, geomorphology and topography may be changed, thereby affecting vegetation and animals by creating an unfavorable environment (i.e., altering the slope of vertical structures where certain species of organisms are found and exposing them to more sunlight).

The movement of rocky substrates will vary based on size of the substrate and the energy regime of the habitat. Boulders, for example, are moved mainly by high energy waves that occur during severe storms, while smaller substrates can be transported by waves with average energy (Pethick 1984; Trenhaile 1987).

[5] A group of networking organisms that inhabit a particular area and form an ecological community.

In some cases, extreme waves may break off pieces of rocky substrates from established rocky habitats, thereby changing the habitat's shape. Rocky substrates that are put in place by practitioners to restore rocky habitats can be dislodged by intense waves or by some other means influencing geomorphology and topography, as well as affecting biota. As a result of dislodged rocks, restoration progress towards maintaining and supporting various species may be restricted. Modifications may then have to be made to the restoration project, such as replacing dislodged rocky substrates and adjusting the timeline for monitoring progress toward achieving a naturally sustainable rocky habitat.

Differences in topography and roughness of rock types are important features that define the rocky habitat. These characteristics can disperse wave energy, potentially influencing nutrient and food distribution, which in turn influence species diversity and abundance (Archambault and Bourget 1996). Crevices and tide pools can also influence distributional patterns by providing microhabitats for mobile and sessile organisms. During restoration, if a rocky habitat is significantly altered because of construction such as the use of heavy machinery, organisms that occupy these areas may be disturbed or destroyed. Textural roughness of the rock also plays a role in rocky shore communities by increasing water retention, providing refuge for benthic recruits (Littler 1980), and acting as a pool for shore-based contaminants (e.g., oil). As previously mentioned, topography and geomorphology play a significant role in supporting organisms and should be considered when developing a restoration plan. Monitoring topography and geomorphology changes and noting, whenever possible, of the source responsible for the change, can help the practitioner determine whether modifications can be made so that the project can be continued or whether the project should be discontinued because the source responsible for degrading the habitat is constant.

Measuring and Monitoring Methods

Line chain transect - The quality of the surface topography influences the number of refuge locations for living marine organisms and drainage from the rock surfaces (i.e., the persistence of intertidal pools) (Trudgill 1988). An index of rugosity (roughness) can be measured using a line/chain transect (Figure 9) over a given area by extending the chain/line taut along the contours of the surface of an area, and then allowing the line to relax within the crevices. The relaxed measured length along the contours of the surface divided by the taut length provides the rugosity (Trudgill 1988).

Aerial photographs or satellite images - The abundance of rocky shores along the coastline may be mapped using aerial photographs or satellite images. Maps, aerial photographs, videos, and other information providing data shoreline geophysical characteristics are useful when selecting restoration sites (Murray et al. 2002). As maps are made at a variety of different spatial scales, they must be chosen for use based

Figure 9. Monitoring a rocky shoreline. The transect is located within the rockweed (*Fucus)* dominated stratum, and markers define the locations of randomly-selected, permanent quadrats. Photo courtesy of Michael Foster, Moss Landing Marine Laboratories, California.

in part on the scale necessary to select a suitable site.

Ground truthing - Shoreline data may also be obtained by "ground truthing" the site, or from trained observers boating close to the shore or walking along the shoreline. These individuals can gather quantitative information on the habitat's physical characteristics and determine whether the potential study area is suitable for restoration (Littler and Littler 1987; Murray et al. 2002).

Side-scan sonar imagery - A new mapping scheme for characterizing seafloors, based primarily on the interpretation of side-scan sonar imagery, has been developed to easily map and identify rock, gravel, and soft sediments (Barnhard et al. 1998). With the use of a geographic information system (GIS), these and other available data (e.g., seismic profiles, grab samples, submersible dives, and cores) can be referenced to a collective geographic base, superimposed on bathymetric contours, and then incorporated into surficial geologic maps of the study area. This digital representation of the seafloor encompasses depth, bottom type, and other features that allow analysis of rocky habitats (Barnhard et al. 1998).

HYDROLOGICAL

Currents and Tides

Continuous current flows occur along rocky shores and help to shape the rocky structure and influence species zonation. Some species can survive when exposed to continuous current flow, while others cannot and may easily be swept away. Periwinkles (*Littorina saxatilis*), for example, live in the upper intertidal zone (splash zone) and are exposed to waves for short periods of time (Lees et al. 1980; Nybakken 1982; Little and Kitching 1996). Vegetation and animals living on rocky shores must be able to adapt to continuous water flow. The rising and descending tides also affect life on rocky shores. Once the tide descends, plants and animals on rocks are exposed to air and therefore must be able to adapt to environmental changes in order to survive until the tide rises again. Organisms which live very low on the shore, on the other hand, are only briefly exposed to air.

Subtidal rocky habitats are generally located near areas where strong tidal currents and turbulent waters are common (Denny et al. 1985; Denny 1988; Paine and Levin 1981; Bertness et al. 2001). Organisms on rocky bottoms must therefore be firmly attached to the substrate or seek protection within cracks and crevices. Water movement also directly impacts the survival of benthic rocky bottom organisms when exposed to high hydrodynamic forces. These forces may improve the transport of gases, nutrients, and food; influence the movement of benthic substrate such as sediment and rock; and influence the impacts of flow on predation (Riedl 1971; Denny 1988; Paine and Levin 1981). Current flow should be considered when selecting a restoration site and monitoring the restoration effort because currents influence the biological community (as previously discussed) and can cause substrates to be moved that may affect restoration progress by shifting geomorphology.

Measuring and Monitoring Methods

Current profilers - Current profilers are instruments to measure the velocity and direction of currents. The most commonly-used current profilers are acoustic Doppler current profilers (ADCP). This instrument involves the use of underwater sound to measure vertical profiles of horizontal currents. The ADCP transmits acoustic pulses from a transducer along four beams. The transducers receive backscattered echos from small particles and plankton present in the water currents. The ADCP then converts the backscattered sound into elements that identify water current velocity, measure current speed and direction, and make a profile of the measurements (Appell et al. 1987; Fitzgerald et al. 2003).

Wave Energy

As previously discussed, waves can influence the vertical elevation of the biological community. Wave energy also influences the rates of recovery, whether through natural processes or restoration. Severe wave action can remove individual kelp plants and sessile organisms from their place of attachment, particularly in exposed areas compared to sheltered areas, or overturn these hard substrates on which they are attached, destroying the kelp and other macroalgae and disturbing faunal communities (Murray et al. 2002). For example, intertidal fucoid algae found along moderately wave-exposed rocky intertidal areas along the California coast decreased in size and abundance when exposed to greater wave energy in intertidal areas (Blanchette et al. 2000). Increased wave forces may limit the activity of mobile species, whereas a decline in wave energy may increase thermal and dessication stress because the intertidal habitat is not frequently dampened by wave splash or spray (Bertness et al. 2001). As a result of increased or reduced wave energy, progress towards successfully restoring a rocky habitat may be affected and modifications to the monitoring plan, such as extending the monitoring timeline to observe any changes in biota, may need to be considered.

Sampling and Monitoring Methods

Wave force meter - Waves can be measured by estimating cumulative water motion or maximum wave force directly. Wave force can be measured directly using a wave force meter (Bell and Denny 1994). This device is simple and inexpensive to construct, and can easily be used in large numbers. A number of recorders were used to quantify maximal daily water energy and velocities at three intertidal habitats on the central coast of California (Bell and Denny 1994). This device has proven to provide accurate estimates for wave energy in intertidal habitats. Wave energy can also be measured indirectly using biological indicators such as the presence of an indicator species, or physical indicators such as fetch or the distance that waves travel (Murray et al. 2002).

Wave buoys - Wave buoys are also used to assess wave energy. They are fixed at certain locations in the ocean and record information about wave conditions. Wave buoys use electronic sensors to measure wave heights, wave directions, and time periods between waves (Davies 1996). This method may be relatively expensive to use, so data gathered using this method, particularly near the potential restoration site, may be available from scientists in the field. Such data sharing encourages collaborative efforts between experts and other practitioners. Other sources that provide methods for measuring wave energy, direction, height, and periods include: Draper et al. (1974), Brumley et al. (1991), and AshokKumar and Diwan (1996).

Water Source

The health and growth of rocky habitat biological communities can be modified by water quality. In some instances, the source of water inflow entering rocky habitats may be polluted by effluents or metals, or may bring with it freshwater that dilutes salinity levels which in turn affects the rocky habitat biota (discussed further in the "Salinity" section of this chapter) (Ardisson and Bourget 1997). Sources responsible for negatively affecting the biological community of rocky habitats include:

- Pollutants from upland areas
- Increases in freshwater discharge from channels or creeks that have been diverted for various purposes (e.g., construction)
- Industrial discharges (e.g., heavy metals)

- Sewage outfalls, drains, and contaminated river flows, and
- Oil and chemical spills

By identifying the source of water input, the practitioner will be more prepared to handle impacts to the habitat and select parameters suitable for following progress of restoration efforts over time.

The biological community of rocky habitats can also be affected by degraded water quality as a result of turbidity or pollutants entering the habitats. Industrial effluent discharges, for example, can influence species diversity, abundance, and spatial distribution of the intertidal fauna (Littler and Murray 1975). Researchers assessed the effects of a low volume discharge of raw sewage on rocky marine intertidal communities near Wilson Cove, San Clemente Island, California. Results showed that near the outfall pipe, species diversity, standing stocks of large, canopy-forming intertidal macrophytes (which largely had been replaced by a low-growing algal turf) and an abundance of suspension-feeding animals were reduced. The most productive macrophytes, however, were those in the sewage outfall area (Littler and Murray 1974). In other cases, macroinvertebrate populations in rocky intertidal areas exposed to domestic sewage had higher energy contents than those in unpolluted areas and grazed greater proportions of blue-green algae and bacteria in the polluted area (Littler and Murray 1978). Other forms of pollutants such as industrial and agricultural chemicals as well as oil can also affect animals such as birds that breed along rocky habitats and feed on fish and molluscs there. If rocky habitats are polluted, some birds may migrate to more suitable feeding areas because organisms are no longer edible, thereby affecting the restoration project if the goal was to restore or maintain bird communities (Ferns 1993). Because of the tremendous impact that water quality has on the biological community of rocky habitats as well as restoration progress, water quality monitoring and water source identification should be considered when developing a restoration plan, as they can influence progress toward restoring a naturally sustainable rocky habitat.

CHEMICAL

Nutrient Concentrations

Nutrients that support rocky ecological communities are primarily from decayed plants and animals. In some cases, additional nutrients in the water may result from terrestrial runoff. Plant life such as algae can be found attached to rocks on the shorelines and on hard bottom substrates. Like other aquatic vegetative species, algae use the sun's energy to produce organic material that can be used by organisms. Other types of algae such as kelp that are found in deeper waters use their leaf blades to help recycle nutrients in the water column. Waves, currents and tides also distribute organic material throughout the water column for plant and animal use. For instance, kelp and other types of algae on rocky substrate absorb nutrients from the water while the nutrients are being transported by tides, etc., to support plant growth (see Chapter 5: "Restoration Monitoring of Kelp and Other Macroalgae" for more details).

Salinity

Salinity changes can affect rocky substrate biota, particularly in estuarine areas or close to the mouth of coastal rivers (Carriker 1967; Dethier and Schoch 2000; Murray et al. 2002), and thereby affect restoration progress. A decrease in salinity levels, for example, may be caused by precipitation (e.g., rainfall) or inflow of freshwater (e.g., diverted streams or channels) to estuaries and marine systems; an increase in salinity may occur as a result of chemical runoff. Such changes in salinity can shift the distribution and abundance of plants and animals that occupy rocky habitats (Ardisson and Bourget 1997; Witman and Grange 1998). If the goal of the restoration effort at a designated site is to increase or sustain vegetation and animals, a significant change in salinity can prevent this habitat from supporting biota and becoming naturally sustainable.

In estuaries along the Danish Straits, species diversity of marine benthic macroalgae declined due to reduced salinity levels compared to marine-freshwater green algae (Middleboe et al. 1997). Another study showed that reduced salinity levels in the shallow waters of a rocky fjord caused a decline in mussels (*Mytilus galloprovincialis)* and marine predators such as mobile invertebrates (Witman and Grange 1998). Large numbers of marine predators were seen just below the lower boundary of the low salinity levels (LSL) during February and April 1993. Approximately 20 to 80 percent of the mussel population was consumed below the LSL boundary, which indicates that the LSL represents a spatial refuge from predation. In some cases, salinity changes may indirectly affect intertidal communities, most notably plant and animal distribution and abundance, by affecting the toxicity of pollutants such as heavy metals (Vernberg and Vernberg 1974). Overall, changes in salinity levels within a rocky habitat being restored can ultimately affect restoration progress towards sustaining the habitat's biological community.

Measuring and Monitoring Methods

Refractometer - Salinity can be measured using a hydrometer, refractometer or a salinity meter. A refractometer is a hand-held instrument used to measure salinity. This instrument measures the bending of light between dissolved salts as it passes through seawater (Rogers et al. 2001). Salinity is measured on a calibrated refractometer by first placing a few drops of the seawater sample under the transparent slide, and then reading the salinity measurement through the eye piece (Rogers et al. 2001).

Hydrometer - A hydrometer is used to determine salinity by placing the instrument into a tall flask with the sample water and taking a reading at eye level at the water's surface, at the bottom of the meniscus[6] (Rogers et al. 2001). Hydrometers are typically calibrated for use at a specific temperature and a conversion chart must be consulted to estimate salinity of a sample taken at a different temperature (Rogers et al. 2001).

CTD Instrument - A conductivity, temperature, and depth (CTD) instrument can be used to measure salinity in deeper water. This instrument is lowered through the water column and continuously records conductivity, temperature, and depth. Salinity is then calculated in practical salinity units (psu) based on conductivity because electric current passes readily through waters that have higher salinity levels. Therefore if conductivity of the water is known, then salinity can be determined.

[6] The semi-circular-shaped surface at the edge of a liquid column.

FUNCTIONAL CHARACTERISTICS OF ROCKY HABITATS

The primary functions of rocky habitats include:

Biological

- Providing habitats and shelter for vegetation, fish, and invertebrates
- Providing breeding, feeding, and nursery grounds for many marine species
- Providing a hard structure for substrate attachment
- Providing refuge from larger predators

Physical

- Protecting coastal areas from erosion

By performing these functions, rocky habitats are able to support important recreational and commercial fisheries and their food sources, as well as maintain plant and animal diversity and abundance. Understanding how rocky habitats function is important to the success of restoration efforts. Monitoring should be performed to determine whether the habitat is functioning efficiently and to track the success of the restoration project or evaluate natural recovery. This section concentrates on the biological and physical functions performed by rocky substrates. Also provided are some methods to sample, measure, and monitor species affiliated with each of the functional characteristics. For example, rocky substrates may be used as breeding and feeding grounds by many species of animals. These functions can be estimated by counting the number of individual animals and identifying the species type using the habitat for these reasons. Not all functional characteristics described here, however, are expected to be measured. The following information illustrates the role each characteristic plays in the functioning of the habitat. Restoration practitioners must determine what functional characteristics should be monitored in order to meet the goals of their particular project.

BIOLOGICAL

Provides Habitat and Shelter

Rocky habitats provide shelter for many aquatic species. The crevices within the rocky shores shelter organisms such as snails, crabs (Figure 10), and lobsters. Oysters and mussels are also found on rocky substrates along the shoreline. Sessile species such as barnacles, tunicates, soft corals, and sea anemones attach to rocky substrates. Fishes such as striped bass and toadfish occupy rocky habitats that extend deep into the water. As these habitats have great species diversity and abundance, food must be readily available for all levels in the food chain.

Vegetation such as macroalgae is commonly found on rocky substrates in the intertidal and subtidal zones because these areas are not exposed to extreme light intensity, high temperatures, and desiccation as in upper shorelines (Barnes and Hughes 1988). Seaweed, for example, grows in both rocky intertidal and subtidal zones, although most seaweed biomass and productivity is subtidal. These macroalgae types also provide nutrition to mobile organisms that

Figure 10. Kelp crab (*Pugettia producta*) on rocky substrate. Photo courtesy of Russell Bellmer, Project Leader, United States Fish and Wildlife Service.

live throughout the tidal zone (similar to other species of macroalgae) and are tolerant to light and air exposure (Stephenson and Stephenson 1972; Barnes and Hughes 1988; Little and Kitching 1996). The most common seaweed types include red, brown, and green algae. Kelp species such as giant kelp (*Macrocystis*), bull kelp (*Nereocystis luetkeana*), and winged kelp (*Alaria marginata*) (Figure 11) are also present in subtidal rocky zones.

Species grow at different zones on the rocky shoreline. Seaweed *Microcladia coulteri,* for example, lives on other plants that inhabit rocks between the high intertidal and subtidal zones; feather boa kelp lives on rocks between the middle of the tidal zones; sea moss (green algae) grows between the high and middle intertidal zones (Little and Kitching 1996).

Measuring and Monitoring Methods

Vegetation - Percent cover of macroalgae can be determined using quadrats, with biomass determination requiring destructive sampling. A quadrat is a square, rectangular, circular, or other shaped area used as a sample unit. They can be used to identify and assess vegetation composition, species richness, abundance, and biomass in a given area. Quadrats can be fixed so that a sample area can be measured repeatedly (Albert and Lehman 2001; Murray et al. 2002), or sampled in combination with photography to determine the percent cover and evaluate species recovery (Choi et al. 2001).

Line transects - Line transects and plot-based sampling methods can also be used to study rocky intertidal macrophyte populations, as well as populations of animals such as mussels that may cover extensive areas of the substrate (Murray et al. 2002). The frequency and cover of macrophyte populations can be documented using these methods. If available, collected data can be compared with records from earlier studies to determine whether species composition and abundance have changed over time. Figure 12 shows researchers observing, measuring, and documenting growth of vegetation along an intertidal rocky habitat.

Many mobile and sessile organisms are also found either on the shoreline or ocean bottom. In some cases, some organisms can be found at both locations. Animals commonly found along rocky habitats (both in the intertidal and subtidal zones) include:

Figure 11. Boulder shoreline in central California. The lower shore is dominated by winged kelp, *Alaria marginata*. Photo courtesy of L. McConnico, NOAA Monterey Bay National Marine Sanctuary, California.

Figure 12. Researchers assessing growth of vegetation on an intertidal rocky habitat. Photo courtesy of Russell Bellmer, Project Leader, United States Fish and Wildlife Service.

- Limpets
- Chitons
- Crustaceans
- Lobsters
- Sea urchins (Figure 13)
- Hydroids
- Barnacles
- Fishes (Figure 14) (Barnes and Hughes 1988)

Provides Breeding Grounds

The rocky shores provide breeding grounds for birds, amphibians, reptiles, and fish. Following are several examples of the value provided by this habitat to different species of organisms. Many animals breed in various locations along rocky areas most suitable for them. Birds, for example, nest in crevices that are further inland on the shore to avoid being swept away by waves; amphibians and reptiles nest in moister areas with adequate protection to avoid predation; some fish breed in rocky habitats near upwelling areas where currents transport food. Garibaldi (*Hypsypops rubicundus*) prefer rocky bottom habitats in southern Baja California as breeding grounds (Sikkel 1998). From the shores of Baja, California to Alaska, the California sea lion (*Zalophus californianus*) uses rocky habitats as breeding grounds. The breeding population of *Z. californianus* along San Nicolas Island, California usually peaks at the beginning of July. During the 1969, 1970, and 1971 breeding seasons, at least 2957, 2271, and 3500 sea lion pups, respectively, were born on San Nicolas Island (Odell 1975).

Provides Feeding Grounds

Rocky habitats act as net exporters of nutrients to marine and terrestrial ecosystems (as feeding grounds). They provide food for sea and shore birds, otters, and other marine organisms. When marine organisms such as fish or algae die, they decompose and become detritus. Detritus forms the base of the food chain for soft-bottom habitats, and it serves as food for filter feeders, such as barnacles, in other habitats. Deposit- and filter-feeding worms, clams, and other invertebrates are food for birds and fish that forage along rocky habitats. The transfer of biomass from the rocky intertidal habitat to other habitats ties the health and productivity of kelp and rockweed in the rocky intertidal area to that

Figure 13. Sea urchins attached to rocky substrates. Photo courtesy of Russell Bellmer, United States Fish and Wildlife Service.

Figure 14. Black and yellow rockfish (*Sebastes chrysomelas*) seeking shelter within rocky substrates. Photo courtesy of Russell Bellmer, United States Fish and Wildlife Service.

of soft-bottom dwellers (e.g., dungeness crabs, *Cancer magister*) and flatfish (e.g., halibut, *Hippoglossus stenolepis*) (Lees et al. 1980; Sanger and Jones 1984; Alaska Department of Fish and Game 1993).

Crevices within rocky substrates may act as a food basin for many species. They also provide feeding grounds for resident organisms and non-permanent residents such as gulls, egrets and ducks, gulls, terns, and skimmers. Molluscs or small fishes occupy shallow water crevices along the shore, allowing easy access for birds to feed on them periodically. Barnacles, hydroids, oysters, and mussels also receive nutrients from incoming currents along the shore. Crustaceans and other invertebrates feed on the algae that are attached to the rock surface. Fish tend to feed on algae, sea urchins, bivalves, and shrimp species that are present (Vrtiska et al. 2003).

The rocky intertidal zone is also an important foraging area for the California sea otter (*Enhydra lutris*) which must live close to abundant food supplies to maintain their high metabolism. Otters use rocky shores as resting areas and for foraging on faunas such as shore crabs. The rocky intertidal zone is also a critical foraging area for waterfowl, such as black, surf, and white-winged scoters (*Melanitta nigra, M. perspicillata,* and *M. fusca*), and harlequin ducks (*Histrionicus histrionicus*) which feed predominantly on mussels (*Mytilus* spp.). While many shorebirds are associated with mudflats, surfbirds (*Aphriza virgata*) and black and ruddy turnstones (*Arenaria interpres* and *A. melanocephala*) prefer to forage on rocky substrates and gravel beaches (Alaska Department of Fish and Game 1993). Mammalian species such as rats, rabbits, deer, and even sheep will also forage on available rocky shores (Feare and Summers 1985).

Sea urchins (e.g., *Stronglyocentrotus* spp.) are common grazers of kelp that is attached to rocky substrates. Snails and small crustaceans also graze on kelp fronds. Limpets (*Ancylidae)* as well as other species of mollusks can also be found grazing on algae attached to rocky substrates (Forrest et al. 2001) (Figure 15). Researchers have recorded grazing activity of organisms such as gastropods on intertidal rocky substrates (Forrest et al. 2001). Grazing occurrences for limpets (e.g., *C. tramoserica)* are positively correlated to gastropod numbers in nearby areas during low tide. Densities of gastropods measured when limpets were inactive during low tide demonstrated good estimates of grazing activity throughout high tide.

Provides Nursery Grounds

Rocky habitats are important nursery areas for juvenile fauna such as fish. Rockfish (*Sebastes*

Figure 15. A limpet attached to rocky substrate. Photo courtesy of Russell Bellmer, United States Fish and Wildlife Service.

spp.) and other fish species use this habitat as nursery areas because food is readily available and the rocky structure provides protection for juveniles against predation and extreme tidal current (Carlson and Straty 1981). The rocky substrate is an important feature for nursery grounds, as well as the presence of algae that grows on the hard substrate. In some cases, the mat of algae growing on rocky substrates is also used by some species as nursery areas. Giant kelp (*Macrocystis pyrifera*) which form underwater forests and/or kelp beds attach to rocky substrates and provide nursery areas for reef fishes (Holbrook et al. 1990). These examples show that rocky substrates directly and indirectly support numerous fauna types, and therefore any disturbance to rocky substrates can disrupt their ecological community.

Provides Refuge from Predation

The crevices within rocky habitats provide protection against predation for some species such as polychaetes, crustaceans, and juvenile fish (Bertness et al. 2001). Gastropods and amphipods, for example, hide in crevices within the rocky substrates to avoid predation by fish (Wennhage and Pihl 2002). In some instances, the gastropod's shell color is similar to rock coloration and therefore, they are able to camouflage themselves. In the San Juan Archipelago, the acorn barnacle (*B. glandula*) seeks refuge from predation in the higher intertidal rocky shores (Schubart et al. 1995). Polychaetes and juvenile fish also seek refuge in crevices to avoid being preyed upon by birds.

Provides Substrate Attachment

Algae (e.g., kelp and other macroalgae) (Figure 16) are commonly found attached to rocky substrates (Schiel and Foster 1992). To maintain growth and reproduction, algae consume nutrients that are readily available in the water column. Rocky substrates not only provide a place of attachment for kelp, but kelp in turn provides attachment surfaces for many sessile and drifting life forms of various sizes. Some species such as barnacles, bryozoa, and foraminifera also attach themselves to leaves of kelp for support against currents (Hogan and Enticknap 2003). Blades of kelp also filter nutrients in the water column that can be utilized by sessile organisms attached to the kelp and

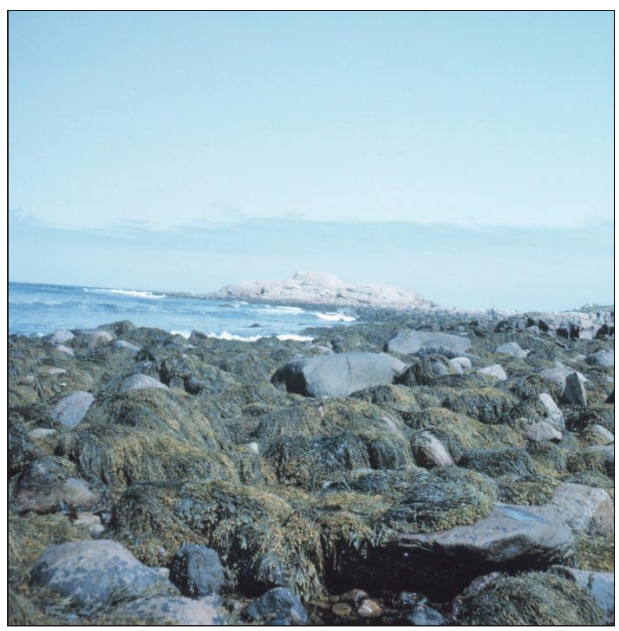

Figure 16. Rocks along the Massachusetts coast covered with the brown algae *Ascophyllum nodosum.* Photo courtesy of Mary Hollinger, NOAA National Oceanographic Data Center. Publication of NOAA Central Library. http://www.photolib.noaa.gov/coastline/line0738.htm.

rocky substrates. The most common sessile organisms found attached to rocky substrates and kelp include bryozoans, sponges, tunicates, cup corals, and anemones (Coates 1998; Carrington 2002). These organisms are able to grow by consuming nutrients that are transported by waves throughout the water column or washed onto the shore.

Sampling and Monitoring Methods

Practitioners should ensure that a restoration monitoring plan includes comparison sites, organisms to be sampled, and a sampling design. Once this is accomplished, sample distribution in space and time must be specified. It is not necessary to consider sample allocation in space if all individuals in the restored and comparison sites are sampled. In this case, the true population abundances are known, not estimated, and restored and comparison sites can be directly compared. Restoration or natural recovery sites may be so large that this cannot be done, except perhaps for species with very large individuals such as marine mammals or birds. For smaller species, it is usually necessary to estimate abundances from sub-samples taken within the restored and comparison areas. In BACI designs (as discussed previously in the 'Monitoring Designs for Quantitative Hypothesis Testing' section), it is often best to sample fixed (permanent) sub-areas that represent the entire site. These might be stratified depending on the distribution of the organisms to be sampled. In ACI designs, random allocation of samples is required if an estimate for the entire restoration site is desired. These may be allocated completely at random or at random within pre-defined strata. For example, it is well known that organisms occur within zones on rocky shorelines. If one knows that species X only occurs over a particular vertical range on a rocky shore, then species X should only be sampled within that range or stratum. If it is sampled in all zones, there will be many samples with zero abundance, the variance of the abundance estimates will increase, and the ability to detect change will decline.

Strata are commonly defined by first sampling along transects across the environmental gradient that directly or indirectly causes the stratification (e.g., vertical height on rocky shorelines, depth on subtidal rocky bottom) (see Choat and Schiel 1982 for sampling procedures). Other stratification may occur, such as designating crevices as a stratum because they are the only sub-habitat where abalone are found. Such strata within subtidal rocky habitats are often difficult to visually characterize because of poor visibility. Side-scan sonar can provide very accurate substrate characterizations, but may be difficult to use at depths less than 30 meters, particularly if there are seaweeds in the water column obstructing the sensor. Stratification can greatly increase the ability to detect changes, but requires a good understanding of the natural history of the habitat.

Allocation in time must also be considered, specifically how often and for how long monitoring should occur. In BACI designs, each sample time is a replicate, so sampling frequency is particularly important. In ACI designs, allocation in time might be roughly estimated from the literature on recovery for similar habitats. As mentioned earlier, recovery in rocky habitats seems to range from one to ten years, so planning to sample yearly for ten years might be a reasonable starting point.

Presented are several methods to sample, measure, and monitor various animal species in order to track their abundance, distribution, and diversity.

Fish - Purse seining can be used to sample fish along the shoreline. Purse seine nets are projected from land and used mainly in shallow waters close to the shoreline. The seine net is supported by floats, weights, and poles (Hart and Reynolds 2002). The floats keep the net afloat at the surface. The lower part of the net contains weights that sink the bottom of the net below the surface of the water. The net is then stretched out using poles that are attached on both sides of the net. Persons holding the net surround the shoal of fish and then pull the net ashore using the attached poles. Fish caught in the net are then identified and counted (Hart and Reynolds 2002).

Fish distribution and density estimates can be determined using belt-transect surveys, but such surveys require the use of scuba diving equipment in the shallow subtidal zone (Rogers et al. 2001). Survey nets can also be used to assess fish assemblages (Pihl et al. 1994). Samples of macrovegetation can also be collected with nets and used to compare fish assemblages with the vegetation biomass.

Underwater photography and baits/traps can be used to estimate fish and invertebrate densities and species composition in submerged intertidal rocky habitats. In some cases, macrofauna may be collected by trawling as well as hook and line fishing (Moore and Mearns 1980). Data collected using underwater photography (e.g., using a baited camera) can identify whether there is an increase in fish species abundance and density related to water column depth (Moore and Mearns 1980).

Marine Mammals - During aerial surveys, sea otter habitats may be classified as rocky, or sandy and rocky (Laidre et al. 2002). These animals may be radiotagged to calculate their maximum foraging depths and maximum distance from shore. These estimates may be used to approximate the offshore extent of sea otter habitat.

Aerial counts may be used to monitor the trend in numbers of seals along rocky habitats throughout each season (Frost et al. 1999). A linear model can then be developed to show the day, date, and time relative to tidal changes that significantly affected seal counts. This information will provide the practitioner with a good representation of the number of seals that generally occupy the rocky habitat and whether these numbers changed over time.

Invertebrates - Invertebrate density and cover can be assessed using video or digital cameras. A practitioner can select how frequent photographs are to be taken in designated areas within the restoration site over the length of the study. The images can then be analyzed by identifying species type and counting the number of organisms present in each image. Data collected from each image can then be compared to determine whether diversity of invertebrate abundance and distribution changed over time (see Murray et al. 2002).

Sampling units which include point quadrats and transects may also be used to define the spatial extent of the individual sample (Figure 17). Once strata are defined on rocky shorelines, the usual sample units are quadrats within which the abundances of organisms are determined. For organisms that occur as discrete individuals, such as sea stars, counts within the quadrats are the usual metric for abundance. The optimal quadrat size depends on the abundance and dispersion of the organism being sampled (Green 1979). If more than one species is counted in the same quadrat, some species will be sampled better than others (i.e., “one size does not fit all”). One solution to this problem is to use nested quadrats of different sizes. Many marine species such as some macroalgae, tunicates, and sponges spread by vegetative growth or are colonial, and individuals are very difficult to distinguish. Other species like barnacles can form very dense populations of small individuals. Percent cover is commonly used as the measure of abundance for these organisms. Counts and percent cover are usually done within the same quadrats. There are numerous ways to estimate cover, in part depending on how “layered” the organisms are. If a sample area has an overstory of 100

Figure 17. Sampling with count (number of individuals) and point quadrats (percent cover) in an intertidal mussel zone. Photo courtesy of Michael Foster, Moss Landing Marine Laboratories, California.

percent cover of seaweeds and an understory of barnacles, a single photo of the area cannot be used to estimate the cover of both seaweeds and barnacles. A good discussion of the various sampling units is included in Murray et al. (2002).

Quadrats are also used to define areas for destructive sampling for biomass estimates or to identify and count organisms too small or cryptic to be accurately counted in the field. To conduct destructive sampling, there should be good scientific justification (as discussed previously in the 'Deciding What to Monitor' section). Due to constraints such as wave and current motion, large plants in the water column, and time spent on the bottom with scuba diving equipment, intertidal sampling units must commonly be modified for efficient use underwater (examples in Coyer et al. 1999). Transects may also be used to collect field data by recording observations made or by collecting samples of species along a line or within a habitat. Line transects involve recording organisms in each sampling unit along the line (Murray et al. 2002).

The number of sample units taken within a particular restoration site or comparison site(s) are sub-samples, not true replicates of the "restoration" and "comparison" treatments. Sub-samples are important, however, because the number taken will affect the accuracy of the mean abundance estimate. It is the mean that is used in BACI analyses as described earlier, and the parameter that is usually used for similarity comparisons. Typically the number of samples needed to accurately define the mean can be found by plotting the mean versus the number of sub-samples used to calculate it and determining the number of sub-samples required for the mean value to stabilize. This number will change as the abundance changes in the restored area. A rough estimate can be obtained by pilot sampling in the comparison area. It is always better to take more rather than fewer samples.

PHYSICAL

Reduces Wave Energy and Erosion Potential

Rocky habitats act as a protective barrier against wave action and storms. As waves rush toward the shoreline, the rocky structure slows down the energy of the waves, thereby preventing erosion of the shoreline and elimination of the various ecological communities present. On upper rocky shores, for example, organisms that occupy rocky substrates cannot tolerate extreme wave energy compared to those located on the lower rocky shores. Thus, rocky structures help to reduce extreme wave energy before it reaches the upper portions of the rocky shores.

CHEMICAL

The chemical functions associated with rocky habitats are performed by epiphytes, algae, and filtering organisms that are found on the rocky substrates and *not* the rocks. These functions include modification of chemical water quality and dissolved oxygen, and supporting nutrient cycling. Chapter 5: "Restoration Monitoring of Kelp and Other Macroalgae" of this document provides detail information on the role of macroalgae in supporting rocky habitats.

PARAMETERS FOR MONITORING STRUCTURAL/FUNCTIONAL CHARACTERISTICS OF ROCKY HABITATS

The following matrices present parameters for restoration monitoring of the structural and functional characteristics of rocky habitats. These matrices are not exhaustive, but represent those elements most commonly used in such restoration monitoring strategies. These parameters have been recommended by experts in rocky habitat restoration as well as in the literature on rocky habitat restoration and ecological monitoring. The closed circle (●) denotes a parameter that should be considered in monitoring restoration performance. Parameters with an open circle (❍) may also be measured depending on specific restoration goals.

Parameters to Monitor the Structural Characteristics of Rocky Habitats

Parameters to Monitor	Biological: Habitat created by rocky substrates	Physical: Sediment grain size	Physical: Topography/Geomorphology	Hydrological: Currents	Hydrological: Tides/Hydroperiod	Hydrological: Water source	Hydrological: Wave energy	Chemical: Nutrient concentration
Geographical								
Acreage of habitat types	●							
Biological								
Plants								
Species, composition, and percent cover of algae	●[7]							
Phytoplankton diversity and abundance	❍[8]							
Hydrological								
Physical								
Shear force at sediment surface				❍			❍	
Temperature						❍[8]		
Water column current flow and velocity				❍				
Wave energy						❍	●	
Chemical								
Salinity (in tidal areas)					●[9]	●[9]		
Toxics						❍		
Soil/Sediment								
Physical								
Basin elevations			❍					
Topography/Geomorphology (slope, basin cross section)			●					
Organic content			❍		❍			❍
Percent sand, silt, and clay			❍[7]					❍[7]
Sedimentation rate and quality		❍	❍	❍	❍			❍
Chemical								
Pore water nitrogen and phosphorus								❍[8]

[7] Key variable for rocky shore, alternative variable for rock bottom.
[8] Rock bottom habitat only.
[9] Key variable for rock bottom, alternative variable for rocky shore.

Parameters to Monitor the Functional Characteristics of Rocky Habitats

Functional Characteristics

Parameters to Monitor	Biological: Provides breeding grounds	Provides feeding grounds	Provides nursery areas	Provides refuge from predation	Provides substrate for attachment	Supports a complex trophic structure	Supports biomass production	Supports biodiversity	Physical: Reduces erosion potential	Reduces wave energy	Chemical: Modifies chemical water quality	Modifies dissolved oxygen	Supports nutrient cycling
Geographical													
Acreage of habitat types	●	●	●	●	●				●	●			
Biological													
Plants													
Species, composition, and % cover of:													
Algae	❍	❍	❍	❍	❍				❍	❍			
Herbaceous vascular	❍[7]	❍[7]	❍[7]	❍[7]	❍[7]				❍[7]	❍[7]			
Epiphytes	❍[8]	❍[8]				❍[8]	❍[8]	❍[8]			❍[8]	❍[8]	❍[8]
Invasives	❍	❍	❍	❍		❍		❍					
Interspersion of habitat types	❍	❍	❍	❍					❍	❍			
Phytoplankton diversity and/or abundance		❍[9]											
Plant health (herbivory damage, disease[9])		❍											
Biological													
Animals													
Species, composition, and % abundance of:													
Birds	●[7]	●[7]	●[7]	●[7]									
Fish	●[9]	●[10]	●[10]	●[10]									
Invasives		❍	❍	❍									
Invertebrates	●	●	●	●									
Hydrological													
Physical													
Fetch									❍[8]	❍[8]			
Current flow and velocity									❍[8]				
Wave energy	●	●	●	●					●				
Chemical													
Toxics	❍	❍	❍										
Soil/Sediment													
Physical													
Geomorphology (slope, basin cross section)	●	●	●	●	●				●				
Sediment grain size (OM[11]/sand/silt/clay/gravel/cobble)					❍				❍	❍			
Sedimentation rate and quality									❍				

[7] Key variable for rocky shore, alternative variable for rock bottom.
[8] Rock bottom habitat only.
[9] Key variable for rock bottom, alternative variable for rocky shore.
[10] Rocky shore habitat only.
[11] Organic matter.

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Witman, J. D. and K. R. Grange. 1998. Links between rain, salinity, and predation in a rocky subtidal community. *Ecology* 79:2429-2447.

APPENDIX I: ROCKY HABITATS ANNOTATED BIBLIOGRAPHY

This annotated bibliography contains summaries of restoration case studies and basic ecological literature. It is designed to provide restoration practitioners with examples of previous restoration projects as well as overviews of papers from the ecological literature that offer more detail than that covered in the associated chapter. Entries are presented from both peer reviewed and grey literature. They were selected through extensive literature and Internet searches as well as input from reviewers. They are not, however, a complete listing of all of the available literature. Entries are arranged alphabetically. Wherever possible, web addresses or other contact information has been included in the reference to assist readers in easily obtaining the original resource. Summaries preceded by the terms '*Author Abstract'* or *'Publisher Introduction*' or similar descriptors were taken directly from their original source. Summaries without such descriptors were written by the author of the associated chapter.

Addessi, L. 1994. Human disturbance and long-term changes on a rocky intertidal community. *Ecological Applications* 4: 786-797.

Author Abstract. The effects of human recreational activities on a rocky intertidal habitat on the coast of San Diego, California, USA were investigated. Organisms susceptible to collection for food, bait, or aquaria were identified and served as key species for the study of biota disturbance. This study examined three major aspects: (1) Distribution and activities of people along the shoreline were documented. (2) Distribution and density of echinoderms and molluscs inhabiting the cryptic underrock surface were sampled along an identified gradient of disturbance. (3) Densities of conspicuous organisms inhabiting the underrock surface at the most disturbed location detected in the spring of 1971 were compared with those detected in the spring of 1991. Surveys of human activity made during weekends with low tides exposing most of the intertidal zone (below 0 MLLW) during the daylight hours between December 1990 and August 1991 showed a definite pattern. People concentrated in an area with a 200 m radius centered on the primary accesses; areas farther from these points were less visited. The study site stood along a gradient of human disturbance, and the sampling of organisms along this indicated a gradient of biota disturbance as well. The density of all species was reduced in the more heavily visited intertidal area. The underrock community at the most heavily visited location changed substantially from spring 1971 to spring 1991. The density of most of macroorganisms decreased between the two dates, with the exception of the density of small gastropods, which increased. Even if more long-term studies are needed for determining the actual status of communities under the influence of human disturbance, the combination of spatial and long-term studies shows the importance of setting better policy and establishing more effective reserves in order to enhance and maintain species diversity and density.

Benson, B. L. 1989. Airlift sampler: Applications for hard substrata. *Bulletin of Marine Science* 44: 752-756.

Author Abstract. Airlift samplers (ALS) have been developed to efficiently and quantitatively sample subtidal benthic and epibenthic organisms. Washington State Department of Fisheries (WDF) biologists have used ALS's to collect quantitative samples of epibenthic organisms from natural and artificial reefs and benthic organisms from gravel substratum in Puget Sound, Washington. The primary advantage of ALS's, for these types of substrates, is their ability to collect the motile microinvertebrates (< 1 cm) missed by visual assessment and settling plate/substrate removal methods. ALS's used by WDF can collect organisms up to 5 cm in diameter. Operated by mobile divers, ALS's can sample with greater spatial precision and reach areas inaccessible to methods operated from surface vessels. Sampling capacity of an ALS is directly related to operating depth, sample mass and amount of compressed air available. Increasing depth or mass increases air consumption and generally reduces sampling capacity. See publication for additional information on the ALS method used to quantify subtidal benthic and epibenthic organisms.

Bokn, T. L, F. E. Moy and S. N. Murray. 1993. Long-term effects of the water-accommodated fraction (WAF) of diesel oil on rocky shore populations maintained in experimental mesocosms. *Botanica Marina* 36:313-319.

Author Abstract. The long-term effects of continuous doses (average hydrocarbon concentration = 129.4 mu g/L and 30.1 mu g/L) of the water-accommodated fraction (WAF) of diesel oil on 15 rocky littoral populations were determined at three tidal levels in experimental mesocosms over two years. At each tidal level, most species exhibited similar abundance changes in both oil-contaminated and control (average background hydrocarbon concentration = 5.6 mu g/L) mesocosms. Significant changes in species abundances attributable to oil (WAF) were demonstrated for only two of ten seaweeds and three of five invertebrates. Compared with the other mesocosms, significantly greater reductions in upper-level cover were recorded in the basin receiving the highest oil dosage for the seaweeds *Phymatolithon lenormandii* and *Fucus evanescens* together with lower recruitment of the barnacle *Semibalanus balanoides*. The mussel *Mytilus edulis* was strongly affected by the oil treatments and essentially disappeared from both oil-contaminated mesocosms. Numbers of the starfish *Asterias rubens* also fell to zero at the lowest tidal level in the basin receiving the highest oil dosage. There were no demonstrable differences in the abundance patterns of the gastropod *Littorina littorea,* the crab *Carcinus maenus*, and a total of eight brown (*Ascophyllum nodosum, Fucus serratus*, *F. vesiculosus*, *Laminaria digitata*), red (*Chondrus crispus*), and green (*Cladophora rupestris, Enteromorpha* spp., *Ulva lactuca*) seaweeds in the oil-contaminated compared with the control mesocosms.

Brosnan, D. M. and L. L Crumrine. 1994. Effects of human trampling on marine rocky shore communities. *Journal of Experimental Marine Biology and Ecology* 177:79-97.

Author Abstract. The effects of human trampling on two marine intertidal communities were experimentally tested in the upper-shore algal-barnacle assemblage and mid-shore mussel bed communities. On two shores, we trampled experimental plots 250 times every month for a year, and then allowed plots to recover for a further year. Results from the upper shore community showed that foliose algae were susceptible to trampling, and suffered significant declines shortly after trampling started. Canopy cover remained high in untrampled control plots. Barnacles were crushed and removed by trampling. Algal turf was resistant to trampling, and increased in relative abundance in trampled plots. In general the algal-barnacle community recovered in the year following trampling. In the mussel bed community, mussels from a single layer bed were removed by trampling. By contrast, mussels at a second site were in two layers, and only the top layer was removed during the trampling phase. However, mussel patches continued to enlarge during the recovery phase, so that by the end of the second year, experimental plots at both sites had lost mussels and bare space remained. Mussel beds did not recover in the 2 years following cessation of trampling. Control plots lost no mussels during the trampling and recovery phase. Barnacle and algal epibionts on mussels were significantly reduced by tramping. Overall, trampling can shift community composition to an alternate state dominated by low profile algae, and fewer mussels.

DeVogelaere, A. P., M. Jacobi, R. Walder and M. Foster. 1999. A Summary of Rocky Shore Monitoring Projects in the Monterey Bay National Marine Sanctuary: Monitoring the Rocky Intertidal Communities Within the Gulf of the Farallones and the Northern Portion of the Monterey Bay National Marine Sanctuaries. Contact information: Jan Roletto, Gulf of the Farallones National Marine Sanctuary, San Francisco, CA 94123, Phone # (415) 561-6622 or Fax # (415) 561-, jrolletto@ocean.nos.noaa.gov: http://montereybay.nos.noaa.gov/research/techreports/rockyshores99/rocky99_site04.html

Researchers have been conducting since 1995 a monitoring project on the rocky intertidal communities near Monterey Bay, south of Half Moon Bay approximately 20 miles. They collected baseline data on species abundance, diversity and distribution for assessment of natural and anthropogenic disturbances to rocky intertidal populations of algae and invertebrates. The site was assessed by establishing 12 quadrats (6 permanent and 6 stratified random quadrats) in the low, middle, and high algal zones. Each quadrat was 30 x 50 cm. A random point contact method (Foster et al. 1991) was used to assess species distribution, richness, and percent cover. Two photographs (f-stop of 5.6 and 8.0) were taken of each quadrat. Three 12 m transects were assessed at each location to determine the density of dominant species. Transects were positioned by a tape measure. Transects coincided with at least three permanent quadrats and a minimum of one transect began at the highest point devoid of vegetation and extended through each zone to the waterline. A 30 x 50 cm quadrat was placed at each meter mark and analyzed for presence/absence in the winter sampling and abundance measurements during the summer sampling. See contact or website for additional information on monitoring rocky shores.

DeVogelaere, A. P., M. Jacobi, R. Walder and M. Foster. 1999. A Summary of Rocky Shore Monitoring Projects in the Monterey Bay National Marine Sanctuary: Successional and Seasonal Variation of the Central and Northern California Rocky Intertidal Communities as Related to Natural and Man-induced Disturbances. Mineral Management Service, Camarillo, CA. Contact information: Mary-Elaine Dunaway, Phone # (805) 389-7520, mary_elaine-dunaway@smtp.mms.gov. http://montereybay.nos.noaa.gov/research/techreports/rockyshores99/rocky99_site12A.html

Researchers are conducting ongoing monitoring studies on rocky intertidal communities in areas influenced by natural and man-induced disturbances in Monterey Bay, CA. The first sample was taken March 13, 1984. Their objective was to supply the Mineral Management Service with a proposed Field Survey Plan for evaluating species composition and abundance of organisms and the effects of disturbance on organisms. Methods used include: Point-contact sampling along four vertical transects with descriptions of substrata and a map of transect locations; transects were arranged to cross over as many groupings as possible within each site in an area appropriate for field survey. See website or contact for additional information on methods used for monitoring rocky intertidal communities.

DeVogelaere, A. P., M. Jacobi, R. Walder and M. Foster. 1999. A Summary of Rocky Shore Monitoring Projects in the Monterey Bay National Marine Sanctuary: A Quantitative Assessment of Human Trampling Effects on a Rocky Intertidal Community. Contact information: Kate Beauchamp, University of California at Davis, Davis, CA. http://montereybay.nos.noaa.gov/research/techreports/rockyshores99/rocky99_site14B.html

Researchers conducted a quantitative assessment of rocky intertidal communities at the Natural Bridges site B, adjacent to Natural Bridges State Park, De Anza Mobile Estates and Long Marine Laboratories. Their objectives were to compare species diversity and density of organisms in an intertidal area with three levels of human usage and identify organisms that appear vulnerable to human trampling. Sampling was performed three consecutive days in December 1977 and three consecutive days in December 1978. Dominance diversity curves for animal numbers and wet weights of algae by season and site were constructed in twenty 10 x 10 cm plots and randomly placed within a 10 m^2 area within each of 3 sites. Each site experienced different levels of human disturbance (trampled, intermediate, untrampled). Plots were scraped of plants and animals and then collected. Shell lengths of mussels were also measured. *Pelvetiopsis limitata* was sampled in 24 random 1/4 m^2 plots with photos. Percent cover of *P. limitata* was determined by projecting slides on paper, tracing the outline of the algal covering and weighing the paper cut outs. Animals and algae were identified using Smith and Carlton (1975) and Abbott and Hollenberg (1976) respectively. See website or contact for additional information on quantifying the effects of trampling on rocky intertidal communities.

DeVogelaere, A. P., M. Jacobi, R. Walder and M. Foster. 1999. A Summary of Rocky Shore Monitoring Projects in the Monterey Bay National Marine Sanctuary: Biodiversity of the Rocky Intertidal in the Monterey Bay National Marine Sanctuary: A 24-year Comparison. Institute of Marine Sciences, University of California, Santa Cruz, CA. Contact information: John Pearse, Phone # (831) 426-0542, pearse@biology.ucsc.edu. http://montereybay.nos.noaa.gov/research/techreports/rockyshores99/rocky99_site14B.html

Pearse conducted quarterly sampling from fall 1971 to spring 1973 and from spring 1996 to spring 1997 throughout intertidal zones (site 15, Almar street, Monterey Bay Marine Sanctuary, CA) in order to evaluate biodiversity of the organisms there. The objective was to organize data collected in 1971 to 1973 on species found at selected rocky intertidal sites along the central California coastline and compare data with the data collected at the same sites during 1996 to1997. Data collected include: changes in species diversity, composition, and abundance. Students from the University of California at Santa Cruz resurveyed species richness in 1996 to 1997 at the same areas sampled in a 1971 to 1973 study. Relative abundance data on major plant and animal macroscopic taxa were taken. Relatively abundant, easily identified plants and animals abundance were estimated by counting absolute numbers or the number of 10 x 10 cm squares within a 50 x 50 cm quadrat that include the species. See website or contact for additional information on methods for evaluating biodiversity along rocky intertidal zones.

Fletcher, H. and C. L. J. Frid. 1996. Impact and management of visitor pressure on rocky intertidal algal communities. ECSA Meeting Special Issue. *Aquatic Conservation: Marine and Freshwater Ecosystems* 6: 287-297.

Author Abstract. Human trampling was investigated in order to quantify the 'recreational carrying capacity' of two rocky intertidal areas in northeast England. Estimation of 'recreational carrying capacity' was made by subjecting experimental plots in pristine areas of shore to different intensities of sustained trampling. The algal community was subsequently monitored for 16 months. Changes in algal community composition occurred at both sites at all intensities. Compositional changes were rapid (1-2 months) and timing was dependent on both trampling intensity and site. Trampling resulted in consistently reduced abundances of some species, for example fucoids, *Phymatolithon lenormandii* and turf species. Open space was present in greater quantities in trampled than untrampled plots. In the summer months, this was subsequently colonized primarily by *Enteromorpha* spp. Recreational carrying capacity is being exceeded in some areas at both sites in the summer months. Possible management strategies are discussed in the light of these experimental results.

Gilfillan, E. S., T. H. Suchanek, P. D. Boehm, E. J. Harner, D. S. Page and N. A. Sloan. 1995. Shoreline impacts in the Gulf of Alaska region following the *Exxon Valdez* oil spill. *Exxon Valdez* Oil Spill: Fate and Effects in Alaskan Waters, ASTM, Philadelphia, USA, pp. 444-481.

Author Abstract. Researchers sampled forty-eight sites in the Gulf of Alaska region (GOA-Kodiak Island, Kenai Peninsula, and Alaska Peninsula) in July/August 1989 to assess the impact of the March 24, 1989, *Exxon Valdez* oil spill on shoreline chemistry and biological communities extending hundreds of miles from the spill origin. Five of the Kenai sites and 13 of the Kodiak and Alaska Peninsula sites were sampled 16 months after the spill. Oiling levels at each site were estimated visually and/or quantified by chemical analysis. The chemical analyses were performed on sediment and/or rock wipe samples collected with the biological samples. Additional sediment samples were collected for laboratory amphipod toxicity tests. Mussels were collected and analyzed for hydrocarbon content to assess hydrocarbon bioavailability. Biological investigations at these GOA sites focused on intertidal infauna, epifauna, and macroalgae by means of a variety of common ecological techniques. For rocky sites the percentage of hard substratum covered by biota was quantified. At each site, up to 5 biological samples (scrapes of rock surfaces or sediment cores) were collected intertidally along each of 3 transects, spanning tide levels from the high intertidal to mean-lowest-low-water (zero tidal datum). Organisms (down to 1.0 mm in size) from these samples were sorted and identified. Community parameters including organism abundance, species richness, and Shannon diversity were calculated for each sample. As expected for shores so far from the spill origin, oiling levels were substantially lower, and beached oil was more highly weathered than in Prince William Sound (PWS). Samples of oiled GOA shoreline sediment were not statistically more toxic in bioassay tests than sediment from unoiled reference sites. As a consequence of the lower oil impact, the biological communities were not as affected as those in the sound. Biological impacts, although present in 1989 in the GOA, were localized, which is consistent with the patchy and discontinuous nature of much of the oiling in GOA. Some organisms were locally reduced or eliminated in oiled patches but survived in unoiled patches nearby. In areas where oiling occurred, impacts were generally limited to middle and upper intertidal zones. Analyses of mussel samples indicate that by 1990 little of the shoreline oil remained bioavailable to epifauna. Quantifiable measures of the overall health and vitality of shoreline biological communities, such as organism abundance, species richness, and Shannon diversity for sediment infauna, show few significant differences between oiled and reference sites in 1990.

Hawkins, S. J. and R. G. Hartnoll. 1983. Changes in a rocky shore community: An evaluation of monitoring. *Marine Environmental Research* 9:131-181.

Author Abstract. The basic aim of this study was to record the changes in the communities on a moderately exposed rocky shore by a program of repeated nondestructive sampling ('monitoring') and to determine the causes of these changes. Possible causative factors were investigated by the combined approach of analysing detailed sea-temperature and meteorological data for the period of the study and establishing manipulative field experiments. Fixed quadrats (2 m by 1 m) at three levels were visited at 6-8 weekly intervals for 30 months and the abundance and spatial pattern of major species assessed. Only certain of the changes could be atributed to the physical environmental-most were biologically controlled. For example, manipulative experiments showed that the blooms for ephemeral algae and the decline of *Patella* in the high-shore quadrat, and the decline of *Actinia* in the mid-shore quadrat, were due to decreases in the fucoid canopy. The conclusion must be that the monitoring of rocky shores as a means of detecting and measuring pollution is likely to be an unproductive investment of time and resources.

Lopes, C. F., J. C. C. Milanelli, V. A. Prosperi, E. Zanardi and A. C. Truzzi. 1997. Coastal monitoring program of Sao Sebastiao Channel: Assessing the effects of 'Tebar V' oil spill on rocky shore populations. *Marine Pollution Bulletin* 34:923-927.

Author abstract. Due to a pipeline rupture on May 15th 1994, 2700 m^3 of a crude oil reached the sea, affecting rocky shore communities, which have been monitored since 1993. These biological data, analyzed by BACI approach, were integrated to chemical and toxicological analysis of the oil. BACI approach can also be used to analyze data during and after restoration efforts have been completed. This will provide information on the status (survival and growth) of fauna and flora communities on the rocky shore. Results of Student's t-test did not indicate a significant difference between the percent cover average of the monitored populations (mussels and barnacles) from samples taken before and after the oil spill. The acute and chronic toxicity tests showed high toxicity of the oil. The lack of stress (i.e., mortality) on the populations can be mainly associated to: the sampling area was not highly contaminated despite the great amount of oil which reached surrounding areas; there were not enough physical (smothering) or chemical (toxicity) effects of the oil to alter the density of the populations which are considered moderately resistant to oil.

Miller, A. W. and R. F. Ambrose. 2000. Sampling patchy distributions: Comparison of sampling designs in rocky intertidal habitats. *Marine Ecological Progress Series* 196:1-14.

Author Abstract. Any attempt to assess species abundances must employ a sampling design that balances collection of accurate information for many species with a reasonable sampling effort. To assess the accuracy of commonly used within-site sampling designs for sessile species, we gathered cover data at 2 rocky intertidal locations in Southern California using a high-density point-contact method that maintained the spatial relationships among all points. Different sampling approaches were compared using simulated sampling. Different sampling units (single points, line transects, and quadrats) were modeled at high and low sampling efforts. Sampling units were either distributed randomly or with stratified random methods. Sampling accuracy was assessed by comparing cover and species richness estimated by the sampling simulations to the actual field data. Randomly placed single point-contacts provided the best estimates of cover but are usually not logistically feasible in the rocky intertidal, so ecologists typically use quadrats or line transects. With quadrats, some form of stratified random sampling usually gave estimates that were closer to known values than simple random placement. In nearly all stratified cases, optimum allocation of sample units, where quadrats are allocated among strata according to the amount of variability within each stratum, yielded the most accurate estimates. With 1 exception, line transects placed perpendicular to the elevational contours (vertical transects) approached or exceeded the accuracy of the best stratified quadrat efforts. The estimates for rare species were consistently poor since sampling units often missed such species altogether, suggesting a systematic bias. Species richness was substantially underestimated by all sampling approaches tested, whereas these same approaches accurately estimated diversity (H'). These results illustrate the difficulty of obtaining accurate cover estimates in rocky intertidal communities.

Minerals Management Service Program. 2001. Shoreline Rocky Intertidal Monitoring. United States Department of the Interior, Coastal Marine Institute of University of California, Santa Barbara, University of California, Santa Cruz and University of California, Los Angeles. Contact information: Mary.Elaine.Dunway@mms.gov, http://www.mms.gov/eppd/sciences/esp/profiles/pc/PC-00-02-03-04-05.htm

Researchers conducted studies monitoring the health of rocky intertidal habitats along the mainland of Southern California adjacent to oil and gas activity. Data was collected as field notes, slides and videotaped, and were analyzed and placed in a database.

Photos, counts, and measurements of selected species (e.g., black abalone, owl limpets, and seastars) were collected at four sites in San Luis Obispo County, four sites in Orange County, two sites in Ventura County and nine sites in Santa Barbara County. Minerals Management Service (MMS) biologists assisted with collecting data in Santa Barbara and Ventura Counties. Slides are scored and maintained at the respective University campuses. The role of the university scientists and trained technicians is to maintain field equipment, write annual and three-year reports and participate in MARINE committees.

Data collected by several MMS funded efforts and the MMS Intertidal Team allowed MMS to understand the interaction between oil and rocky intertidal resources and provided linkages between academic institutions. See contact for additional information on the project conducted.

Pagola-Carte, S. and J. I. Saiz-Salinas. 2001. Changes in the sublittoral faunal biomass induced by the discharge of a polluted river along the adjacent rocky coast (N. Spain). *Marine Ecology Progress Series* 212:13-27.

Author abstract. Sublittoral hard bottom assemblages such as rock bottoms in the 'Abra de Bilbao' Bay (N. Spain) were described in terms of biomass in order to record spatial changes on scales of a few km that reflect the prevalence of perturbation gradients. This method is useful for not only monitoring rock bottom communities after anthropogenic impacts but also for restoration monitoring of rock bottom communities to evaluate the gradual increase or decrease in functionality of the habitat. Several criteria and levels of data aggregation were proposed and tested in an attempt to obtain information on the degree of redundancy achieved by such communities for further monitoring programs. The area of study is at present recovering from a highly stressed situation of turbidity and sedimentation. In this way, the fauna/flora biomass ratio (AN) proved to be a useful descriptor indicative of several environmental conditions from healthy to grossly perturbed on rocky communities. See publication for additional information on methods used for evaluating faunal biomass in hard bottom communities. In addition, the high degree of redundancy shown by the macrozoobenthos allows efforts to be concentrated on only the faunal component, using different approaches and data aggregation levels. As a result, the cost-effectiveness of monitoring programs could increase considerably. Moreover, the use of several techniques (univariate, multivariate) and approaches (taxonomic, trophic, mixed) is recommended for the monitoring of hard bottom communities, in order to test the robustness of the results obtained and achieve other complementary perspectives upon the biota with the same data sets. In this case study, relevant information was acquired on the possible temporal changes of intermediate zones of the 'Abra de Bilbao' due to the biological recovery of the area. Therefore, an adequate combination of biomass values and the concepts of redundancy-sufficiency is suggested as a realistic way of developing future monitoring programs for rock bottoms along with other hard bottoms in various areas.

Renones, O., J. Moranta, J. Coll and B. Morales-Nin. 1997. Rocky bottom fish communities of Cabrera Archipelago National Park (Mallorca, Western Mediterranean). *Scientia Marina* (Barcelona) 61: 495-506.

Author Abstract. In the present study, the fish communities of the rocky bottoms of Cabrera Archipelago (Balearic Islands) are analyzed and provide data for future evaluation and monitoring of any changes produced by management or during restoration projects. Visual counts were carried out by diving along transects situated in areas of rocky blocks at depths of -10 m, -25 m and -41 m and at vertical cliffs -15 m deep. In the 10 stations studied, 48 species belonging to 19 families have been recorded. The increase in depth principally produced a specific impoverishment and a decrease in the density of mesophagous and macrophagous carnivore species. This tendency became more noticeable changing from the infralittoral to the circalittoral stage. In the infralittoral stage the substrate rugosity was a more important factor than depth in the structure of the fish community. However, other specific characteristics of each zone such as algal cover, hydrodynamic conditions and fishing pressure, as well as habitat changes with size of some species, also affected the specific composition and demographic structure of the fish community.

Roletto, J., N. Cosentino, D. A. Osorio and E. Ueber. 2000. Rocky intertidal communities at the Farallon Islands, pp. 359-362. In Browne, D. R., K. L. Mitchell and H. W. Chaney (eds.), Proceedings of the Fifth California Islands Symposium. U. S. Department of the Interior, Minerals Management Service, Pacific OCS Region 770 Paseo Camarillo, Camarillo, CA.

Author Abstract. The rocky intertidal communities of the Farallon Islands, within the Gulf of the Farallones National Marine Sanctuary, have been monitored since 1993. Methods used included point-frames, haphazard shore search, and photographic recording. A total of 221 taxa have been documented. Eight species are considered to be rare in this region or outside the limit of their normal range: *Branchioglossum undulatum, Myriogramme variegata*, *Cirrulicarpus* sp., *Hommersandia palmatifolia, Lithophyllum proboscideum, Mazzaella cornucopiae, Peyssonnelia pacifica*, and *Ulva conglobata.* Three algal species commonly found on the California mainland, *Fucus gardneri, Pelvetia fastigiata,* and *Pelvetiopsis limitata*, were not observed on any of the Farallon Islands. The mean annual percent cover for algae and sessile macroinvertebrates at the South Farallon Islands ranged from 122 to 255%. *Corallina, Mazzaella, Ulva, Mastocarpus, Mytilus,* and *Anthopleura* were the dominant taxa found on the islands. Algal species known to be negatively impacted by oil spills are common and abundant on the Farallon Islands. These sites can be used as either controls or to monitor the effects of recovery of the intertidal zones after an oil or diesel spill.

Schoch, G. C. and M. N. Dethier. 1996. Scaling up: The statistical linkage between organismal abundance and geomorphology on rocky intertidal shorelines. *Journal of Experimental Marine Biology and Ecology* 201:37-72.

Author Abstract. The objective of this study was to test for a statistical relationship between species abundance and a suite of physical factors so that inferences can be made about species distributions over large spatial scales if geomorphology is known. This has application to oil spill damage assessments, inventory and monitoring programs, global change and biodiversity studies where economical or logistical constraints dictate a reliance on data collected from relatively localized areas but there is a need to extrapolate to broad spatial scales. Complex shorelines can be partitioned into relatively distinct segments with generally homogenous abiotic characteristics. These segments can be characterized using common geomorphological parameters, thus differentiating horizontal (among-segment) and vertical (within-segment) characteristics. Shoreline segments with similar characteristics can then be statistically clustered into groups of like habitats. This technique was applied to 5 km of rocky shoreline on San Juan Island, Washington and then analyzed the relationship between 3 clusters of geomorphologically homogenous shoreline segments and local floral and faunal abundances. Using standard transect techniques at 3 elevations, we compared the variance in abundance of organisms (i) among 3 transects within one homogenous shoreline segment selected from a moderate-angle bedrock segment cluster; (ii) among 3 shoreline segments from the same moderate-angle bedrock cluster; and (iii) among 3 separate clusters representing low-angle, moderate-angle and high-angle bedrock segments. Researchers hypothesized that variance in organismal abundance would be low among transects and among similar segments but high among segments from different clusters. See publication for additional information on techniques used for determining organism abundance on rocky intertidal shorelines.

Sousa,W. P. 1979a. Disturbance in marine intertidal boulder fields: The non-equilibrium maintenance of species diversity. *Ecology* 60: 476-497.

Author Abstract. Small boulders, with a shorter disturbance interval, support only sparse early successional communities of the green alga, *Ulva* and barnacles. Large, infrequently disturbed boulders are dominated by the late successional red alga, *Gigartina canaliculata*. Intermediate-sized boulders support the most diverse communities composed of *Ulva*, barnacles, several middle successional species of red algae, and *G. canaliculata*. Comparison of the pattern of succession on experimentally stabilized boulders with that on unstable ones confirms that differences in the frequency of disturbance are responsible for the above patterns of species composition. The frequency of disturbance also determines the degree of between-boulder variation in species composition and diversity. Small boulders sample the available pool of spores and larvae more often. As a result, a greater number of different species occur as single dominants on these boulders. Boulders with an intermediate probability of being disturbed are most variable in species diversity. Observations on the local densities of 3 species of middle successional red algae over 2 yr-long periods indicate that most of these are variable in time. More local populations went extinct or became newly established on boulders than remained constant in size. These species persist globally in the boulder field mosaic by colonizing recent openings created by disturbances. These results lend support to a nonequilibrium view of community structure and, along with other studies suggest that disturbances which open space are necessary for the maintenance of diversity in most communities of sessile organisms. See publication for additional information on techniques used for evaluating marine intertidal boulder field disturbances.

Sousa, W. P. 1979b. Experimental investigations of disturbance and ecological succession in a rocky intertidal algal community. *Ecological Monograph* 49: 227-254.

Author Abstract. Mechanisms of ecological succession were investigated by field experiments in a rocky intertidal algal community in southern California. The study site was an algal-dominated boulder field in the low intertidal zone. The major form of natural disturbance which clears space in this system is the overturning of boulders by wave action. Algal populations recolonize cleared surfaces either through vegetative regrowth of surviving individuals or by recruitment from spores. Boulders which are experimentally cleared and concrete blocks are colonized within the first month by a mat of the green alga, *Ulva*. In the fall and winter of the first year after clearing, several species of perennial red algae including *Gelidium coulteri, Gigartina leptorhynchos, Rhodoglossum affine*, and *Gigartina canaliculata* colonize the surface. If there is no intervening disturbance, *Gigartina canaliculata* gradually dominates the community holding 60-90% of the cover after a period of 2 to 3 years. If undisturbed, this monoculture persists through vegetative reproduction, resisting invasion by all other species. During succession diversity increases initially as species colonize a bare surface but declines later as one species monopolizes the space. Several contemporary theories concerning the mechanisms of ecological succession were tested. The early successional alga, *Ulva*, was found to inhibit the recruitment of perennial red algae. Selective grazing on *Ulva* by the crab, *Pachygrapsus crassipes*, accelerates succession to a community of long-lived red algae. Grazing by small molluscs, especially limpets, has no long-term effect on the successional sequence. See publication for additional information on techniques used for evaluating rocky intertidal disturbances.

Stekoll, M. S. and L. Deysher. 1996. Recolonization and restoration of upper intertidal *Fucus gardneri* (Fucales, Phaeophyta) following the *Exxon Valdez* oil spill. *Hydrobiologia* 326-327: 311-316.

Author Abstract. The *Exxon Valdez* oil spill in March 1989 and subsequent cleanup caused injury to intertidal *Fucus gardneri* populations especially in the upper intertidal. A survey in 1994 in Prince William Sound, Alaska showed that the upper boundary of *Fucus* populations at oiled sites was still an average of 0.4 m lower than the upper boundary at unoiled sites. Restoration of severely damaged *Fucus* populations was started on a small-scale at a heavily oiled rocky site in Herring Bay, Prince William Sound. Experiments employed mats of biodegradable erosion control fabric to act as a substratum for *Fucus* germlings and to protect germlings from heat and desiccation stress. A series of plots was covered with mats made from a resilient coconut-fiber fabric in June 1993. Half of the mats were inoculated with *Fucus* zygotes. A series of uncovered control plots was also monitored. There was no enhancement of *Fucus* recruitment on the rock surfaces under the mats. Dense populations of *Fucus* developed on the surface of all of the mats by the summer of 1994. The natural rock surfaces in the control plots, both inoculated and not, were barren of macroscopic algal cover. By September 1994, the juvenile thalli on the mats were approximately 2 cm in length. Inoculating the mats had an effect only in the upper region of the intertidal. It is expected that the thalli will become fertile during the 1995 season. These thalli may serve as a source of embryos to enhance the recovery of new *Fucus* populations in this high intertidal area.

Teruhisa, K., N. Masahiro, K. Hiroshi, Y. Tomoko, M. L. Research and O. Kouichi. 2003. Impacts of the Nakhodka heavy-oil spill on an intertidal ecosystem: An approach to impact evaluation using geographical information. *Marine Pollution Bulletin* 47: 99-104.

Author Abstract. A major heavy-oil spill from the Russian tanker Nakhodka occurred in the Sea of Japan on 2 January 1997. Researchers investigated the impacts of this spill on a rocky intertidal ecosystem along the southern coast of the Sea of Japan. They selected Imago-Ura Cove as our study site to observe temporal changes along the oiled shore, because minimal cleaning effort was made in this area. Field surveys were conducted every autumn and spring from 1997 to 2000. Researchers measured coverage by macroalgae in 1x1-m^2 quadrats and counted the animals in 5x5-m^2 quadrats along the intertidal zone. Changes in the ecosystem caused by the oil spill were analyzed by applying a geographical information system (GIS) to the Sea of Japan for the first time. The GIS showed that following the accident there were heavily oiled areas in sheltered regions, but these decreased over the three years. It also showed that coverage by macroalgae and the number of animals increased, although some species of algae with microscopic sporophyte generations, and some populations of perennial shellfish, remained stable or decreased during the study period. GIS was able to trace temporal changes in intertidal communities resulting from the impacts of heavy oil on flora and fauna at a spatial scale of 10-100 m. GIS is thus a practical tool for visualizing, analyzing, and monitoring changes in an ecosystem polluted by oil, taking into account topographic differences along the coastline. The methods used here not only allows the impact to be evaluated but will also allow restoration efforts that are performed to be monitored and evaluated on rocky shores.

Zhuang, S., K. Wang and L. Chen. 2001. Study on invertebrate communities in rocky intertidal zones influenced by human activities. *Journal of Oceanography of Huanghai and Bohai Seas/Huangbohai Haiyang Qingdao* 19: 54-64.

Author Abstract. Researchers found that *Chthamallus challengeri* was the most dominant species in rocky intertidal communities, and the dominance and function of chief dominant species (*Ostrea denselamellosa, Littorina brevicula, Vignadula atrata, Mytilus edulis*) and common species (*Patelloidae spp., Acanthochiton rubrolineatus, Nereis spp., Anthopleura spp*.) show marked differences, though the faunal composition in the community at 6 stations seemed similar. Three kinds of K-dominance curve based on Riv, RB and RD were used in the study. It was noticed that RB- and RIV-K-dominance curves were more useful to interpret the variation in species diversity and community structure, which was imposed by disturbance and pollution, and the result showed that all communities at 6 investigated stations were disturbed and polluted by human activities though those at Zhifu Islet and Yangma Islet were less disturbed. It was also suggested that the community diversity index ($H_{B'}$ sub(B'), $H_{IV'}$, J) based on RB and RIV were suitable for illustrating the community structure and population distribution, and the 6 stations arranged in order of magnitude of H' value to be Zhifu Islet, Yangma Islet, Shigoutun, Yantai Hill, Yudai Hill and Moon Bay. The variations in community composition and structure in the investigated intertidal zones resulted mainly from human activities such as collection, tourism, water eutrophication and urban sewage discharge. For additional information on methods used for monitoring invertebrates on disturbed rocky shorelines see publication.

APPENDIX II: ROCKY HABITATS
REVIEW OF TECHNICAL METHODS MANUALS

This Review of Technical Methods Manuals includes a variety of sampling manuals, Quality Assurance/Quality Control (QA/QC) documents, standardized protocols, or other technical resources that may provide practitioners with the level of detail needed when developing a monitoring plan for a coastal restoration project. Examples from both peer reviewed and grey literature are presented. Entries were selected through extensive literature and Internet searches as well as input from reviewers. As with the Annotated Bibliographies, these entries are not, however, a complete list. Entries are arranged alphabetically by author. Wherever possible, web addresses or other contact information is included in the reference to assist readers in easily obtaining the original resource. Summaries preceded by the terms '*Author Abstract'* or *'Publisher Introduction*' or similar descriptors were taken directly from their original source. Summaries without such descriptors were written by the authors of the associated chapters.

Babcock, M. M., G. V. Irvine, P. M. Harris, J. A. Cusick and S. D. Rice. 1996. Persistence of oiling in mussel beds three and four years after the Exxon Valdez oil spill, pp. 286-297. In Rice, S. D., R. B. Spies, D. A. Wolfe, B. A. Wright (eds.), Proceedings of the Exxon Valdez Oil Spill Symposium. American Fisheries Society Symposium 18.

Author Abstract. Dense beds of the mussel *Mytilus trossulus* affected by Exxon Valdez crude oil in Prince William Sound and along the Kenai and Alaska peninsulas were intentionally left untreated during shoreline cleanup activities in 1989-1991. In 1992 and 1993, mussels and sediments from 70 mussel beds in Prince William Sound and 18 beds along the Kenai and Alaska peninsulas were sampled to establish the geographic extent and intensity of Exxon Valdez oil persisting in mussel beds. Sediments collected in 1992 and 1993 from 31 of the oiled mussel beds in the sound had total petroleum hydrocarbon (TPH) concentrations greater than 10,000 mu g/g wet weight. The highest concentrations were in sediments collected from Foul Bay (62,258 plus or minus 1,272 mu g TPH/g, mean plus or minus SE). Five of the 18 beds sampled along the Kenai Peninsula showed sediment TPH concentrations greater than 5,000 mu g/g. The mean concentration of total polynuclear aromatic hydrocarbons (TPAH) in mussels from these same beds ranged up to 8.30 plus or minus 0.26 mu g/g (Squirrel Island) in Prince William Sound and 4.01 plus or minus 1.54 mu g/g along the Kenai Peninsula (Morning Cove, Pye Islands). Polynuclear aromatic hydrocarbon fingerprints of mussel tissue collected from surveyed sites indicated the contaminant source was Exxon Valdez oil. In 1993, mean TPH concentrations in sediments and mean TPAH concentrations in mussels were lower by more than 50% compared with these concentrations in 1992. Some beds showed little reduction in oil. Almost all the beds showing only small decreases in hydrocarbons were in protected, low-energy areas, where there probably was little remobilization of residual oil underlying the beds. This study has produced analytical evidence showing that substantial residual Exxon Valdez oil persists in sediments underlying mussel beds in the area affected by the spill. Residual crude oil is a source of chronic contamination of mussels and their predators. In the more-protected intertidal areas, natural flushing and remobilization of Exxon Valdez oil will be slow; some of these mussel beds potentially can be manually cleaned.

Davies, J., J. Baxter, M. Bradley, D. Connor, J. Khan, E. Murray, W. Sanderson, C. Turnbull

and M. Vincent. 2001. Marine Monitoring Handbook. UK Marine Science Project, and Scottish Association of Marine Science. Joint Nature conservation Committee, English Nature, Scottish Natural Heritage, Environment and Heritage Services, http://www.jncc.gov.uk/marine/mmh/Introduction.pdf.

The UK Marine Science Project developed this handbook to provide guidelines for recording, monitoring, and reporting characteristics and conditions of marine habitats. However, based on location and other environmental conditions methodologies will have to be modified to suit the structural characteristics of the habitat. This manual addresses the fundamentals and procedures for monitoring different parameters in marine habitats, management tools, and benefits and costs for developing a monitoring project. Topics presented in this document include establishing marine monitoring programs highlighting what needs to be measured and methods to use; provides guidance when developing a monitoring program; selecting proper monitoring techniques to attain precision and accuracy; and procedural guidelines for monitoring a specific marine habitat. Detailed information on the tools needed for monitoring marine habitats are described within the marine monitoring handbook.

Davis, G. E., K. R. Faulkner and W. L. Halvorson. 1994. Ecological Monitoring in Channel Islands National Park, California, pp. 465-482. In Halvorson, W. L. and G. J. Maender (eds.), The 4th California Islands Symposium: Update on the Status of Resources.

Author abstract. Natural resource managers need to understand the natural functioning of and threats to ecosystems under their management. They need a long-term monitoring program to gather information on ecosystem health, establish empirical limits of variation, diagnose abnormal conditions, and identify potential agents of change. The approach used to design such a program at Channel Islands National Park, California, may be applied to other ecosystems worldwide. The design of the monitoring program began with a conceptual model of the park ecosystem. Indicator species from each ecosystem component were selected using a Delphi approach. Scientists identified parameters of population dynamics to measure, such as abundance, distribution, age structure, reproductive effort, and growth rate. Short-term design studies were conducted to develop monitoring protocols for pinnipeds, seabirds, rocky intertidal communities, kelp forest communities, terrestrial vertebrates, land birds, terrestrial vegetation, fishery harvest, visitors, weather, sand beach and coastal lagoon, and terrestrial invertebrates (indicated in priority order set by park staff). Monitoring information provides park and natural resource managers with useful products for planning, program evaluation, and critical issue identification. It also provides the scientific community with an ecosystem-wide framework of population information.

DeVogelaere, A. P., M. Jacobi, R. Walder and M. Foster. 1999. A Summary of Rocky Shore Monitoring Projects in the Monterey Bay National Marine Sanctuary: Recovery of Rocky Intertidal Assemblages Following the Wreck and Salvage of the F/V Trinity. Monterey Bay National Marine Sanctuary, Monterey, CA. Contact information: Andrew DeVogelaere, Phone # (831) 647-4213, andrew.p.devogelaere@noaa.gov. http://montereybay.nos.noaa.gov/research/techreports/rockyshores99/rocky99_site19.html

Researchers Foster, Walder and DeVogelaere performed recovery efforts of rocky intertidal assemblages. Recovery efforts were done 100 m south of Point Pinos on Trinity wreck site. The recovery of the F/V Trinity, a 51-foot steel hull seiner, on April 20, 1996 resulted in 251 m^2 of physical and 287 m^2 of chemical influence to the rocky intertidal habitat. Researchers investigated biological damage and recovery. They also tested a potential restoration technique to enhance recovery. Evaluations were made on low intertidal surf grass, mid intertidal mussel and mid/high intertidal red algae assemblages. Recovery rates within surf grass, mussel, and red algal assemblages were determined by sampling species composition and percent cover of sessile organisms in 0.25 x 0.25 m plots within areas where new rock surfaces were exposed. Sampling was performed in June, August, and December of 1996, June and December of 1997 and June 1998. Plots were established on recently disturbed horizontal rock surfaces in the surf grass, mussel and red algal assemblages. Each disturbed plot was matched with a control plot (wreck control) that was placed in the undamaged habitat adjacent to disturbed plots and another (spill control) was placed outside the potential chemical spill area for comparisons to be made. Point quadrat technique described by Foster et al. (1991) was used to determine percent cover. Plots were photographed in June 1996 and every June following to show temporal change. Recovery of rubble beds, newly exposed vertical rock surfaces and sand plots were qualitatively assessed. Additional information on methods used can be retrieved from this reference.

DeVogelaere, A. P., M. Jacobi, R. Walder and M. Foster. 1999. A Summary of Rocky Shore Monitoring Projects in the Monterey Bay National Marine Sanctuary: Rocky Intertidal Monitoring Protocols. Monterey Bay Fitzgerald Marine Reserve, Moss Beach, CA.. Contact Information: Bob Breen, Phone # (415) 728-3584. http://montereybay.nos.noaa.gov/research/techreports/rockyshores99/rocky99_site01B.html

Researchers are conducting ongoing research on rocky intertidal shoreline which began 1995 on the Fitzgerald reserve - B, near Monterey Bay in California. Their objectives are to monitor changes in the intertidal communities due to human impacts such as trampling. Seven monitoring sites were selected of 100 square meters each. Barriers were placed around three of the experimental sites at every low tide and restricted from public access. The remaining four are used as control sites and are not restricted from access. Two of the control sites are mussel beds. Sites are surveyed monthly for species abundance using PVC quadrats and photoquadrats are to be taken periodically of the sampling area. See contact for additional information on techniques used for monitoring rocky shores. Data that has already been collected since 1995 can be obtained by getting in touch with the contact person mentioned above.

Harris, R. R., S. D. Kocher, J. Gerstein, F. Kearns, D. Lindquist, D. Lewis, J. Leblanc, W. Weaver and N. M. Kelly. 2002. Monitoring Fish Habitat Restoration Project. California Coastal and Salmonid Restoration Monitoring and Evaluation Program. University of California, Berkley, Center for Forest and Center for the Assessment and Monitoring of Forestry Environmental Resources. Draft Final Report to the Department of Fish and Game. http://www.dfg.ca.gov/nafwb/pubs/2003/200303_Interim_Protocol_Manual.pdf

This document provides monitoring protocols for fish habitat restoration projects such as rock bottoms. Projects conducted were designed to: improve fish movement through streams or prevent fish from entering man-made facilities, develop better conditions for one or more fish life stages, prevent erosion and sediment transportation through streams, control planting of vegetation (e.g., removal of exotic plants), and improve management practices. The types of monitoring performed included: implementation monitoring to evaluate whether or not a specific action has occurred as planned; effectiveness monitoring to evaluate whether or not the implemented action has yield preferred effects; validation monitoring in which a model is used to predict performance or events is evaluated; and trend monitoring in which ecological and environmental changes over time are evaluated. Monitoring protocols include: photography timing, field sampling, and permanent markers for photo points. Timing refers to sequential photographs being taken over time to show changes in site conditions. Photo field sampling is performed when a site consists of many features (e.g., road improvements, crossing streams, rolling dips, or riparian plantings). These photos provide a good representation of the site. Permanent markers are used to easily relocate photo points for subsequent photographs. Additional information on methods used can be obtained from this report.

Minerals Management Service Program. 2001. Shoreline Rocky Intertidal Monitoring. United States Department of the Interior, Coastal Marine Institute of University of California, Santa Barbara, University of California, Santa Cruz and University of California, Los Angeles, CA. Contact information: Mary.Elaine.Dunway@mms.gov. http://www.mms.gov/eppd/sciences/esp/profiles/pc/PC-00-02-03-04-05.htm

Researchers conducted studies monitoring rocky intertidal sites along the mainland of Southern California adjacent to oil and gas activity. The objective was to monitor the health of rocky intertidal habitats adjacent to OCS oil and gas activities in the Pacific Region and to understand the connection between changes that occurred and their potential causes. This study included about a third of the total number of monitored sites supported by 14 federal state, local agencies and private organizations. Data were collected in the form of field notes, slides, and videotape and analyzed and placed in a database. Photos, counts and measurements of selected species (e.g., black abalone, owl limpets, and seastars) were collected at four sites in San Luis Obispo County, four sites in Orange County, two sites in Ventura County and nine sites in Santa Barbara County. Slides were scored and maintained at the University campuses. Data collected was used by the trustees to evaluate impacts from the oil spill on rocky intertidal areas. Additional information on methods used and results of this study are described in this report.

Murray, S. N., R. F. Ambrose and M. N. Dethier. 2002. Plots or Quadrats. In Methods For Performing Monitoring, Impact and Ecological Studies on Rocky Shores, pp. 97-100. United States Department of the Interior, Minerals Management Service, Pacific OCS Region.

Chapter 5 in this document discusses the use of transects, plots and quadrats to estimate cover, density, or biomass of attached and mobile organisms on rocky shores. Quadrats and plots are positioned randomly in an area, or targeted for specific conditions. They can be permanently fixed at a specific locaton so that the same location is sampled repeatedly over time or placed in a different location during sampling. Band transects are used for sampling large and uncommon species of an area that are distributed over large region. These transects function regardless of other sampling units or in conjunction with transects that are positioned for line-intercept or point contact sampling. Plots are used to estimate densities of relatively uncommon species in an area when a sampling region expands over approximately several meters, and for sampling species in certain microhabitats (e.g., deep cracks and crevices). The author concludes that to determine species abundance, line transects and plots or quadrats provides accurate estimates using appropriate sampling strategies. Further information on the methods used for sampling rocky shore organisms can be seen in this document.

Murray, S. N., R. F. Ambrose and M. N. Dethier. 2002. Boulderfields. In Methods For Performing Monitoring, Impact and Ecological Studies on Rocky Shores, pp. 108-111. United States Department of the Interior, Minerals Management Service, Pacific OCS Region.

Authors describe quantitative sampling methods used in rocky intertidal areas. Researchers Pless and Ambrose (unpublished observations) sampled boulderfields in order to compare their communities with that of solid rock benches. The horizontal edges of a leveled sampling quadrat were vertically launched onto the substratum and contours marked with a lumber crayon or chalk. The extent of available substratum was assessed; the total area of rock substrata within the lumber chalk marks was estimated using small wire quadrats of different dimensions (2x2 cm, 4x4 cm, 5x5 cm, 10x10 cm) as a visual reference. Boulder surface was measured separately by top, side, or bottom within sampling quadrat borders. The top of solid rock benches were also measured, however if the surfaces were not relatively flat the sides were measured as well. Macroscopic organisms were sampled within the marked borders of the $0.25m^2$ quadrats. Estimates were determined separately for each substratum surface orientation category (top, side, bottom), which is useful for some purposes but not necessary for an inventory. Boulders were temporarily overturned to assess the abundances of organisms found on their undersides. Macrophytes cover and sessile macroinvertebrates were estimated using visual counts of individual species in an area in order to determine biomass. Further information on the methods used for sampling physical structure of boulder fields and the organisms that reside there can be seen in this document.

Murray, S. N., R. F. Ambrose and M. N. Dethier. 2002. Quantifying Abundance: Density and Cover. In Methods For Performing Monitoring, Impact and Ecological Studies on Rocky Shores, pp. 117-147. United States Department of the Interior, Minerals Management Service, Pacific OCS Region.

Chapter 6 describes the use of plots and quadrats for quantifying density and cover. Direct counts are used for measuring density of mobile intertidal invertebrates. Once organisms are counted, the numbers are converted to density or the number of individuals per unit area of intertidal surface. Quadrats are used for sampling intertidal seaweeds and macroinvertebrates. Counted individuals are marked once they are observed so they traced. If organisms are abundant (>50) a hand-held mechanical counter is used because the counting process can be done faster. Additional information on quantifying density is discussed in the document.

There are three methods described in this document for estimating percent cover of rocky intertidal populations. These methods include: (1) The use of scanning plots to visually estimate the planar surface area of a plot covered by the species or material to be measured. Researchers then divide plots into subsections to make easy estimates and enhance accuracy of estimates made; (2) Determining the number of point intercepts along a line or within an area. Species percent cover is calculated by dividing the number of its point intercepts by the total number of points distributed within the sampled area of plot; and (3) Tracing silhouettes or photographic images of organisms by planimetry or with image analysis software. Additional information on estimating percent cover is discussed in the document.

Oregon Watershed Enhancement Board. 1999. Oregon Aquatic Habitat: Restoration

and Enhancement Guide. Phone # (503) - 986-0178. http://www.oweb.state.or.us/publications/habguide99.shtml

This guide was developed to provide guidance on restoration and enhancement measures that would assist in aquatic ecosystem recovery. The guide is divided into five sections: An overview of restoration activities, activity guidelines, overview of agency regulatory functions and sources of assistance, grants and assistance, and monitoring and reporting. The purpose of this document is to provide information that will assist in developing effective restoration projects; to define standards and priorities that will be approved by state and receive funding or authorized restoration projects; to identify state and federal regulatory requirements and receive assistance in restoration projects. Additional information on monitoring techniques for salmonid restoration and guidelines and considerations for reporting restoration progress over time are described within the document.

Pohle, G. W. and M. L. H. Thomas. 2001. Monitoring Protocol for Marine Benthos: Intertidal and Subtidal Macrofauna. A Report by the Marine Biodiversity Monitoring Committee (Atlantic Maritime Ecological Science Cooperative, Huntsman Marine Science Centre) to the Ecological Monitoring and Assessment Network of Environment Canada. Contact information: Gerhard Pole, arc@sta.dfo.ca. http://www.eman-rese.ca/eman/ecotools/protocols/marine/benthics/intro.html.

This document provides methods used for sampling and monitoring intertidal and subtidal macrofauna. The information presented here is for monitoring and sampling in hard bottoms and soft bottoms habitats. The tools for monitoring these habitats allow changes in fauna abundance and diversity to be detected with regard to natural variability, and what elements are responsible for altering the habitat conditions. Depth and sediment grain size significantly affects species composition of benthic macrofauna therefore should be sampled at comparable depths and measured within a narrow scope size of grain size. Methods that are recommended for sampling intertidal and subtidal soft bottom areas and described in this document include: subtidal grab sampler or corer methods for quantitative sampling; and dredge and trawls for qualitative sampling in subtidal areas. Methods of analysis for data collected include: univariate (measures species richness), multivariate, graphical, indicator species, and taxonomic reductions. Additional information on methods used for sampling is described in this document.

Puget Sound Water Quality Action Team. 1997. Recommended guidelines for sampling marine sediment, water column and tissue in Puget Sound. In Puget Sound Protocols and Guides, Puget Sound Water Quality Action Team, Olympia WA. http://www.psat.wa.gov/Publications/protocols/protocol.html

This document provides guidelines for sampling marine sediment, water column, and tissue for the chemical analysis of metals and organics as well as microbiological and bioassay testing. Also provided are recommended methods for sampling, quality control, and quality assurance procedures, field health and safety protocols and documentation requirements. These guidelines were established to help standardized methods that are used in various Puget Sound monitoring and regulatory programs. By standardizing field sampling and measurement methods researchers can produce comparable data when conducting studies in Puget Sound. The document also aims to consolidate and enhance access to marine sampling guidelines and field information for a variety of matrices and target analytical parameters. It allows practitioners to utilize the information to suit the goals of their project but by no means state that all sampling *must* be performed using these methods. Some of the protocols presented in this chapter include guidelines for: collecting environmental samples in Puget Sound; measuring organic compounds; measuring metals; measuring conventional variables; and conducting laboratory bioassays.

Raposa, K. B. and C. T. Roman. 2001. Monitoring Nekton in Shallow Estuarine Habitats. A Protocol for the Long Term Monitoring Program at Cape Cod National Seashore. Narragansett Bay National Estuarine Research Reserve Prudence Island, RI, National Park Service, Graduate School of Oceanography, University of Rhode Island, Narragansett, RI. 39 pp. Contact information: Kenny@gso.uri.edu. http://www.nature.nps.gov/im/monitor/protocoldb.cfm

Author Abstract. Long term monitoring of estuarine nekton has many practical and ecological benefits but efforts are hampered by a lack of standardized sampling procedures. This study develops a protocol for monitoring nekton in shallow (<1m) estuarine habitats for use in the Long term Coastal Monitoring Program at Cape Cod National Seashore. Sampling in seagrass and salt marsh habitats is emphasized due to the susceptibility of each habitat to anthropogenic stress and to the abundant and rich nekton assemblages that each habitat supports. Extensive sampling with quantitative enclosure traps that estimate nekton density is suggested. These gears have a high capture efficiency in most habitats and are small enough (typically 1 m^2) to permit sampling in specific microhabitats. Other aspects of nekton monitoring are discussed, including seasonal sampling considerations, sample allocation, station selection, sample size estimation, parameter selection, and associated environmental data sampling. Developing and initiating long term nekton monitoring programs will help track natural and human-induced changes in estuarine nekton over time and advance our understanding of the interactions between nekton and the dynamic estuarine environments.

Shelton, L. R. 1994. Field guide for collecting and processing stream-water samples for the National Water Quality Assessment Program. U.S. Geological Survey Report 94-455, Sacramento, CA. http://ca.water.usgs.gov/pnsp/pest.rep/sw-t.html

Author Abstract. The U.S. Geological Survey's National Water-Quality Assessment program includes extensive data-collection efforts to assess the quality of the Nation's streams. These studies require analyses of stream samples for major ions, nutrients, sediments, and organic contaminants. For the information to be comparable among studies in different parts of the Nation, consistent procedures specifically designed to produce uncontaminated samples for trace analysis in the laboratory are critical. This field guide describes the standard procedures for collecting and processing samples for major ions, nutrients, organic contaminants, sediment, and field analyses of conductivity, pH, alkalinity, and dissolved oxygen. Samples are collected and processed using modified and newly designed equipment made of Teflon to avoid contamination, including nonmetallic samplers (D-77 and DH-81) and a Teflon sample splitter. Field solid-phase extraction procedures developed to process samples for organic constituent analyses produce an extracted sample with stabilized compounds for more accurate results. Improvements to standard operational procedures include the use of processing chambers and capsule filtering systems. A modified collecting and processing procedure for organic carbon is designed to avoid contamination from equipment cleaned with methanol. Quality assurance is maintained by strict collecting and processing procedures, replicate sampling, equipment blank samples, and a rigid cleaning procedure using detergent, hydrochloric acid, and methanol.

Trippel, E. A. 2001. Marine Biodiversity Monitoring: Protocol for Monitoring of Fish Communities. A Report by the Marine Biodiversity Monitoring Committee (Atlantic Maritime Ecological Science Cooperative, Huntsman Marine Science Centre) to the Ecological Monitoring and Assessment Network of Environment Canada. http://www.eman-rese.ca/eman/ecotools/protocols/marine/fishes/intro.html#Rationale

This document presents a monitoring protocol for estimating species diversity of bottom dwelling or demersal fish species inhabiting the Canadian continental shelf regions. Monitoring protocols presented in this document can be used to monitor and evaluate fish communities in regions other than the Canadian continental shelf. Methods used to estimate the abundance of different demersal fish species include random stratified sampling and fixed station sampling. Using these standardized procedures helps to maintain precision. Some factors taken into consideration when monitoring fish communities include depth, temperature, salinity, seasonal shifts, and diurnal behavior patterns. Additional information found in this document includes size of area and sampling intensity, sampling gear, sampling procedures, and treatment of data.

United States Environmental Protection Agency (USEPA). 1992. Monitoring Guidance for the National Estuary Program. United States Environmental Protection Agency, Office of Water, Office of Wetlands, Washington D.C. EPA Report 842-B-92-004.

This document provides guidance on the design, implementation, and evaluation of the required monitoring programs. It also identifies steps to be taken when developing and implementing estuarine monitoring programs and provides technical basis for discussions on the development of monitoring program objectives, the selection of monitoring program components, and the allocation of sampling effort.

Some of the criteria listed for developing a monitoring program and described in this document include: monitoring program objectives, performance criteria, establish testable hypotheses, selection of statistical methods, alternative sampling designs, use of existing monitoring programs, and evaluate monitoring program performance. Additional information on guidelines for developing a monitoring program is described in this document.

United States Environmental Protection Agency (USEPA). 1993. Volunteer Estuary Monitoring. In Ohrel, R. L. Jr., and K. M. Register (eds.), A Methods Manual. U.S. Environmental Protection Agency, Washington, D. C., Office of Water. EPA Report- 842-B-93-004. 176 pp. http://www.epa.gov/owow/estuaries/monitor/.

This document presents information and methodologies specific to estuarine water quality. Information presented in the first eight chapters include: understanding estuaries and what makes them unique, impacts to estuarine habitats and human's role in solving the problems; guidance on how to establish and maintain a volunteer monitoring program; guidance for working with volunteers and ensuring that they are well-positioned to collect water quality data safely and effectively; ensuring that the program consistently produces high quality data; and managing the data and making it readily available to data users. Also presented are water quality measures that determine the condition of the estuary are physical (e.g., substrate texture), chemical (e.g., dissolved oxygen) and biological parameters (e.g., plant and animal presence and abundance). The importance of each parameter and methods used to monitor the conditions are described in a gradual process. Proper quality assurance and quality control techniques must also be described in detail to ensure that the data are beneficial to state agencies and other data users.

United States Environmental Protection Agency (USEPA). 1997. Volunteer Stream Monitoring: A Methods Manual. United States Environmental Protection Agency, Office of Water 4503F, Office of Wetlands, Washington D.C. EPA Report 841-B-97-003. http://www.epa.gov/volunteer/stream/stream.pdf.

This document has been developed to provide guidance for project managers when developing monitoring programs and describes the importance of volunteer monitoring. Described in the document are parameters that are monitored in stream habitats but will vary depending on project goals as well as methods used for sampling and conducting surveys. Some methods described in this document include a watershed survey, a visual assessment that describes the geography, land, and water use, and potential and current pollution sources, history of the stream and its watershed; biological monitoring of macroinvertebrates which involves collecting, processing, and analyzing aquatic organisms that can help determine health of the habitat. Surveys may be performed by using the rock rubbing method which involves randomly picking a rock from the bed and removing organisms from the rock surface or the stick picking method which collects several sticks from the stream, place in water and then remove it to examine organisms present on the stick over a pan; and water quality examination by measuring stream flow, temperature, turbidity, dissolved oxygen, pH, fecal bacteria, nutrients, total solids, conductivity, and alkalinity. Additional information on methods and parameters used for monitoring stream habitats are described in detail in this document.

Wenner, E. L. and M. Geist. 2001. The National Estuarine Research Reserves Program to Monitor and Preserve Estuarine Waters. *Coastal Management* 29:1-17.

The National Estuarine Research Reserve (NERR) sites in 1992 coordinated a program that would attempt to identify and track short-term variability and long-term changes in representative estuarine ecosystems and coastal watersheds. Water quality parameters that were monitored include: pH, conductivity, temperature, dissolved oxygen, turbidity, and water level. Standardized protocols were also used at each site so that sampling, processing, and data management techniques were consistent among sites. Statistical techniques are being used to identify periodicity in water quality variables. Periodic regression analysis indicated that diel periodicity in dissolved oxygen is a larger source of variation than tidal periodicity at sites with less tidal amplitude. Authors of this document stress how understanding the functions of estuaries and how they change over time will help predict how these systems respond to change in climate and anthropogenic sources.

APPENDIX III: LIST OF ROCKY HABITAT EXPERTS

The expert listed below has provided his contact information so practitioners may contact him with questions pertaining to the restoration or restoration monitoring of this habitat. Contact information is up-to-date as of the printing of this volume. The list below includes only those experts who were 1) contacted by the authors and 2) agreed to submit their contact information. In addition to this resource, practitioners are encouraged to seek out the advice of local experts as well faculty members and researchers at colleges and universities. Engineering, planning, and landscape architecture firms also have experts on staff or contract out the services of botanists, biologists, ecologists, and other experts whose skills are needed in restoration monitoring. These people are in the business of providing assistance in restoration and restoration monitoring and are often extremely knowledgeable in local habitats and how to implement projects on the ground. Finally local, state, and Federal environmental agencies also house many experts who monitor and manage coastal habitats. In addition to the National Oceanic and Atmospheric Administration (NOAA), the Environmental Protection Agency (EPA), the Army Corps of Engineers (ACE), Fish and Wildlife Service (FWS), and the United States Geologic Survey (USGS) are important Federal agencies to contact for assistance in designing restoration and monitoring projects as well as potential sources of funding and permits to conduct work in coastal waterways.

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CHAPTER 7: RESTORATION MONITORING OF SOFT BOTTOM HABITATS

Stephen Lozano, NOAA Great Lakes Environmental Research Laboratory[1]
David Merkey, NOAA Great Lakes Environmental Research Laboratory[1]

INTRODUCTION

Soft bottom habitats within coastal environments are characterized by loose, unconsolidated sediment types (Cowardin et al. 1979). The sediments are fine to coarse-grained with at least 25% of the particles smaller than 2 cm and have a vegetative cover less than 30%. Soft bottom habitats are restricted to subtidal, permanently flooded water regimes, characterized by the general lack of areas for plant and animal attachment and by lower energy levels than rocky substrate habitats. The composition of plants and animals present is determined by temperature, salinity, light penetration, and the substrate type that is, in turn, structured by the exposure to wave and current action. Managing the ecological health of soft bottom habitats is integral to managing the health of aquatic systems as a whole. Many organisms live in and on sediments and use sedimentary particles as food. Crustaceans, polychaetes, and gastropods dominate these habitats and are the primary sources of food for many of the larger estuarine organisms such as fish (Boesch et al. 1994).

Soft bottom habitats are often classified into four subclasses:

- Cobble-gravel, composed of unconsolidated particles smaller than stones, predominantly cobble and gravel, although finer sediments may be intermixed
- Sand-type, composed of unconsolidated particles smaller than gravel, predominantly sand, although finer or coarser sediments may be intermixed
- Mud, consisting of unconsolidated particles smaller than gravel, predominantly silt and clay, although coarser sediments or organic material may be intermixed
- Organic, composed of unconsolidated material smaller than gravel and is predominantly organic (Miner 1950; Smith 1964; Abbott 1968; and Ricketts and Calvin 1968)

The composition of the sea bottom (i.e., fine mud, sand, gravel, cobble, boulders, and rock) determines which plants and animals live in particular areas.

In freshwater areas, substrate type is largely determined by current velocity. Within the Great Lakes, soft bottom habitats tend to develop in low energy zones such as harbors, embayments, or drowned river mouths. The plants and animals present in and on the sediment surface also exhibit a high degree of morphological and behavioral adaptation to flowing water. Usually there is a high correlation between the nature of the substrate and the number and abundance of species. For example, when light is present and oxygen is high, sediments tend to be lower in ooze-like organic material and higher in species diversity.

In marine waters, soft bottom habitats are generally found in relatively shallow water (< 30 m) and adjacent to beaches (or other sediment sources). Marine soft bottom habitats include worm mounds and sand dollar beds and are not vegetated.

Soft bottom habitats perform a variety of functions beneficial to humans and wildlife. They act as filters for runoff from upland development and help moderate nutrient flow to downstream waters. Soft bottom communities recycle nutrients from the water column and

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other habitats. Organic detritus from kelp and other macroalgae, dead animals, zooplankton, phytoplankton, and other sources of nutrients and carbon rain down on the substrate where they can be eaten by benthic animals. This dead and/or decomposed material along with the associated nutrients are then buried and stored in the sediment. Occasionally, if sediments are disturbed, buried nutrients can make their way back into the water column where plants can once again use them. Research into the nutrient cycling dynamics of soft sediment communities has provided helpful management information for flatfish and other commercial species (Kaiser et al. 2000). Benthic communities can also be used to assess the presence of pollution in the water column as contaminants in the water column settle and accumulate in soft sediments.

HUMAN IMPACTS

Sediment contamination is an environmental problem that poses a threat to a variety of aquatic ecosystems. Sediments act as a reservoir for common chemicals such as pesticides, herbicides, polychlorinated biphenyls (PCBs), polycyclic aromatic hydrocarbons, and metals. Contaminated sediments are directly toxic to aquatic life and can be a source of contaminants to humans through bioaccumulation in the food chain. Studies conducted by the United States Environmental Protection Agency (EPA) suggest that contaminated sediments are among the most significant sources of non-point source pollution in the United States and pose one of the largest risks to the aquatic environment. Many of the organic contaminants listed above bond well to the smaller grain sizes found in soft bottom sediments (Kukkonen et al. 2003).

The impact of fishing gear on marine benthic habitats is dependent upon the benthic species and fishing effort (Kaiser et al. 2000). The size of benthic species populations are positively associated with the availability of high quality nursery habitats (Turner 1977; Cibb et al. 1999). Unfortunately, relatively few studies of habitat disturbance have included a temporal component (study over time) of sufficient duration to address longer-term changes that occur as a result of bottom fishing disturbance. Collie et al. (2000) found the vulnerability of animals was based on morphology and behavior. Lugworms (*Arenicola* spp.), for example, have a large initial response to disturbance, which is not surprising given that these animals are the target of a commercial fishery. When fishing effort data is collected at a small spatial (~10 km^2) resolution (Rijnsdorp et al. 1998), fish effort is patchily distributed, and some relatively small areas of the seabed are scoured frequently (200-400 times a year) while others go unfished. This suggests that re-colonization of disturbed, heavily fished areas is more likely to come from active immigration into disturbed patches rather than reproduction within patches. When sampling soft bottom habitats, practitioners need to know the intensity of fishing in the restoration area as well as adjacent habitats that may contribute individuals during restoration of the habitat.

STRUCTURAL CHARACTERISTICS OF SOFT BOTTOM HABITATS

Estuarine/wetland sediments are affected by physical, hydrological, and chemical forces. Soft bottom habitats are characterized by variable physical and chemical conditions that influence the organisms living in these habitats. There are often large changes in physical-chemical parameters with increasing depth. Concentration of dissolved components such as oxygen, for example, can fluctuate considerably. Tides and tidal currents can also move large amounts of water and suspended material around within the habitat and between soft bottoms and adjacent areas. The structural characteristics of soft bottom habitats that influence these biological, physical, and chemical functions include:

Physical

- Sediment grain size
- Topography/Bathymetry

Hydrological

- Current velocity

Chemical

- Nutrient concentration
- DO
- Sediment Contaminants

PHYSICAL

Understanding the many physical forces acting on soft bottoms is essential to understanding the ecology of this habitat type. Major sediment inputs to soft bottom habitats are deposited by the annual flow of rivers into estuaries. During fall and winter there are numerous resuspension events that move particles at different rates. Physical factors such as temperature, light, turbidity, currents, and wave action interact to form soft bottom habitats that are characterized by zones of low energy, little plant life, and high deposition of sediments.

Sediment Grain Size

Grain size is the most fundamental physical property of sediment. Geologists and sedimentologists use information on sediment grain size to study:

- Trends in surface processes related to the dynamic conditions of transportation and deposition
- The permeability and stability under different sediment loads, and
- The movement of subsurface fluids (McCave and Syvitski 1991)

With these reasons in mind, the objectives of a grain-size analysis are to accurately measure individual particle sizes, to determine their frequency distribution, and to calculate a statistical description that characterizes the sample.

Classification schemes for benthic invertebrate communities have been developed based on sediment texture: i.e., the proportion of silt, clay, sand, and water. (Boswell 1961; Jones 1956). Biomass is greater in muddy sand compared to other textures. Sanders (1956) identified a soft-bottom polychaete-mollusc community in Long Island Sound on the basis of sediment texture. Hughes et al. (1972) observed that 46% of the polychaetes and echinoderms in a coastal bay were associated with an area of soft sediments.

The sediment type and grain size is important in determining the benthic community composition because behavioral and morphological adaptations evolve to suit a specific substrate. For example, flatfish body shapes can dig into the sediment and their coloration and markings mimic their surroundings. Clams and worms also prefer a certain grain size and depth. Because sediment grain size controls how easily fish bury and the type of prey dwelling within, each species and life stage prefers a specific size. Sediments that differ in grain size also differ in other properties that are important to organisms. Algae and bacteria, for example, are found in greater abundance in softer sediments. The distribution and abundance patterns of amphipods such as *Diporeia* spp. reveal a positive relationship with sediment-associated bacteria (Sly and Christie 1992).

Sampling and Monitoring Methods

The characteristics of coastal sediment particles are shaped by variations in the hydrological conditions affecting the littoral area of soft sediment habitats. The source of sediments from the surrounding source area also will determine the hardness, shape, and ultimately the size of sediment particles. Important physical conditions in the littoral zone include the oscillating nature of seasonal wave patterns and the seasonal deposition of sediments during river floods. There can be considerable variability in sediment grain size over short periods of time (hours to weeks), therefore these changes are usually considered as "noise" compared to the spatial distribution of sediment types. Thus, repeated measurements over the short-term are less important than the sampling over a larger area to determine source and connection to open waters (Guillén and Hoekstra 1996).

Sediment grain size can be measured directly by drying and sifting samples through a series of different sized sieves (Poppe et al. 2003). It can also be measured indirectly through measuring bulk density. Bulk density is the dry weight of the sediment per unit of volume (Steyer et al. 1995). It is generally low (e.g., 0.2 to 0.3 g/cm^3) for sediments with high organic matter content and high (e.g., 1.0 to 2.0 g/cm^3) for sediments with high mineral content (Mitsch and Gosselink 2000). Detailed methods for sampling sediment characteristics such as grain size, nutrient concentration, and organic content can be found in Folk (1974), Gosselink and Hatton (1984), Poppe et al. (1986; 2000), Liu and Evett (1990), and Steyer et al. (1995), as well as other resources listed in the second appendix of this chapter.

Topography/Bathymetry

As mentioned earlier, soft bottom habitats are found in a variety of settings, usually associated with reduced water flow and high deposition rates. The sediments in these habitats consist of three primary components: particulate mineral matter, organic matter in various stages of decomposition, and an inorganic component of biogenic origin such as diatom shells. Particle size and organic matter of sediments is important to the distribution and growth of benthic invertebrates. Sediments with large amounts of organic matter are found in areas associated by high rates of littoral production (Wetzel 1983).

Sampling and Monitoring Methods

Sedimentation rate, nutrient cycling, and other important physical processes are defined by the topography of the soft bottom habitat. The bathymetric features of soft bottoms can be sampled using a boat and a method to measure depth such as a weighted rope, pole, or radar. Methods will vary depending on the amount of detail desired and the size of the habitat being mapped. For larger areas or where more detail is desired, remote sensing techniques can be used. High-resolution aerial imagery can be used to create detailed maps of bathymetry over large areas that would be hard to sample with traditional methods. These technologies (LIDAR, multi-beam sonar, and side-scan sonar) have been successfully demonstrated in mapping estuary and marsh topography (Blomgren 1999; Barnes et al. 2002; Clayton et al. 2002; Gardner and Mayer 2002; Pickrill and Todd 2002). Imagery can also be analyzed to determine different sediment types (Lee et al. 2001; Dierssen et al. 2003; Louchard et al. 2003).

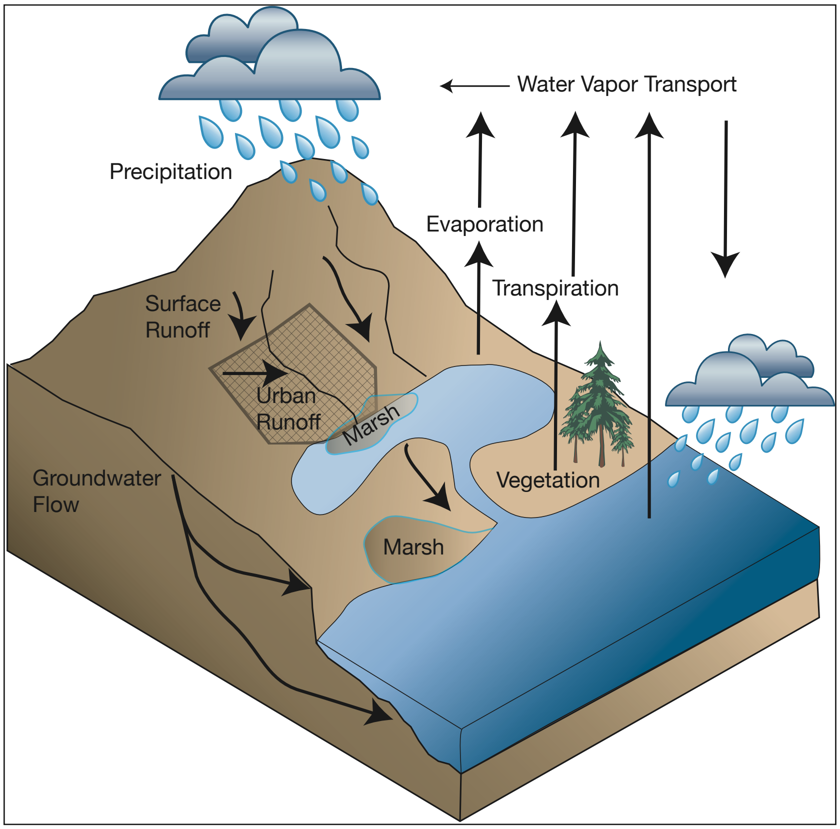

Figure 1. The hydrologic cycle. As water returns to earth as rain, it carries with it a variety of suspended and dissolved material on its return to open bodies of water. The characteristics of the land over and through which water flows determines the characteristics of the water once it reaches its destination. Graphic by Stephen Lozano, NOAA Great Lakes Environmental Research Laboratory.

HYDROLOGICAL

Hydrologic processes play an important role in the transportation of sediments to soft bottom habitats. Nutrients, sediments, toxic compounds, and metals are delivered to soft bottom habitats through groundwater flow, surface runoff, and precipitation (Figure 1). Land use also impacts the quality of water reaching soft sediments by affecting evaporation rates, the amount of water infiltrating to ground water, and the rate of run-off and erosion.

Current Velocity

Geological character and history shape the distribution of sediment and substrate, but the speed and direction of currents help determine the grain size of soft bottom materials such as silt and sand. In general, faster current areas contain more coarse-grained sediments. Ripple marks and sand waves are also indicative of very strong currents (Driskell 1979). Movement of bottom sediments by waves and currents is a dominant physical process influencing the structure of benthic communities in soft bottom areas (Oliver 1980; Simenstad et al. 1991).

Sediments enter and settle in the estuary from both terrestrial and open-water resources. As rivers and creeks flow seaward, they carry with them sediments from the land, while flood tides bring in sands from the sea (de Johge and van Beusekom 1995). The runoff from rains and snowmelt also carries sediments into nearby streams. Removal of vegetation from agricultural, logging, and construction operations promotes erosion and increases the sediment loads of rivers and creeks.

The size of sediments in soft bottom habitats ranges from small rocks and coarse gravel to silt and clay particles. The faster the current, the greater the size of sediment particles a stream can move. In the slower currents of a river's lower reaches, only the finest sediments will remain suspended in the water. In the tidewater portion of the river, fine sediments begin settling out and are deposited in several ways. In large flood tides, the river currents stop or even reverse course, allowing even finer particles to rain out. In a process called flocculation, tiny particles clump together, become heavier, and settle to the bottom. This occurs in estuaries where freshwater meets and mingles with salt water, particles collide and stick together forming larger aggregates or clumps of sediments called flocs which then settle out of suspension. Consequently, deposition can change along the course of the estuary. Sediments are also deposited wherever currents are slowed, such as the bend of a stream where sediments will settle and create shallows.

CHEMICAL

Nutrient Concentration

Large areas of sediments in soft bottom habitats are able to exchange nutrients with overlying regions of the estuary or wetland where plants can grow. Most of the nutrients are nitrogen and phosphorous from agricultural sources but also from human waste and industrial discharge. Microbial activity, burrowing animals, and resuspension of sediments increase the release of nutrients into the water. High concentrations of nutrients in the water column stimulate algal growth, eutrophication, oxygen depletion, and ultimately, fish kills due to lack of oxygen. It has been shown that bottom sediments directly influence water quality by releasing nitrogen to overlying waters and by consuming dissolved oxygen from the water column in the process. High primary productivity may, in turn, alter the entire benthic community composition and possibly the species composition of higher levels in the food chain (Burkholder 1998).

Animals also affect the physical, chemical, and biological aspects of their environment. Feeding by freshwater deposit feeders such as oligochaetes and the burrowing amphipod *Diporeia* spp. can mix sediments by highly ordered or random movement of sediment particles (McCall and Tevesz 1982). The mixing of sediments is not a feeding strategy but is created by suspension feeders, deposit feeders, and omnivores as they move, burrow, and feed in the sediments. The mixing of sediments by *Diporeia* is important in the Great Lakes. Robbins et al. (1979) found that ^{137}C labeled clay was uniformly distributed in the top 1.5 cm of a sediment column. The net effect of amphipod feeding and burrowing activity is to mix sediments randomly. Similar to polychaetes in marine waters, oligochaetes are among the most potent movers of sediments in fresh water. In Lake George, 85% of the worm population was found below 12 cm (Brinkhurst and Kennedy 1965).

Another important component of soft bottom sediments is the organic carbon content. Sediment organic matter is derived from plant and animal detritus, bacteria, plankton, or derived from natural and anthropogenic sources in catchments. Organic matter in sediment consists of carbon and nutrients in the form of carbohydrates, proteins, fats, and nucleic acids. Bacteria quickly eat nucleic acids and many of the proteins. Sediment organic matter can be a source of recycled nutrients for water column productivity when it degrades. Dissolved oxygen (DO) concentrations are usually lowered when organic aerobic bacteria degrade matter, and anoxic and hypoxic conditions may develop under stratified conditions.

Sampling and Monitoring Methods

Sampling, handling, and processing nutrient samples requires special instrumentation and reagents. Methods for measuring nutrients in bottom sediments are summarized in *Standard Methods for the Examination of Water and Wastewater* (1998). More information on monitoring nutrient concentrations in estuarine habitats is available at: http://www.epa.gov/owow/estuaries/monitor.

Dissolved Oxygen (DO)

The level of oxygen in fine sediments can become limiting for all aquatic life. In addition to its use in respiration in plants and larger animals such as fish, DO is used by bacteria in the process of breaking down organic matter. A characteristic feature of all sediments is a vertical zonation into a surface layer with oxygen and a subsurface layer where dissolved oxygen is depleted. Vertical distribution of sediment plants and animals is restricted by these vertical gradients. Bacteria are important in creating this zonation. Bacteria use oxygen as a hydrogen acceptor and are found to a depth that oxygen can penetrate the surface sediments. Below this depth are bacteria capable of anaerobic respiration and chemosynthesis. Under conditions of very low or no oxygen, many benthic taxa are eliminated (Boesch et al. 1976).

Sampling and Monitoring Methods

Measurements of DO should be taken at least weekly. Measurements should be year round but are particularly important during the growing season. Methods for measuring DO in bottom sediments are summarized in *Standard Methods for the Examination of Water and Wastewater* (1998). A variety of electronic oxygen sensors are commercially available.

Sediment Contaminants

Contaminated sediments are directly toxic to aquatic life or can be a source of contaminants for bioaccumulation in the food chain. Contaminated sediments are among the most significant sources of non-point source pollution in the United States and pose one of the largest risks to the aquatic environment. The U.S. Environmental Protection Agency has published a manual on new methods for testing freshwater organisms in the laboratory to evaluate the potential toxicity or bioaccumulation of chemicals in whole sediments (USEPA 1994). The *Standard Methods for the Examination of Water and Waste Water* (1998) also provides extensive methods for measuring a variety of chemical contaminants.

FUNCTIONAL CHARACTERISTICS OF SOFT BOTTOM HABITATS

Many of the physical and chemical functions performed by soft bottom habitats were covered with the associated structural characteristics above. The following section focuses on the biological functions. A list of common functional characteristics of soft bottom habitats includes:

Biological
- Provides habitat for the benthic community

Physical
- Alters turbidity

Chemical
- Modifies chemical water quality
- Modifies dissolved oxygen
- Supports nutrient cycling

BIOLOGICAL

Provides Habitat for the Benthic Community

The benthic community of soft bottom habitats is composed of a wide range of bacteria, plants, and animals. The most important function of benthic organisms is to link primary producers, such as phytoplankton, with the higher trophic levels, such as finfish, by consuming phytoplankton and then being consumed by larger organisms. They also play a major role in breaking down organic material. Another important functional characteristic of soft bottom habitats is the transformation of chemicals by bacteria and other microorganisms (Figure 2). Transformation

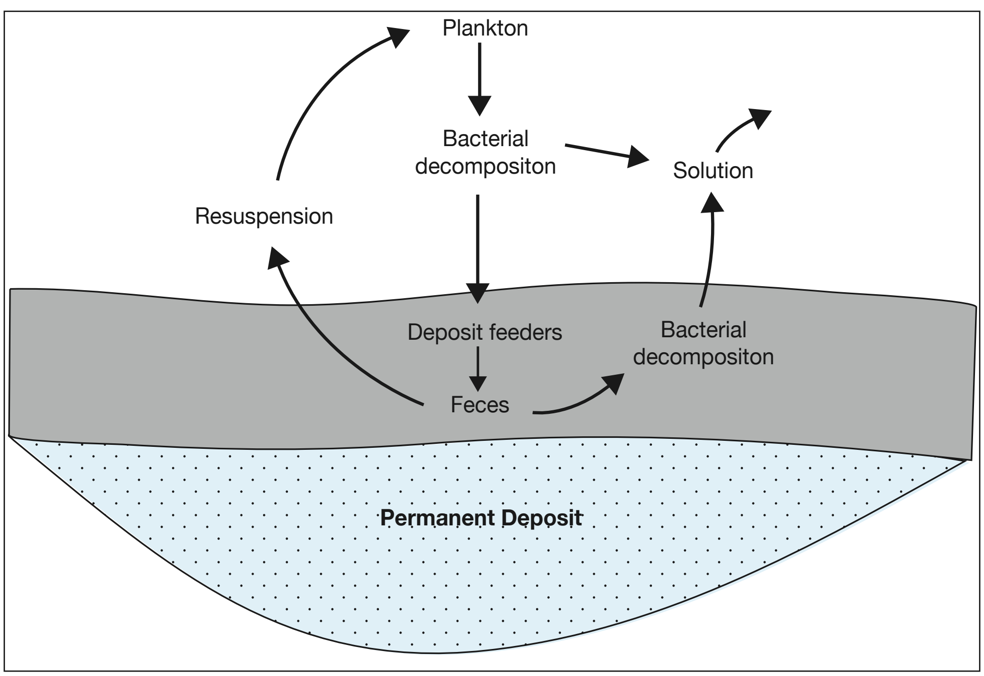

Figure 2. Bacterial recycling of organic matter. As phytoplankton and zooplankton die, the decomposition by bacteria begins in the water column. Deposit feeders (e.g. oligochaetes, amphipods) also break down pelagic material. Organic matter is re-suspended from feces or bacterial decomposition of fecal material. Graphic by Stephen Lozano, NOAA Great Lakes Environmental Research Laboratory.

reactions are intimately tied to the deposition of organic matter. Some of the most important transformation reactions resulting from bacteria decomposition of organic matter are the removal of dissolved oxygen, the production of carbon dioxide, the reduction of nitrate, the reduction of sulfate, and the production of ammonia, phosphate, hydrogen sulfide, and methane (Berner 1974; Alongi 1997).

The use of benthos in aquatic ecological research, and particularly in evaluating marine pollution, is effective in assessing long-term changes and detecting input from diffuse sources (Boesch et al. 1976; Simboura et al. 1995; Hyland et al. 1996). The benthos reflects the effects of pollutants or organic enrichment by responding through measurable changes in population size on a time scale of weeks to years. Benthic assemblages are used because they consist of largely sessile organisms that must tolerate the pollution or die. Benthic organisms are resident year round, naturally abundant and diverse, and most are not harvested or intentionally managed by humans. Benthic monitoring is a relatively sensitive, effective, and reliable technique that can detect subtle changes that serve as an early indicator before more drastic environmental changes occur. Some benthic taxa are able to tolerate high levels of organic enrichment and low dissolved oxygen, while others are quickly eliminated under low DO conditions (Boesch et al. 1976). Benthic indices have been developed based on the ability of benthic taxa to tolerate different levels of DO, organic enrichment, pesticides, and metal contaminants (USEPA 1994).

Macroinvertebrates

The restoration and monitoring of fresh and salt-water soft bottom habitats begins with the benthic community, usually the benthic macroinvertebrates associated with specific sediment types. Benthic animals are divided into three distinct groups: infauna (animals that live in the sediment), epifauna (animals living on the surface of the sediment or other substrate such as debris), and demersal (bottom-feeding or bottom-dwelling fish and other free moving organisms). This division also reflects differences in sampling techniques for the three groups.

In estuarine soft bottom systems, the benthic community is dominated primarily by species that burrow into the sediments (infauna), either living within tubes or burrow systems. Dominant types of infauna in most estuaries are segregated by salinity and include:

Small worms (polychaetes and oligochaetes)
Amphipod crustaceans
Clams, and
Insect larvae

In temperate regions, the diversity, or species richness, of the benthic communities in soft substrates on the continental shelf and slope may rival that in shallow tropical seas (Brusca and Brusca 1990). Benthic animals generally consume detrital or planktonic food sources with some predatory species present, and are in turn prey for finfish, shrimp, and crabs.

The diversity of benthic invertebrates is large. In marine soft bottom habitat, the dominant benthic organisms include:

Worms (polychaetes)
Amphipods
Clams
Crabs, and
Sea urchins (Simenstad et al. 1991; Ward 1975)

In habitats with gravel substrates, dominant animals are the mussels *Modiolus* and *Mytilus*, the brittle star *Amphipholis*, the soft-shell clam *Mya*, and the Venus clam *Saxidomus*. In sandy areas (Figure 3) dominant animals include:

Wedge shells (*Donax* spp.)
Scallops (*Pecten* spp.)
Tellin shells (*Tellina* spp.)

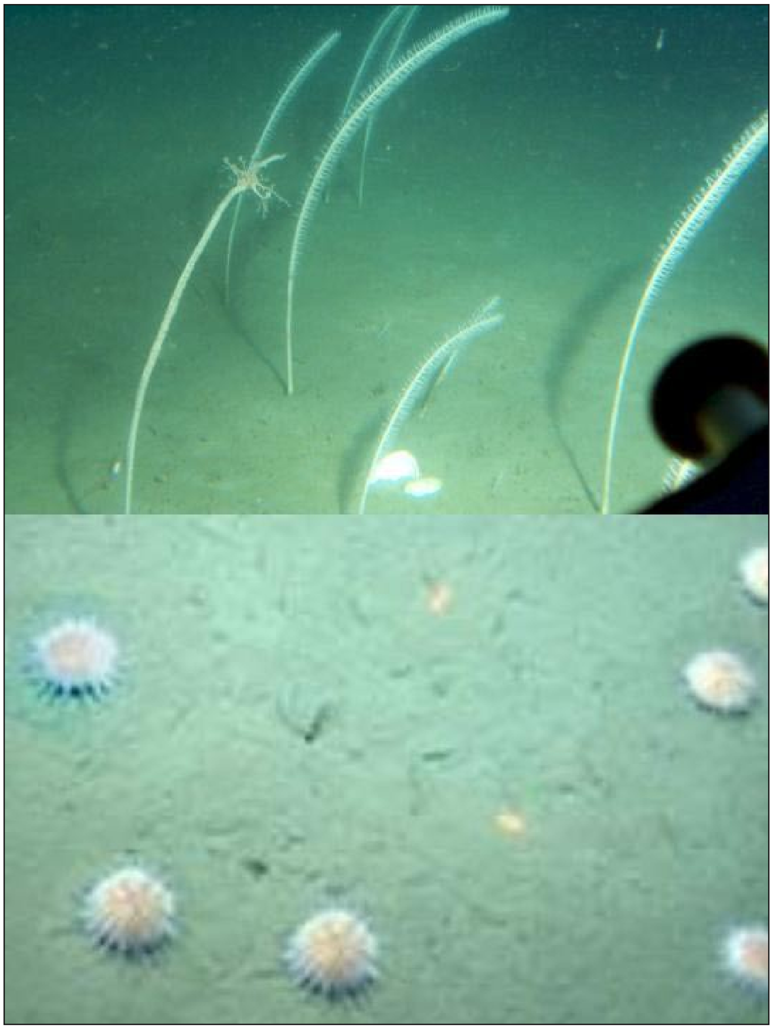

Figure 3. Sea urchins and fans on soft sediments, examples of animals that live on soft bottoms in marine estuaries. Photos from NOAA National Ocean Service.

Heart urchins (*Echinocardium* spp.)
Lugworms
Sand dollars (*Dendraster* spp.), and
Sea pansies (*Renilla* spp.)

In mud, dominant types include:

Terebellid worms (*Amphitrite* spp.)
Boring clams (*Platyodon* spp.)
Deep-sea scallops (*Placopecten* spp.)
Quahogs (*Mercenaria* spp)
Macomas (*Macoma* spp.)
Echiurid worms (*Urechis* spp.)
Mud snails (*Nassarius* spp.), and
Sea cucumbers (*Thyone* spp.) (Miner 1950; Smith 1964; Abbott 1968; Ricketts and Calvin 1968; Hodgson and Nybakken 1973).

Within the Great Lakes, much of the fauna of soft bottom habitats in wetlands are characterized by low abundance, high diversity, and great variability in both time and space. This variability is due to the physical instability of this habitat. Downwelling and oscillating thermoclines cause wide fluctuations in bottom temperatures, and waves and bottom currents cause resuspension of bottom substrates (Cook and Johnson 1974). Dominant freshwater benthic organisms include:

Oligochaetes (*Stylodrilus heringianus*, *Tubifex* spp., *Limnodrilus* spp.)
Amphipods (*Diporeia*, *Gammarus* spp.)
Mayflies (*Hexagenia* spp.)
Pea mussels (*Pisidium* spp), and
Chironomid larvae (Chironomidae) (Pennak 1978; Barton and Hynes 1978)

Sampling

The soft-bottom, infaunal benthos can be sampled relatively well by retrieving quantitative samples of the sediment and sieving them to extract the fauna. Grabs and corers are the devices generally used for sampling benthic invertebrates. Holme (1964), Holme and McIntyre (1971), and McInyre et al. (1984) have reviewed a large variety of grab and corer devices generally used for sampling benthic invertebrates. A review of methods for collecting and processing benthic samples can also be found in EVS Environment Consultants (1993), USEPA (1987), and USEPA (2001).

PHYSICAL

The main physical function performed by soft bottom habitats (alteration of turbidity) was described with the associated structural characteristics.

CHEMICAL

The main chemical functions performed by soft bottom habitats (modification of chemical water quality, modification of dissolved oxygen, and support of nutrient cycling) were described with their associated structural characteristics.

PARAMETERS FOR MONITORING STRUCTURAL/FUNCTIONAL CHARACTERISTICS

The matrices of structural and functional parameters for restoration monitoring provided below was developed through extensive review of the restoration and ecological monitoring literature. Additional input was received from recognized experts in the field of soft bottom ecology. This listing of parameters is not exhaustive, it is merely intended as a starting point to help restoration practitioners develop monitoring plans for this habitat type. Additional parameters not in this list, such as human dimensions parameters, may also be appropriate for restoration monitoring efforts. Parameters with a closed circle (●) are those that, at the minimum, should be considered in monitoring restoration progress. Parameters with an open circle (❍) may also be monitored depending on specific restoration goals. Information on why these parameters are important for monitoring and how they relate to structural and functional characteristics as well as to one another is found throughout the text. Literature directing readers toward additional information on the ecology of soft bottom habitats and restoration case studies can be found in Appendix I, an annotated bibliography of soft bottoms. Information on sampling strategies and techniques can be found in Appendix II, a review of technical methods manuals.

Parameters to Monitor the Structural Characteristics of Soft Bottom Habitats

Parameters to Monitor	Physical: Sediment grain size	Physical: Topography / Bathymetry	Hydrological: Current velocity	Chemical: pH, salinity, toxics, redox, DO
Hydrological				
Physical				
Shear force at sediment surface			❍	
Water column current velocity			●	
Chemical				
Dissolved oxygen				❍
Nitrogen and phosphorus				
Salinity (in tidal areas)				●
Toxics				❍
Soil/Sediment				
Physical				
Basin elevations		❍		
Geomorphology (slope, basin cross section)		●		
Organic content	●			
Percent sand, silt, and clay	●			
Sedimentation rate and quality	●	●	●	
Chemical				
Dissolved oxygen				❍
Salinity (in tidal areas)				❍
Toxics				❍

Parameters to Monitor the Functional Characteristics of Soft Bottom Habitats

Parameters to Monitor	Biological	Physical	Chemical		
	Provides habitat for benthic community	Alters turbidity	Modifies chemical water quality	Modifies dissolved oxygen	Supports nutrient cycling
Geographical					
Acreage of habitat types	●	●	●	●	●
Biological					
Animals					
Species, composition, and abundance of:					
Fish	❍				
Invasives	❍				
Invertebrates	●				
Hydrological					
Physical					
Current velocity		❍			
Trash		❍			
Chemical					
Chlorophyll concentration		❍	❍	❍	❍
Dissolved oxygen	❍		❍	❍	❍
Nitrogen and phosphorus		❍	❍		❍
PH			❍		
Toxics	❍		❍		
Soil/Sediment					
Physical					
Basin elevations	❍				
Sediment grain size (OM[3]/sand/silt/clay/gravel/cobble)		●	●	●	●
Sedimentation rate and quality		●			
Trash	❍				
Chemical					
Organic content in sediment		❍	❍	❍	❍

[3] Organic matter

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APPENDIX I: SOFT BOTTOM HABITATS ANNOTATED BIBLIOGRAPHY

This annotated bibliography contains summaries of restoration case studies and basic ecological literature. It is designed to provide restoration practitioners with examples of previous restoration projects as well as overviews of papers from the ecological literature that offer more detail than that covered in the associated chapter. Entries are presented from both peer reviewed and grey literature. They were selected through extensive literature and Internet searches as well as input from reviewers. They are not, however, a complete listing of all of the available literature. Entries are arranged alphabetically. Wherever possible, web addresses or other contact information has been included in the reference to assist readers in easily obtaining the original resource. Summaries preceded by the terms '*Author Abstract*' or '*Publisher Introduction*' or similar descriptors were taken directly from their original source. Summaries without such descriptors were written by the authors of the associated chapter.

Alongi, D.M. 1998. Coastal Ecosystem Processes. CRC Press, Boca Raton, LA.

Editors Comments. This book is about how food webs process energy and nutrients in the coastal ocean. I have taken a process-functional approach to show not only how coastal ecosystems reply on exchanges among biota, but also how they are influenced by physical, chemical, and geological forces.

Barnes, P.W., G.W. Fleischer, J.V. Gardner and K.M. Lee. 2002. Using laser technology to characterize substrate morphology of lake trout spawning habitat in Northern Lake Michigan. Symposium on the Effects of Fishing Activities on Benthic Habitats: Linking Geology, Biology, Socioeconomics, and Management. Tampa, FL. November 12-14, 2002.

Author Abstract. As part of a strategy to re-establish devastated native lake trout stocks, six areas of offshore and coastal Lake Michigan habitat were mapped with SHOALS bathymetric lidar in late summer 2001 in cooperation with the U.S. Army Corps of Engineers. Decimeter elevation/bathymetric data referenced to IGLD85 datum were obtained on a 4 m grid over a total area of about 200 km^2 in water depths from 0 to 30 m. Shaded relief and color-coded depth images were developed within coarser regional gridded bathymetry and subaerial DEM as a basis for maps and initial interpretation. Sparse substrate samples, underwater diver and useful but local video observations supplement the morphologic information. Three geologic regimes are present in the area and form the basis for substrate, habitat and morphologic classification. Devonian and Silurian carbonates underlie the region. Morphologic scarps and bedding lineations suggest bedrock at or near the surface at all of the mapped areas, but confirmation is lacking. Overlying bedrock are glacial deposits including compacted clay tills and outwash gravel and sand. The orphology and video observations suggest NW-SE basal till lineations and small (1-3 km) cobble and boulder moraines with outwash deposits. Post-glacial reworking appears minimal in depths greater than 10m. Modern sand deposits appear as thin down-drift (to the east) bedforms, sand sheets and depositional lobes, except along the coast of Little Traverse Bay where well developed, en-echelon nearshore bars are present at the head of the bay. Laser waveform data is being analyzed for benthic albedo information and biologic data is being incorporated with the morphologic and geologic observations toward classifying and mapping preferred lake trout spawning habitat.

Bedford, K. W. 1992. The physical effects of the Great Lakes on tributaries and wetlands. *Journal of Great Lakes Research* 18:571-589.

Author Abstract. Wetlands and tributary confluences are susceptible to physical influences imposed by the Great Lakes, particularly through the effects of short and long-term water level fluctuations and accompanying transport disruptions including flow and transport reversals. With there being few, if any, direct observations of these disruptions based upon velocity measurements, the objective of this paper is to review the possible physical effects on these regions by first, reviewing the relevant contributing physics known about the Great Lakes; second, contrasting possible marine estuary transport mechanisms with what little is published about the Great Lakes circumstances; and third, summarizing modeled results exemplifying these behaviors from a study of Sandusky Bay, Lake Erie. Because it exhibits the strongest response to storms and the clearest measurable signals resulting from them, attention is centered on Lake Erie. In contrast to a typical research paper, the objective herein is to provide a summary of what is known and commonly accepted about these physics which can serve as a backdrop for the other papers in this special issue.

Clayton, T.D., J.C. Brock and C.W. Wright. 2002. Mapping seagrass boundaries with waveform-resolving lidar: A preliminary assessment. Symposium on the Effects of Fishing Activities on Benthic Habitats: Linking Geology, Biology, Socioeconomics, and Management. Tampa, FL. November 12-14, 2002.

Author Abstract. For ecologists and managers of seagrass systems, the spatial context provided by remote sensing has proven to be an important complement to *in situ* assessments and measurements. The spatial extent of seagrass beds has been mapped most commonly with conventional aerial photography. Additional remote mapping and monitoring tools applied to seagrass studies include optical satellite sensors, airborne multispectral scanners, underwater video cameras, and towed sonar systems. An additional tool that shows much promise is airborne, waveform-resolving lidar (light detection and ranging). Now used routinely for high-resolution bathymetric and topographic surveys, lidar systems operate by emitting a laser pulse, then measuring its two-way travel time from the plane to reflecting surface(s) below, then back to the detector co-located with the laser transmitter. Using a novel, waveform-resolving lidar system developed at NASA -- the Experimental Advanced Airborne Research Lidar (EAARL) -- we are investigating the possibility of using the additional information contained in the returned laser pulse (waveform) for the purposes of benthic habitat mapping. Preliminary analyses indicate that seagrass beds can potentially be delineated on the basis of apparent bathymetry, returned waveform shape and amplitude, and (horizontal) spatial texture. A complete set of georectified digital camera imagery is also collected during each EAARL overflight and can aid in mapping efforts. Illustrative examples are shown from seagrass beds in the turbid waters of Tampa Bay and the relatively clear

Day, J. W., Jr., C. A. S. Hall, W. M. Kemp and A. Y.-A. (eds.). 1989. Estuarine Ecology. John Wiley and Sons, NewYork.

Editor's Comments. Estuaries are critical to the life cycles of fish and other aquatic animals. This book is a comprehensive synthesis of the field of estuarine ecology, incorporating much new research not covered by other books. The authors provide up-to-date information on the structure and function of estuaries, integrating the various components and processes of these key ecosystems. They also present a classification of estuaries bases on ecological principles. *Estuarine Ecology* is suitable as a text, for it presents all relevant background material – and it is complete and well-referenced enough to serve as a standard reference. Specific environmental impacts are addressed and classified.

Initial chapters describe the physical and chemical aspects of estuaries, with emphasis on nutrient cycling, and show how these fundamental factors provide a setting for the study of estuarine ecology. Middle chapters address estuarine plants, microbial ecology, estuarine consumers, and fish life-history patterns. Considerable information is provided on rates, patterns, and factors controlling primary production; the role of detritus in coastal systems (a topic that has been important in estuarine ecology for thirty years); and estuarine consumers (zooplankton, benthos, nekton, and wildlife). Of special note is the importance of estuaries in supporting fisheries.

Estuarine Ecology also deals with the effects of civilization on estuaries, including commercial fishing, and the side effects of industry and development. The authors examine traditional approaches to fisheries management, then present a modern ecological viewpoint. In the final chapter they present a general classification of the effects of human activities on estuarine ecology and give examples of each.

Estuarine Ecology is a thorough introduction to the subject – it presents an acceptable synthesis of modern estuarine science for those new to the field and develops sophisticated analysis for the professional.

Gardner, J. V. and L. A. Mayer. 2002. Benthic habitat mapping with advanced technologies and their application. Symposium on the Effects of Fishing Activities on Benthic Habitats: Linking Geology, Biology, Socioeconomics, and Management. Tampa, FL. November 12-14, 2002.

Author Abstract. Today's ability to map the seafloor was unheard of two decades ago. Navigational accuracies, as well as spatial and elevation resolutions have now reached the decimeter scale. But are today's resolutions fine enough for biologists trying to characterize specific benthic habitats? Do biologists know what resolutions are necessary to define their benthic habitat of interest? Once biologists have high-resolution data, do they have the technologies to visualize and analyze their newly acquired data? Do Agencies have the budgets required to use 21st century technology? High-resolution seafloor mapping technologies come in a variety of flavors with a variety of resolutions, from airborne lidar to underwater photography. Each system has it's own pros and cons relative to the particular goal of the seafloor mapper. For instance, a living platform coral reef can be efficiently mapped with an airborne lidar but the spatial resolution is 2 m x 2 m, at best, with a depth resolution of a few centimeters. The data are spectacular, albeit costly. But are these resolutions good enough to characterize the platform coral reef habitat for biological or management purposes? If not, then maybe underwater video/still photography is required. Underwater video/still photography is very labor intensive to acquire and process into useful imagery. Although the spatial resolution can be millimeter-scale, there is poor vertical resolution unless stereo photography is collected. And, to map an entire platform coral reef with underwater video or still photography would be an enormous undertaking and expensive. Examples of several seafloor-mapping techniques will be shown and their pros and cons will be discussed.

Guerra-Garcia, J.M. and J.C. Garcia-Gomez. 2004. Soft bottom mollusc assemblages and pollution in a harbour with two opposing

entrances. *Estuarine Coastal and Shelf Science* 60: 273-283.

Author Abstract. Conventional harbours, provided with only one entrance and devoid of channels, are enclosed areas with low water renewal, high sedimentation rate and high concentrations of pollutants in sediments; the soft bottom communities are characterised by low species richness and low values of the diversity and evenness indexes. The harbour of Ceuta, North Africa, presents an unusual structure since it is provided with two opposing entrances and a channel, which increase the water renewal across the middle of the harbour. These unusual characteristics turn the harbour of Ceuta into an adequate locality to test its environmental implications on macrofaunal assemblages. In the present study, the spatial distribution of mollusc community associated with soft bottoms was studied in relation to the influence of environmental factors on the harbour of Ceuta and nearby areas, North Africa. Twenty-one stations (15 inside and six outside the harbour) were sampled and 26 variables were measured in the sediment of each station: depth, % sand, organic matter, lipids, P, N, Al, As, B, Ba, Ca, Cd, Co, Cr, Cu, Fe, K, Li, Mg, Mn, Na, Ni, Pb, S, Sr, Zn. The special configuration of Ceuta Harbour created a great variability in sediment characteristics and environmental measures depending on the stations and, due to this heterogeneity, the mollusc species richness in the sediments inside the harbour (45 species) was higher than in conventional harbours. The multivariate approach based on MDS analysis was much more sensitive than univariate techniques to detect differences between internal and external stations of the harbour of Ceuta. The percentage of sand was the main factor to affect the distribution of the mollusc assemblages according to the BIO-ENV procedure and the CCA. SIMPER showed that the bivalves *Parvicardium exiguum, Ervilia castanea, Spisula subtruncata* and *Digitaria digitata* were the species that most contributed to the dissimilarity between internal and external stations; *P. exiguum, S. subtruncata* and *D. digitata* were more abundant in the internal stations whereas *E. castanea* was more abundant in the external stations. The bivalves *P. exiguum, Abra alba* and *Corbula gibba* and the opistobranch *Retusa obtusa* dominated in the most enclosed stations inside the harbour where sediments contained very high values of organic matter, lipids, and heavy metals. The data of the present study might assist in the building of new harbours in the future.

Heath, R. 1992. Nutrient dynamics in Great Lakes coastal wetlands: Future directions. *Journal of Great Lakes Research* 18:590-602.

Author Abstract. The most comprehensive investigations of N and P dynamics in Great Lakes coastal wetlands have been done at Old Woman Creek National Estuarine Research Reserve (OWC); whether OWC is a good general model of coastal freshwater wetlands remains to be shown. This wetland is probably a nutrient sink, storing P in sediments (at least temporarily) and releasing N by dissimilatory denitrification. Also, its biotic community transforms dissolved inorganic N and P inputs into organic dissolved and particulate outputs, thereby altering nutrient availability to Lake Erie communities. Nutrient dynamics in coastal wetlands probably differs greatly from that of inland marshes (where slow decomposition rates permit peat to accumulate as a nutrient sink) and estuaries (where high salinity alters sediment nutrient dynamics). A conceptual model specific for coastal wetlands is presented that accounts for the wide range of redox potentials encountered over the short vertical span of the shallow OWC wetland ecosystem. Future studies need to be conducted within the context of testable hypotheses generated from this model. Future investigations should focus attention on annualized nutrient budgets, sediment-water nutrient exchanges and their dependence on organic matter generated within the ecosystem.

Kennish, M. 2000. Ecology of Estuaries. Volume I: Physical and Chemical Aspects. CRC Press, Inc., Baca Raton, FL.

Editors Comments. Nearly all estuaries are characterized by highly variable physical and chemical conditions, which impose substantial physiological demands on populations that inhabit them. Consequently, successful organisms must have a broad tolerance in their requirements. Salinity gradients are typically large in estuaries from fresh water of rivers entering at their head to seawater of the nearshore ocean entering at their mouth. For some dissolved components, including oxygen, the nutrient elements nitrogen, phosphorus, and silicon, as well as many of the transition metals, spatial and temporal fluctuations in concentrations can be substantial. Seafloor sediments, in particular, show pronounced changes in certain physical-chemical parameters with increasing depth, such as redox potential (Eh), and oxygen depletion is usually rapid in near-surface layers. Physical factors – temperature, light, turbidity, currents, and wave action also vary abruptly in most estuarine systems.

Both salinity and temperature influence the density of estuarine waters, salinity more so than temperature. Density differences, in turn, drive water circulation and mixing processes. Wind-induced circulation is variable or intermittent. Interactive factors contribute to the complex circulation patters unique to estuaries.

Tides and tidal currents displace substantial volumes of water; both are modified extensively in estuaries compared with their properties in deeper oceanic waters. When resonance takes place between the tidal period of oscillation of an estuary, for example, tides and tidal currents increase in magnitude, sometimes by a large factor. The shoreline and bottom likewise strongly affect tidal currents by obstructing or constricting water flow, thereby altering circulation patterns. The release of energy from tidal currents transports sediments and various life-history stages of organisms and exerts forces on natural and manmade structures.

Llansó, R.J., L. C. Scott and F.S. Kelley. 2001. Chesapeake Bay water/quality monitoring program: Long-term benthic monitoring and assessment component level I comprehensive report. 82 pp. *Prepared by* Versar, Inc., 9200 Rumsey Road, Columbia, Maryland 21045, for Maryland Department of Natural Resources, Resource Assessment Service, Tidewater Ecosystem Assessments, Annapolis, MD.

Author Abstract. Benthic macroinvertebrates have been an important component of the State of Maryland's Chesapeake Bay water quality monitoring program since the program's inception in 1984. Benthos integrate temporally variable environmental conditions and the effects of multiple types of environmental stress. They are sensitive indicators of environmental status. Information on the condition of the benthic community provides a direct measure of the effectiveness of management actions. This report is the 18th in a series of annual reports that summarize data up to the current sampling year. Benthic community condition and trends in the Chesapeake Bay are assessed for 2001 and compared to results from previous years. A study to develop area-based restoration goals in relation to dissolved oxygen levels is included in this report.

McCall, P.L. and M.J.S. Tevesz (Eds). 1982. Animal-Sediment Relations: The Biogenic Alteration of Sediments. Plenum Press, New York.

The most extensive record available for the reconstruction of life on earth over the past seven hundred million years is preserved in ancient rocks and sediments on the bottom of rivers, lakes, and oceans. The interaction between the benthos – organisms that dwell on the bottom – and the sediment in which they live produces complex changes that affect the nature of the sediment, the sedimentary processes, and the ecology of all marine and freshwater environments. Benthic organisms burrow in the sediment for shelter and ingest it in search of food, causing changes in the composition of the sediment already deposited. The sedimentary bottoms act alternately as sources and sinks of nutrient elements and toxic materials; the sediment itself can become a major pollutant when suspended by waves and currents. This volume is the result of recent study of the nature of animal-sediment relations.

Matisoff, G. and J.P. Eaker. 1992. Summary of sediment chemistry research at Old Woman Creek, Ohio. *Journal of Great Lakes Research* 18:603-621.

Sediments are important at Old Woman Creek National Estuarine Research Reserve (OWC) and similar environments because suspended sediments provide a medium for the transport of many nutrients and toxic substances and bottom sediments may serve as either a sink or source of these substances, can influence estuarine productivity and water quality, can serve as substrates for much of the wetlands microscopic and macroscopic flora and fauna, and can contain a record of past conditions at the depositional site. Previous research at OWC has determined that the major sources of sediment supplied to the estuary are from soils and tills and the Berea Sandstone in the drainage basin. These sediments and their associated chemical species are primarily delivered to the estuary during storm events and the majority of the suspended sediment that washes into OWC is trapped and accumulates at the bottom of the estuary. Some postdepositional mobilization and sediment-water exchange of metals such as cadmium (downcore transport) and nutrients such as silica (release from sediments) has been observed and fluxes calculated. Groundwater seepage into the estuary varies with annual rainfall and is greatest near the estuary perimeter. Solute fluxes resulting from groundwater seepage are generally small compared to total fluxes as measured using bottom chambers. Benthic macroinvertebrates may contribute significantly to internal recycling. Both field measurements and computer simulations indicate that the water and solute budgets are controlled, in part, by a barrier sandbar which sometimes separates the estuary from Lake Erie.

Montagna, P. A., R. D. Kalke and C. Ritter. 2002. Effect of restored freshwater inflow on macrofauna and meiofauna in Upper Rincon Bayou, Texas, USA. *Estuaries* 25:1436-1447.

Author Abstract. Construction of two dams in 1958 and 1982 reduced freshwater inflow events to Rincon Bayou, part of the Nueces Delta near Corpus Christi, Texas, USA. Inflow reduction led to a reverse estuary, where low-salinity water flooded the delta on incoming tides and higher salinities were found near the Nueces River. Hypersaline conditions caused by high evaporation rates and low water levels were common during summer in the upper reaches. In October 1995, an overflow diversion channel was created by lowering the bank of the Nueces River to restore inflow events into the Rincon Bayou, which is the main stem creek that runs through the center of the Delta. Hypersaline conditions occurred four times from mid-1994 to mid-1997 and only once after mid-1997. Lower, rather than higher, salinity conditions were found after August 1997 in the upper reaches. Benthic faunal recovery was monitored by changes in macrofauna and meiofauna communities. Macrofauna responded to inflow events with increased abundances, biomass, and diversity but decreased during hypersaline conditions. Meiofauna abundance also increased with increasing inflow. Benthic characteristics were different in Rincon Bayou than in the reference site, upstream from introduced inflow. As inflow events have increased due to the diversion, the opportunities for positive responses to increased flow have increased. Although the overflow channel was filled in at the end of the demonstration project in the fall 2000, the City of Corpus Christi reopened the channel in the fall 2001 because the ecological benefits were credited toward the state-mandated minimum flow requirements for the Nueces Estuary.

Olafsson, E. 2003. Do macrofauna structure meiofauna assemblages in marine soft-bottoms? A review of experimental studies. *Vie et Milieu-Life and Environment* 53:249-265.

Author Abstract. During the past three decades a considerable number of studies have been conducted to reveal effects of macrofauna on meiofaunal assemblages in marine soft-bottoms. The aim of this review is to compile and summarize major findings of studies that have experimentally tested if a given macrofauna species affects some aspect of a meiobenthic assemblage. Altogether 77 studies on 44 macrofaunal species are reviewed. The bulk of the macrofaunal species are conspicuous members of the phyla Crustacea, Annelida and Mollusca, namely 20, 9 and 8 species respectively. Almost all the studies (86%) investigating biogenic structures of macrobenthos indicate some sort of effects on meiofaunal assemblages. Those studies in which diversity of a particular animal group has been considered, almost all agree on enhanced species diversity as a result of biogenic structures. The results of studies that have considered overall effects of macrofauna originating from processes such as predation, physical disturbance, competition for food and biogenic structures also indicate effects on meiobenthos. In only a few studies, researchers have used 3 or more density levels of disturbing macrofauna in their experimental manipulations, including natural levels, for the understanding of ecological rules behind biological disturbances. As biological disturbance created by macrofauna is incredibly variable among species and difficult to rate or categorise, it seems as yet difficult to apply theories to macrofaunal disturbance in general, predicting diversity or abundance patterns in meiofaunal assemblages.

Palmer, T. A., P. A. Montagna and R. D. Kalke. 2002. Downstream effects of restored freshwater inflow to Rincon Bayou, Nueces Delta, Texas, USA. *Estuaries* 25:1448-1456.

Author Abstract. In 1958 and 1982, two dams were built on the Nueces River that impeded freshwater flow to the Nueces Delta marsh. The result was the formation of a reverse estuary where salinity levels increased upstream instead of downstream as they would in a normal estuary. In 1995, channels were dug to restore freshwater flow to the marsh. Benthic organisms were monitored after the channels were dug to assess the effect of the change in hydrology. Results showed that freshwater pulses in the fall increased benthic productivity in the upper reaches of the restored area. The effect, however, only occurs in the fall when rain events are more frequent and flows of freshwater at other times of the year are too low to maintain freshwater conditions in the upper reaches of the estuary. The resulting wide ranges in salinity restricted the upper reaches of the marsh to short-lived, pioneer benthic species. Downstream areas of the marsh that exhibited smaller ranges in salinity levels had more diverse benthic communities.

Peterson, C.H., H.C. Summerson, E. Thomson, H.S. Lenihan, J. Grabowski, L. Manning, F. Micheli and G. Johnson. 2000. Synthesis of linkages between benthic and fish communities as a key to protecting essential fish habitat. *Bulletin of Marine Science* 66: 759-774.

Author Abstract. Several essential fish habitats lack the protections necessary to prevent degradation because of failure to integrate the scientific disciplines required to understand the causes of the degradation and failure to integrate the fragmented state and federal management authorities that each hold only a piece of the solution. Improved protection of essential habitat for demersal fishes requires much better synthesis of benthic ecology, fisheries oceanography, and traditional fisheries biology. Three examples of degraded habitat for demersal fishes and shellfishes are high-energy intertidal beaches, subtidal oyster reefs, and estuarine soft bottoms. In each case, both scientific understanding of and management response to the problem require a holistic approach. Intertidal beach habitat for surf fishes could be protected by constraints on the character of sediments used in beach nourishment and restriction of nourishment activity to biologically inactive seasons. Subtidal oyster-reef habitat for numerous crabs, shrimps, and finfishes could be protected and restored by reduction of nitrogen loading to the estuary and elimination of dredge damage to reefs. Estuarine soft-bottom habitat for demersal fin- and shellfishes could also be protected by reduction of the nutrient loading of the estuary, which could prevent associated problems of nuisance blooms and low dissolved oxygen. Although a broad general understanding of the nature of habitat degradation exists for each of these three examples, the interdisciplinary science needed to sort out the separate and interactive contributions of all major contributing factors is incomplete. Adopting the holistic approach embodied in the principles of ecosystem management sets a course for addressing both the scientific inadequacies and the management inaction.

Pickrill, R.A. and B.J. Todd. 2002. Sea floor mapping on the Scotian Shelf and the Gulf of Maine: Implications for the management of ocean resources. Symposium on the Effects of Fishing Activities on Benthic Habitats: Linking Geology, Biology, Socioeconomics, and Management. Tampa, FL. November 12-14, 2002.

Author Abstract. Multibeam sea floor mapping technologies have provided the capability to accurately, and cost effectively, image large areas of the seabed. Imagery provides base maps of sea floor topography from which targeted surveys can be planned to map sea floor sediments and associated benthic communities. Over the last five years extensive multi-disciplinary surveys have been carried out on Browns, German, and Georges Banks. The government of Canada entered into a partnership with the scallop industry to map bathymetry, surficial sediments and benthic communities. The new knowledge has been used by industry, and has implications for fisheries management. Associations between substrate type and benthic community composition have enabled precise maps of scallop habitat to be produced and links between scallop abundance and substrate to be established. The environmental and economic benefits have been immediate, with reduced effort to catch set quota, less bottom disturbance, and containment of fishing activity to known scallop grounds. Stock assessments and management practices are improved. Other pilot projects in Atlantic Canada and the northeastern USA have demonstrated the value of integrated sea floor mapping in designating marine protected areas (The Gully, Stellwagen Bank), in identifying offshore hazards such as landslides, in siting offshore structures, cables and pipelines, and in addressing environmental issues such as the routing of outfalls and disposal of dredge materials. In recognition of the power of these new tools and digital map products, Canada is considering development of a national mapping strategy to provide the foundation for sustainable ocean management in the 21st century.

Tung J. T. and P.A. Tanner 2003. Instrumental determination of organic carbon in marine sediments. *Marine Chemistry* 80:161–170

Author Abstract. Methodology is presented for the first completely instrumental determination of organic carbon (OC) in marine sediments, using a carbon–hydrogen–nitrogen (CHN) analyzer for total carbon (TC) content and diffuse reflectance infrared Fourier transform spectroscopy (DRIFTS) for in organic carbon IC) content. It utilizes direct calibration or standard addition in quantifying the carbonate combination and intensity at the energy near 2510 cm^{-1}. Since no OC standard reference materials are currently available, we have compared the results for OC from the proposed method with those from more tedious methods, involving wet chemistry. No significant difference was found with determinations, employing the CHN analyzer together with acid-extract analyses by (i) an inductively coupled plasma atomic emission spectrometer (ICP-AES) and (ii) a dissolved organic carbon (DOC) solution analyzer, with the decarbonation mass change being taken into account for the method (ii) involving acid addition. The proposed DRIFTS method is cheap, rapid, and nondestructive.

Vos, J.H., P.J. Van den Brink, E.P. Van den Ende, M.A.G. Ooijevaar, A.J.P. Oosthoek, J.F. Postma and W. Admiraal. 2002. Growth response of a benthic detritivore to organic matter composition in sediments. *Journal North American Benthological Society* 21:443-456.

Author Abstract. The biochemical composition of lake and stream sediments was analyzed and compared to growth and survival of detritivorous larvae of the midge *Chironomus riparius* (Meigen) to determine which biochemical parameters correlated most strongly with sediment food quality. Sediments were collected from soft bottoms of 41 water systems and fed to midge larvae. These sediments were analyzed for organic matter (OM) content, total C, N, and P, carbohydrates, proteins, fatty acids, pigments, and grain-size distribution. A microbial assay was used as an indicator of the fraction of easily biodegradable OM. Positive correlations of larval growth or survival with polyunsaturated fatty acids, pigments, and labile OM were found when these biochemical variables were standardized based on dry mass. When variables were standardized based on mass of OM, additional significant positive correlations between larval growth and P, carbohydrates, proteins, and fatty acids of bacterial origin were detected. Similarly, multivariate analyses revealed stronger correlations between larval growth and survival and biochemical variables standardized by OM compared to those standardized by dry mass. We postulate that dilution of OM by mineral particles caused the difference between the standardization methods. Organic matter content of sediments, particularly labile organic matter, appeared to strongly influence detritivore growth.

APPENDIX II: SOFT BOTTOM HABITATS
REVIEW OF TECHNICAL METHODS MANUALS

This Review of Technical Methods Manuals includes a variety of sampling manuals, Quality Assurance/Quality Control (QA/QC) documents, standardized protocols, or other technical resources that may provide practitioners with the level of detail needed when developing a monitoring plan for a coastal restoration project. Entries were selected through extensive literature and Internet searches as well as input from reviewers. As with the Annotated Bibliographies, these entries are not, however, a complete list. Entries are arranged alphabetically. Wherever possible, web addresses or other contact information is included in the reference to assist readers in easily obtaining the original resource. Summaries preceded by the terms '*Author Abstract'* or *'Publisher Introduction*' or similar descriptors were taken directly from their original source. Summaries without such descriptors were written by the authors of the associated chapter.

American Public Health Association. 1998. Standard Methods for Examination of Water & Wastewater. 20th ed. American Public Health Association, Washington, D.C.

Standard Methods for Examination of Water and Wastewater is an essential resource for any laboratory performing analysis on water samples whether they be for chemical or biological components. Procedures for the sampling of zooplankton, phytoplankton, periphyton, macrophytes, benthic macroinvertebrates, and fish are included as well as general identification keys to these organisms. Each procedure is explained in step-by-step detail with information on the strengths and weaknesses of various measurement methods. To a general practitioner, this resource would be useful to explain the chemical and biological components they are sampling, what the analysis entails, and the meaning of the final value obtained from each type of analysis. Various editions should be available at most any laboratory, scientific, or university library.

Bruce Thompson B., S. Lowe and M. Kellogg. 2000. San Francisco Estuary regional monitoring program for trace substances results of the benthic pilot study1994-1997: part 1–macrobenthic assemblages of the San Francisco Bay-Delta, and their responses to abiotic factors, 39 pp. San Francisco Estuary Regional Monitoring Program for Trace Substances Technical Report 39.

Author Abstract. The Benthic Pilot Study began in 1994 because the original RMP Base Program did not include any *in situ* biological indicators of contaminant effects, and such information was considered to be an important component of Bay assessments. Benthic sampling is a common component of most coastal and aquatic monitoring programs in the US. Benthos are monitored because they are a key component of the ecosystem that links sediments to the aquatic food web and provides food for bottom feeding fish and birds. Benthic organisms facilitate other important sediment functions, such as nutrient and carbon flux, by their burrowing and feeding activities. Most infaunal organisms are not very motile and must respond to a variety of natural environmental factors including changes in salinity, turbidity, and dissolved oxygen. Thus, benthos are considered to be reliable indicators of local sediment conditions. Understanding benthic responses to natural environmental fluctuations is essential before assessment of effects from anthropogenic factors (e.g., diversions of freshwater inflows, dredging, contamination, of introduced species) can be made.

The objective of the Benthic Pilot Study was to evaluate the use of benthic information for determining environmental conditions in the Estuary. The results of the RMP Benthic Pilot Study are reported in two Parts. Part 1 describes the distribution of the benthic assemblages identified in the Bay and Delta, the species composition and abundances of these assemblages, and shows the influences of variable Delta outflow, salinity, and sediment-type on them. The Benthic Pilot Study was a collaborative study including data from the RMP, Department of Water Resources, Bay Area Discharger's Association, and the Bay Protection and Toxic Clean-up Program.

Environment and Natural Resources Institute. 2002. Quality assurance project plan, 59 pp. Alaska Biological Monitoring and Assessment Program, Anchorage, AK. http://www.uaa.alaska.edu/enri/bmap/pdfs/ENRI_QAPP_2-02.pdf

This quality assurance project plan (QAPP) is designed for use in collecting data to assess wadable streams in Alaska focusing on the collection of benthic invertebrates and chemical water quality parameters. It can be used by practitioners restoring and monitoring other coastal habitats as a template of the types of information and level of detail required for a QAPP. QAPPs are important documents for any monitoring effort to have readily available. They are used by to ensure that data are collected in a comparable and consistent fashion regardless of who is obtaining the sampling. Some of the topics included in this QAPP include the identification of responsible parties; procedures for properly selecting sample locations and reference conditions; the collection, handling, and preservation of biological and chemical samples; methods to analyze samples and record data; data management; contingency plans for foreseeable mistakes and accidents; and methods to verify and validate the accuracy of data. Example data sheets and procedures for using specific types of equipment are also included.

Folk, R.L. 1980. The Petrology of Sedimentary Rocks. Walter Geology Library, Web Version 1.0. http://www.lib.utexas.edu/geo/FolkReady/folkprefRev.html

This paper is an out-of-print classic in the field of sedimentary rocks and the interpretation of grain size. For estuary and wetland restoration, the important chapters are on properties of sedimentary rocks and the collection and preparation of samples for analysis.

Gibbons, W.N., M.D. Munn and M.D. Paine. 1993. Guidelines for monitoring benthos in freshwater environments, 81 pp. Report prepared for Environment Canada, North Vancouver, B.C. by EVS Consultants, North Vancouver, B.C.

Historically, benthic invertebrates have been viewed as useful organisms for evaluating environmental impacts on aquatic systems (freshwater and marine) (Klemm et al., 1990; Rosenberg and Resh, 1993). They are relatively sedentary organisms, and are sensitive to changes in sediment and water quality. Benthic communities also reflect the cumulative effects of present and past conditions, because they have low mobility and life cycles of several weeks to years (Wilhm, 1975). Their ecological relationships are relatively well understood (Herricks and Cairns 1982), and they are the major food source for many fish species. For these reasons, sampling benthic communities is regarded as a cost-effective means of assessing the aquatic environment. Although benthos monitoring programs have been conducted for decades (Cairns and Pratt, 1993), in Canada there has been little effort to standardize the wide array of methods and approaches used.

As a first step in achieving standardization, Environment Canada and EVS Consultants hosted a technically-based workshop on benthos monitoring (Gibbons and Booth 1992) to attempt to develop a consensus on the approach to be used when undertaking benthic invertebrate studies (as an environmental monitoring tool) in freshwater environments. The document represents the first stage in the development of a protocol for freshwater benthos monitoring for the purpose of environmental assessment.

Llanso, R.J., L.C. Scott, D.M. Dauer, J.L. Hyland and D.E. Russell. 2002. An estuarine benthic index of biotic integrity for the Mid-Atlantic region of the United States. I. Classification of assemblages and habitat definition. *Estuaries* 25:1219-1230.

Author Abstract. An objective of the Mid-Atlantic Integrated Assessment Program (MAIA) of the U.S. Environmental Protection Agency is to develop an index for assessing benthic community condition in estuaries of the mid-Atlantic region of the United States (Delaware Bay through Pamlico Sound). To develop such an index, natural unimpaired communities must first be identified and variability related to natural factors accounted for. This study focused on these two objectives; Llanso et al. (2002) describe the index. Using existing data sets from multiple years, classification analyses of species abundance and discriminant analysis were employed to identify major habitat types in the MAIA region and evaluate the physical characteristics that structure benthic infaunal assemblages. Sampling was restricted to soft bottoms and to the, index development period, July through early October. The analyses revealed salinity and sediment composition as major factors structuring infaunal assemblages in mid-Atlantic estuaries. Geographical location was a secondary factor. Nine habitat classes were distinguished as a combination of 6 salinity classes, 2 sediment types, and the separation of North Carolina and Delaware-Chesapeake Bay polyhaline sites. The effect of sediment types on faunal assemblages was restricted to polyhaline sites, which were separated into two sediment groups above and below 90% sand content. Assemblages corresponding to each of these 9 habitats were identified in the context of widely recognized patterns of dominant taxa. Differences between North Carolina and Delaware-Chesapeake Bay polyhaline assemblages were attributed to the relative contributions of species and not to differences in species composition. No zoogeographic discontinuities could be identified. Our results reinforce the findings of recent studies which suggest that, with respect to estuarine benthic assemblages, the boundary between the Virginian and the Carolinian Provinces be moved to a new location south of Pamlico Sound.

Merritt, R. W. and K. W. Cummins, (eds.). 1996. An Introduction to the Aquatic Insects of North America. Third edition ed. Kendall/ Hunt Publishing Company, Dubuque, IA, USA.

While the bulk of Merritt and Cummins is on identification of aquatic insects of North America, they include several chapters useful in project planning as well. Various experts in the field of aquatic insect collection and identification have submitted chapters on: the general morphology of aquatic insects, designing studies, collection techniques, aquatic insect respiration, habitat and life history, and the ecology and distribution of aquatic insects. The rest of the manual is devoted to identification keys for each family of aquatic insect found in North America with many detailed and useful pictures of identifying characteristics.

Since this book is continental in scope, it is suggested that practitioners first look for identification keys prepared for their local or regional waterways. This will reduce much confusion in the identification process by eliminating species that are not found locally. Any local aquatics expert or science librarian should be able to locate these materials. If local materials are not available, then Merritt and Cummins will be useful, however, be sure to check the distribution of species identified whenever possible.

Polhe, G.W. and M.L.H. Thomas. 2001. Monitoring protocol for marine benthos: Intertidal and subtidal macrofauna. 32 pp. A report by the Marine Biodiversity Monitoring Committee (Atlantic Maritime Ecological Science Cooperative, Huntsman Marine Science Centre) to the Ecological Monitoring and Assessment Network of Environment Canada, Environment Canada, St. John's, Newfoundland, Canada. http://www.eman-rese.ca/eman/ecotools/protocols/marine/benthics/intro.html

This report recommends guidelines for sampling, sample processing, and data analysis of marine benthos to establish uniformity in procedures that will make data from different investigations more readily comparable. Decisions on the methodology, equipment and analysis will depend on the particular aims of a study, on the nature of the habitat involved, on the staff and facilities available, and on historical or personal preferences. The report consideration is limited to the inter- and subtidal zoobenthos macrofauna, comprising the burrowing fauna (infauna) and surface living fauna (epifauna) retained in a 0.5 mm mesh, and excluding the smaller interstitial meiofauna (small metazoans), microfauna (protozoans and organisms of bacteria size) and the phytobenthos which all require special techniques.

Poppe, L.J., A. H. Eliason, J. J. Fredericks, R. R. Rendigs, D. Blackwood and C. F. Polloni. 2000, Grain-size analysis of marine sediments: methodology and data processing: U.S. Geological Survey Open-File Report 00-358. http://pubs.usgs.gov/of/of00-358/text/contents.htm

Grain size is the most fundamental physical property of sediment. Geologists and sedimentologists use information on sediment grain size to study trends in surface processes related to the dynamic conditions of transportation and deposition; engineers use grain size to study sample permeability and stability under load; geochemists use grain size to study kinetic reactions and the affinities of fine-grained particles and contaminants; and hydrologists use it when studying the movement of subsurface fluids. Therefore, with these reasons in mind, the objectives of a grain-size analysis are to accurately measure individual particle sizes or hydraulic equivalents, to determine their frequency distribution, and to calculate a statistical description that adequately characterizes the sample.

The techniques and equipment used for particle-size analysis must be fast, accurate, and yield highly reproducible results. The accuracy of these measurements is limited by sampling techniques, storage conditions, analytical methods, equipment, and, especially, the capability of the operator. Care and attention to detail must be exercised to achieve the best possible results. As with most types of sedimentological analyses there is no ultimate technique or procedure that will produce the most desirable grain size data for all cases. Several types of analyses have been developed over the years to accommodate the different types and sizes of samples and the reasons for conducting the analysis

Rosenberg, D. M., I. J. Davies, D. G. Cobb and A. P. Wiens. 2001. Protocols for measuring biodiversity: benthic macroinvertebrates in fresh waters. Ecological Monitoring and Assessment Network Coordinating Office, Knowledge Integration Directorate of Environment Canada. http://www.eman-rese.ca/eman/ecotools/protocols/freshwater/benthics/intro.html

Partial Author Introduction: The collection of benthic macroinvertebrates from lakes and streams is usually a straightforward procedure using standard equipment. However, the removal of organisms from background material can be tedious and time-consuming unless available labor-saving strategies are used (see below) and the identification of organisms to the species level, when possible, requires substantial training and skill. The processing of samples can be successfully accomplished by non-specialists, but the involvement of systematists is recommended for species-level identifications. Data-analysis procedures are standard, and can be done by anyone trained in elementary statistics. The following account describes sampling methods for benthic macroinvertebrates in lotic (stream) and lentic (lake) habitats, valuable ancillary information, different analytical paths to follow, and techniques for efficient operation in the field and laboratory.

U.S. EPA. 1987. Recommended protocols for sampling and analyzing subtital benthic macroinvertebrate assemblages in Puget Sound. U.S. Environmental Protection Agency Region 10 Office of Puget Sound and Puget Sound Water Quality Authority. http://www.psat.wa.gov/Publications/protocols/protocol_pdfs/benthos.pdf

Recommended methods for sampling and analyzing subtidal soft-bottom benthic macroinvertebrate assemblages in Puget Sound are presented in this chapter. The methods are based on the results of a workshop and written reviews by representatives from most organizations that fund or conduct environmental studies in Puget Sound. The purpose of developing these recommended protocols is to encourage all Puget Sound investigators conducting monitoring programs, baseline surveys, and intensive investigations to use standardized methods whenever possible. If this goal is achieved, most data collected in the Sound should be directly comparable, and thereby capable of being integrated into a sound-wide database. Such a database is necessary for developing and maintaining a comprehensive water quality management program for Puget Sound.

Before the recommended protocols are described, a section is presented on study design considerations. This section discusses some major elements of the design of subtidal benthic macroinvertebrate studies that were considered at the workshop but left unresolved. Following this initial section, specifications are provided for the field, laboratory, quality assurance/quality control (QA/QC), and data reporting procedures that are recommended for most future benthic macroinvertebrate studies in Puget Sound.

U.S. EPA. 2001. Methods for collection, storage, and manipulation of sediments for chemical and toxicological analyses: technical manual, EPA/823/B-01/002. Office of Water. http://www.epa.gov/waterscience/cs/collection.html

It is now widely known that the methods used in sample collection, transport, handling, storage, and manipulation of sediments and interstitial waters can influence the physicochemical properties and the results of chemical, toxicity, and bioaccumulation analyses. Addressing these variables in an appropriate and systematic manner will help assure more accurate sediment quality data and facilitate comparisons among sediment studies.

This Technical Manual provides current information and recommendations for collecting and handling sediments for physicochemical characterization and biological testing, using procedures that are most likely to maintain *in situ* conditions, most accurately represent the sediment in question, or satisfy particular program needs, to help ensure consistent, high quality data collection

U.S. EPA. 2001. National coastal assessment: field operations manual. EPA 620/R-01/003, 72 pp., U. S. Environmental Protection Agency, Office of Research and Development, National Health and Environmental Effects Research Laboratory, Gulf Ecology Division, Gulf Breeze, FL. http://www.epa.gov/emap/nca/html/docs/c2kfm.pdf

This manual presents a standard set of field data and sample collection techniques for the EPA's National Coastal Assessment, the current state of the EPA's Environmental Assessment Program (EMAP). Though the methods collected here are geared specifically toward this program, some restoration practitioners may find them useful particularly in areas where restoration projects overlap existing monitoring activities, as this will facilitate the comparison of current data with historic trends. The measurement protocols described in this manual include:

- sediment contaminant concentrations
- sediment toxicity
- benthic species composition
- sediment characteristics
- water column dissolved nutrients
- chlorophyll *a* concentrations
- total suspended solids
- surface and bottom dissolved oxygen, salinity, temperature, and pH
- water clarity
- contaminant levels in fish and shellfish
- external pathological condition of fish
- fish community structure

A suggested monitoring routine is presented for data collection at each site to maximize sampling efficiency while in the field. Of particular use to the beginning restoration-monitoring practitioner, a list of necessary field and laboratory equipment is also provided in an appendix.

U.S. EPA. 2001. Volunteer Estuary Monitoring: A Methods Manual. United States Environmental Protection Agency, Office of Water. http://www.epa.gov/owow/estuaries/monitor/

Partial author abstract. This document presents information and methodologies specific to estuarine water quality. The first eight chapters of the manual deal with typical issues that a new or established volunteer estuary monitoring program might face:

- understanding estuaries, what makes them unique, the problems they face, and the role of humans in solving the problems
- establishing and maintaining a volunteer monitoring program
- working with volunteers and making certain that they are well-positioned to collect water quality data safely and effectively
- ensuring that the program consistently produces data of high quality, and
- managing the data and making it available to data users

The remaining chapters focus on several water quality parameters that are important in determining the health of an estuary. These chapters are divided into three units, which characterize the parameters as measures of the chemical, physical, or biological environment of the estuary.

The significance of each parameter and specific methods to monitor it are detailed in a step-by-step fashion. The manual stresses proper quality assurance and quality control techniques to ensure that the data are useful to state agencies and any other data users.

References are listed at the end of each chapter. Appendices containing additional resources are also supplied. These references should prove a valuable source of detailed information to anyone interested in establishing a new volunteer program or a background resource to those with already established programs.

APPENDIX III: LIST OF SOFT BOTTOM HABITAT EXPERTS

The expert listed below has provided his contact information so practitioners may contact him with questions pertaining to the restoration or restoration monitoring of this habitat. Contact information is up-to-date as of the printing of this volume. The list below includes only those experts who were 1) contacted by the authors and 2) agreed to submit their contact information. In addition to this resource, practitioners are encouraged to seek out the advice of local experts as well faculty members and researchers at colleges and universities. Engineering, planning, and landscape architecture firms also have experts on staff or contract out the services of botanists, biologists, ecologists, and other experts whose skills are needed in restoration monitoring. These people are in the business of providing assistance in restoration and restoration monitoring and are often extremely knowledgeable in local habitats and how to implement projects on the ground. Finally local, state, and Federal environmental agencies also house many experts who monitor and manage coastal habitats. In addition to the National Oceanic and Atmospheric Administration (NOAA), the Environmental Protection Agency (EPA), the Army Corps of Engineers (ACE), Fish and Wildlife Service (FWS), and the United States Geologic Survey (USGS) are important Federal agencies to contact for assistance in designing restoration and monitoring projects as well as potential sources of funding and permits to conduct work in coastal waterways.

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CHAPTER 8: RESTORATION MONITORING OF SOFT SHORELINE HABITATS

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Jose L. Vargas Poncini, Spanish Ministry of Environment[2]

INTRODUCTION

Soft shoreline habitats are composed of soft substrates such as mud, sand, and gravel found along the coast. According to Cowardin et al. (1979), these habitats are composed of unconsolidated substrates with less than 75 percent areal cover of stones, boulders, or bedrock and less than 30 percent vegetative cover other than pioneer species. For the purpose of this document, habitats composed of cobble-gravel will not be addressed. This chapter primarily discusses sandy beaches, mudflats, and sandflats.

SANDY BEACHES

Sandy beaches (Figure 1) are land covered by loose material with minimal vegetation, extending landward from the low water line to the place where there is distinct change in material or physical features (Brown et al. 1990; Finkl 2004; USEPA 2004a).

Beaches are influenced by various environmental factors including changes in oceanic and riverine activity as well as ocean salinity. For example, the natural erosion process caused by waves and tides influences the physical features of beaches. These factors are responsible for the extraordinary high hydric deficit (minimum moisture levels) of such beaches. These environmental factors also make a sandy beach one of the most inhospitable places for life forms (Marquinez Garcia et al. 2003).

Vegetation found along sandy beaches is also minimal because plant seeds are not able to settle and establish themselves. However, plant species living in habitats immediately connected with beaches such as dunes include:

Beach wild rye (e.g., *Leymus mollis*)
Beach bur (e.g., *Franseria chamissonis*)
Black sage (e.g., *Salvia mellifera*), and
Beach salt bush (e.g., *Atriplex leucophylla*)

Figure 1. Sandy beaches on Midway Island in the Pacific Ocean. Photo courtesy of NOAA Office of Response and Restoration.

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[2] Fulbright Fellow. NOAA Office of Response and Restoration, 1305 East West Highway, Silver Spring, MD 20910..

Organisms primarily found in beach habitats include:

Amphipods
Crustaceans
Polychaetes, and
Bivalves

Sandy beaches and other soft shoreline habitat types not only support plants and animals by providing shelter, breeding, nursery, and feeding grounds, but these habitats, particularly beaches, support many tourist-related activities. Florida, California, Virginia, Hawaii, the Caribbean, and other parts of the world have developed hotels, resorts (Figure 2), and vacation homes along beach waterfronts that assist in increasing the tourist industry (discussed further in Chapter 14 - Human Dimensions of Coastal Restoration). Beach-related activities that generally support coastal tourism include:

- Marinas
- Recreational fishing
- Water sports (e.g., using jet skis and canoes)
- Beach sports (e.g., volleyball)
- Restaurants and bars
- Snorkeling
- Kayaking
- Sun bathing (Figure 3), and
- Viewing of marine mammals, waterfowl, and shorebirds

Although sand dunes are not discussed in detail in this chapter, it is important to understand the close link dunes have with sandy beaches (Figure 4).

The first stage of dune construction is the embryonic dune, sometimes known as "yellow dune" or primary dune (Figure 5). Yellow dunes develop closest to the beach and form by ripples or raised sand surfaces of the upper beach or by a seaward fringe at the foot of tall dunes (The European Habitats Directive: Natura 2000 code 2110[3]).

The next phase of dune construction is commonly known as "white dune" or secondary dune (Figure 5), and is typically characterized by the presence of European beachgrass (*Ammophila arenaria*). This species has been introduced on the West coast of the United States to help stabilize sand on dunes and beaches since the

Figure 2. Public boat ramps allow easy access to recreational fisheries. Photo courtesy of W.B. Folsom, NOAA National Marine Fisheries Service. http://www.photolib.noaa.gov/fish/images/big/fish1125.jpg

Figure 3. Sun bathers on a sandy beach along the Northern Shore of Oahu, Hawaii. Photo courtesy of Andrew Mason, NOAA National Centers for Coastal Ocean Science.

[3] The "Habitats" Directive (Council Directive 92/43/EEC of May 21, 1992 on the conservation of natural habitats and of wild fauna and flora) is a European Union legislative instrument that establishes a common framework for the conservation of wild animal and plant species and natural habitats. One of its main products is the creation of a network of special areas of conservation, called Natura 2000, to "maintain and restore, at favorable conservation status, natural habitats and species of wild fauna and flora of Community interest" (EEC 1992).

Figure 4. Beach and dunes in the Cantabric Sea. La Lanzada Beach, Pontevedra, Spain. Photo courtesy of Spanish Ministry of Environment.

early 1900s (Knudson 1917; Barbour and Johnson 1977; Crook 1979a, b). This invasive species has threatened coastal sand dunes in the eastern and western United States, displacing native dune species and significantly altering the morphology of dune systems that it invades. White dunes are considered the first "true" stage of a real dune, which contributes to the landscape consisting of sand hills (i.e., cordons of dunes).

MUDFLATS AND SANDFLATS

Mudflats and sandflats (Figure 6) can be found around the high or low watermarks in tidal and intertidal zones. These habitat types develop along gently sloping coastal areas where sediment is available, in areas without strong wave action, and in moderately sheltered coastal inlets and bays where diurnal tides are present (i.e., covered twice daily by tides) (Brown et al. 1990; Hardie and Shinn 1986; Morelock 2000).

There are many sources that provide a good description of mudflats and sandflats such as the European Economic Community's (EEC) "Natura 2000" Habitat Network. The general description of these habitats is that it:

- Consists of fine-grained sediment (sand and mud)
- Connects to seas and/or associated lagoons, and
- Is not covered by sea water at low tide

These habitat types are widely distributed along both coasts of the United States; the Atlantic coast of Europe, particularly around the North Sea; and other parts of the world. Mudflats and sandflats *constantly* covered by water at low tide are not discussed in this chapter but are discussed in Chapter 7 - Restoration Monitoring of Soft Bottom Habitats. Chapter 9 - Restoration Monitoring of Submerged Aquatic Vegetation, Chapter 10 - Restoration Monitoring of Coastal Marhes, and Chapter 11 - Restoration Monitoring of Mangroves also refer

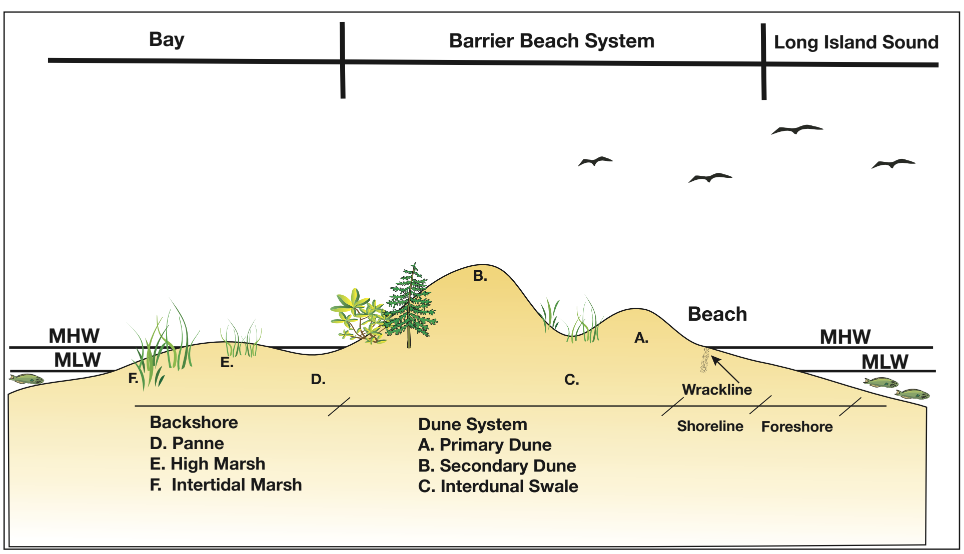

Figure 5. Cross-section of an idealized beach, dune, and marsh system, including the different types of dunes (A, B) adjacent to the shoreline, where beaches are situated. Drawing modified from USEPA Long Island Sound Office.

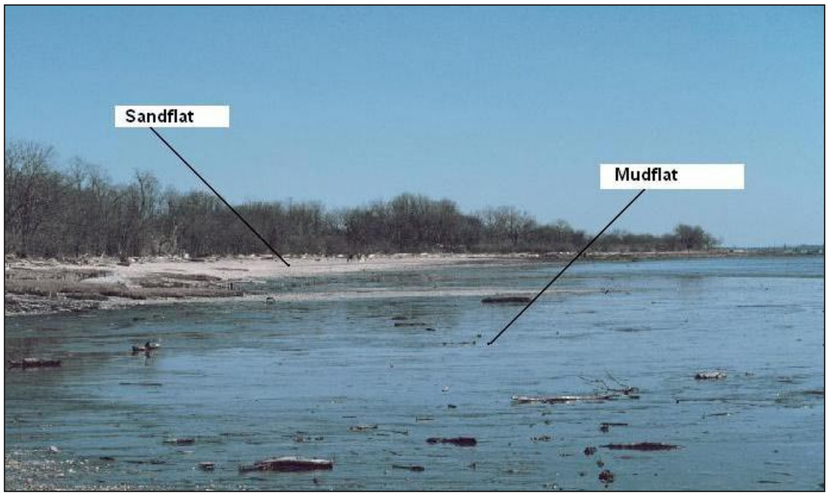

Figure 6. Mud and sand flats of the Delaware River. Photo courtesy of NOAA Restoration Center. NOAA Central Library http://www.photolib.noaa.gov/habrest/r0020104.htm

to soft shoreline habitats because of their close linkage to these habitat types. Soft shoreline habitats for instance provide the substrate upon which marsh, dune, and mangrove vegetation develop.

Mudflats

Mudflats are found in low energy coastal environments and consist mainly of silts, clays, and some sand particles, and they often contain high organic content. Larger mudflats are found in estuaries where the riverine dynamic is lower allowing fine grained sediments to settle. Where there is a strong riverine dynamic, mudflats are created only within the most inner parts of estuaries and in areas adjacent to channels (Marquinez et al. 2003). In areas toward the mouth of estuaries where salinity and wave energy are higher, however, the amount of sand increases, therefore sandflats are more likely to develop.

Mudflats are linked by physical processes and may be dependent on other coastal habitats which help provide sediment such as soft cliffs. These soft cliffs commonly appear in the natural sequence of habitats between subtidal channels and vegetated salt marshes. In large estuaries, mudflats can be several miles wide and commonly form the largest part of the intertidal area of estuaries. For example, about 531,000 hectares of tidal estuarine wetlands exist in Great Britain of which 267,800 hectares are tidal sandflats and mudflats (Davidson and Buck 1997).

Although mudflats are not as popular as beaches with regard to tourist activities, they are very important to the ecological community because they provide rich organic matter for plants and animals to utilize as food. Important plant species found in muddy habitats and other associated habitats include:

- Seagrass (e.g., *Spartinia anglica* and *Zostera* spp.)
- Blunt spike rush (e.g., *Eleocharis obtusa*)
- Bull rush (e.g., *Scirpus* spp.), and
- Mangroves (e.g., *Avicennia* and *Rhizophora*)

Organisms commonly found in mudflats include:

- Molluscs (e.g., oysters and mussels)
- Annelids (e.g., worms), and
- Anthropods (crabs and shrimp) (Moore et al. 1968; Peterson and Peterson 1979)

Different species of birds feed and/or nest in these habitats. For instance, wading birds such as great egret (*Casmerodius albus)* and great blue heron (*Ardea herodias*) feed on small fish, while shorebirds such as clapper rail (*Rallus longirostris)* and piping plover (*Charadrius semipalmatus*) feed on amphipods and insects found on the sediment surface (Soots and Parnell 1975; Recher 1966).

Sandflats

Sandflats tend to develop towards the outer, more exposed shores and offshore banks and bars. They provide substrates that support marsh vegetation in estuaries and other tidal inlets. Sandy foreshores act as constructive pathways that assist in the formation of sand dunes (Doody 2003). The larger sand flats in bigger estuaries are created mainly near the mouth of estuaries, where the high riverine dynamic is more favorable for course-grained (e.g., sand) deposition than fine sediment (e.g., mud) deposition (Marquinez et al. 2003).

HUMAN IMPACTS TO SOFT SHORELINE HABITATS

Soft shoreline habitats experience tremendous pressures from human-induced impacts in the coastal zone, including:

- Habitat loss
- Reduced sediment supply due to erosion
- Changes in sediment patterns
- Changes in wave patterns
- Pollution
- Increased nutrient loads
- Sea level change, and
- Harvesting of animals (e.g., lugworms for fishing)

These impacts can be categorized into three groups: physical disturbances, coastal erosion, and pollution.

Physical Disturbance

Many areas along soft shores are exposed to disturbances as a result of construction during coastal development (Burger 1988). On mudflats in New Jersey, for example, birds moved farther along the beach and out onto mudflats when construction activities and demolition took place. As a result, bird populations were altered and other mobile animals migrated to more suitable areas. In addition, sessile or slow moving organisms in the area under construction were killed during the process, thus resulting in reduced numbers of certain benthic species.

In areas where ports and other industrial-related development is involved, large expanses of tidal flats can be destroyed. Dams, offshore sand extraction, maintenance dredging (in estuaries), and protection of eroding cliffs can reduce both sediment supply to the coast and high erosion rates. Offshore structures such as breakwaters can also restrict long-shore drift as well as change sediment and wave patterns. The construction of artificial barriers (Figure 7) may restrict tidal flow, thereby destroying tidal flats and negatively affecting plant growth and animals that rely on these habitats for food (Davidson et al. 1991).

In some cases, increased urbanization (e.g., as a result of hotels, marinas, water sports, etc.) on exposed sandy beaches can cause detrimental effects to animals living in this habitat such as the disruption and damage to bird nesting areas and crustaceans for ghost crabs (*Ocypode cordimana*) (Barros 2001). Researchers have observed that the number of burrows made by ghost crabs was fewer on urban beaches than on non-urban beaches. Thus, urbanization along beaches destroys habitats for crabs and other species of animals occupying the shoreline and causes a decline in the number of organisms (Barros 2001). Human trampling and use of off-road motor vehicles also disturbs and in some cases kills benthic communities. For example, trampling and motor vehicles may completely uproot plants from the sediment or damage the plant structure, thereby disrupting its normal growth process. Many of these organisms are food sources for other species such as birds or fishes. If the habitat is disturbed and the

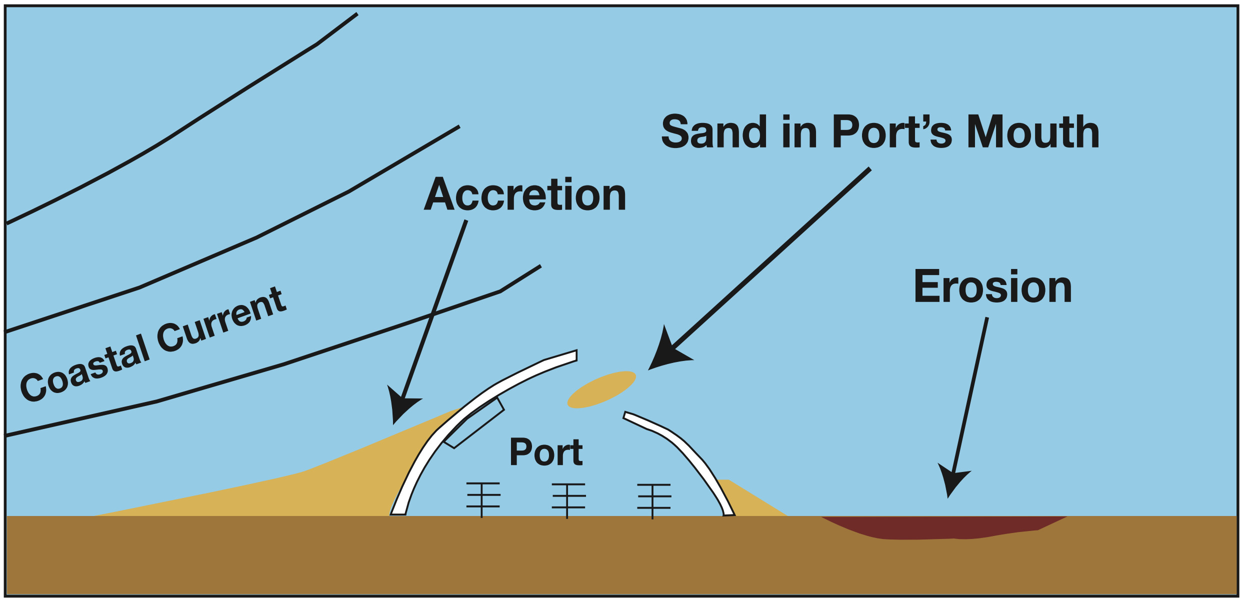

Figure 7. An artificial barrier interrupts coastal currents, thus interrupting the transportation of sand along the near shoreline. Diagram courtesy of the Spanish Ministry of Environment.

number of benthic organisms is significantly reduced, then there may be a shift in fish or bird populations within that specific area.

Mechanical devices used for cleaning beaches can unintentionally destroy soft shoreline habitats by disturbing the vegetative growth on areas of the beach closest to dunes. For example, mechanical beach raking can be harmful to aquatic vegetation, nesting birds, sea turtles, and other types of aquatic life. Beach raking not only prevents the natural re-vegetation process, but also uproots the very few species of plants that colonize sandy habitats, therefore causing the shore to be more vulnerable to erosion (USEPA 2004b).

Coastal Erosion

Coastal erosion is one of the largest socio-economic problems that challenge states and localities. It is always accompanied with shoreward recession of the shoreline and loss of land area. Erosion can cause significant economic losses, social problems, and ecological damages. The problem of erosion may extend hundreds of kilometers along large deltas and may have transboundary implications. In the United States, beach erosion is caused primarily by human-induced sand removal from beaches. Activities that involve the removal of sand include dredging of ship cannels without sand bypassing (i.e., placing sand from where it was originally removed) and sand entrapment by jetties (i.e., rock walls built to keep sand from entering ship channels), groins[4] seawalls, and dams. Construction of ship channels in Port Canaveral, Florida is an example of sand removal from beaches when the dredged sand is not bypassed (Douglas 2002). Throughout the construction of this channel, more than eight million cubic yards were dredged and dumped in deep waters away from the beach. Additional sand was dredged each year to maintain the depths needed for ship clearance (Douglas 2002). Severe beach erosion was also seen on Assateague Island in Ocean City, Maryland as a result of inlet jetties. A sufficient amount of sand was trapped on the updrift[5] side of the jetty and deposited in deep water, resulting in severe erosion and destruction of the downdrift[6] of the barrier island (Douglas 2002).

[4] A low artificial wall-like structure extending from the land to seaward to prevent coast erosion.
[5] The opposite direction to the main long shore movement of beach material.
[6] The main direction in which shoreline materials such as sand are moved.

In other areas outside the United States such as the Mediterranean, coastal erosion has been a longstanding, large-scale issue around the deltaic areas (e.g., the Nile and Po River deltas, and smaller deltas such as for the Albanian River). It has also been a major issue at smaller scales, especially at the municipal and tourist resort beaches along the more densely developed northern Mediterranean coast, following the flux of people to the coast and the sudden increase of the tourism industry. According to the *Atlas of the Italian Beaches* (Fierro and Ivaldi 2001), 27 percent of the Italian beaches - which constitute 61 percent of the Italian coastline - are receding, 70 percent are in equilibrium, and only 3 percent are expanding as a result of sediment deposition or accumulation (i.e., prograding). In pocket beaches however, it could be a local phenomenon affecting only local residents and/or the tourism industry (Özhan 2002).

Pollution

Pollution as a result of industrial discharges can also impact plants and animals along soft shores. For instance, chemicals in industrial discharges can affect meiofauna in mudflats (Mohd Long 1987). A study showed that the density of meiofauna was significantly lower nearest the points of discharge, closest to the shore. Organochlorine pesticide residue runoff was also found in mudflats in Texas where wintering shorebirds are found. Pesticide residues including dichlorodiphenyldichloroethylene (DDE), dieldrin, and toxaphene were detected on shorebirds. Ninety-five percent of shorebirds were exposed to some level of DDE, 13 percent were exposed to dieldrin, and 22 percent were exposed to toxaphene. Levels of DDE increased in all shorebirds from October to December, with potentially hazardous levels accumulating in some long-billed dowitchers (*Limnodromus scolopaceus*) and American avocets (*Recurvirostra americana*) (White et al. 1983). In addition, pesticide residues and other agricultural chemicals may be potentially dangerous to birds and other organisms by inhibiting them to feed and grow, which can result in high mortality rates.

Freshwater flows due to human activities and discharges of sewage effluents may also affect animal and plant communities by reducing environmental quality, such as altering salinity levels and nutrient regimes (Lercari and Defeo 2003). Studies have shown that freshwater canal discharges can negatively affect resident macrobenthos on an exposed sandy beach by lowering salinity, beach width, swash width, and slope. Macrobenthos abundance, biomass, species richness, diversity, and evenness were also significantly reduced closest to the source of disturbance and in areas where salinity was lower (Lercari and Defeo 2003).

Hazardous substance spills can also significantly impact beach communities. Oil spills that occur on beaches, for instance, may negatively affect animals such as birds, crustaceans, and invertebrates that utilize this habitat. In some cases, birds may be covered with oil while attempting to feed on marine organisms in oil-contaminated shallow waters. Once covered with oil, birds become exhausted because of the excess energy they exert while trying to free themselves from the oil-contaminated water. As a result, mobility is often reduced and their bodies subside, causing them to drown.

One of the most well known oil spill events is the *Exxon Valdez* oil spill in Prince William Sound, Alaska in 1989 (Peterson 2000). This spill event negatively affected animal and plant species in many shoreline habitats including sandy beaches and sandflats (Peterson 2000). Following the oil spill, scavenging terrestrial birds such as bald eagles and northwestern crows in the intertidal zone either died or experienced reproductive losses; pigeon guillemots showed reduced feeding on organisms such as sand eels and capelin, and therefore migrated to more suitable feeding areas (Peterson 2000).

Figure 8. Dredgers throwing sand into a nourishment restoration project. Photo courtesy of Bert Visser's Directory of Dredgers. http://www.dredgers.nl

RESTORATION EFFORTS

Restoration efforts for beaches involve beach fills and cleanup, as well as sand nourishment (Figure 8) particularly in eroded areas. Beach nourishment is a method to counteract beach erosion by dredging sand from offshore and then pumping it onto the beach (Nelson 1993). This process, however, may not always be favorable to the ecosystem and may result in short-term decline in animal numbers, biomass, and diversity (Peterson et al. 2000; Rumbold et al. 2001). Nourishment, referred to here, is performed to restore eroded beaches closest to its natural state. Other types of nourishment include:

- Recycling shingle[7] (i.e., coarse gravel) and/or sand by accumulating material and moving it from the accumulated area to the eroding area
- Bypassing sediment, sand, shingle, and
- Using dredged material to re-create tidal sandflats/mudflats and/or create saltmarshes

Such restoration efforts can be expensive and may require funding from various sources. For example, government agencies such as the National Oceanic and Atmospheric Administration (NOAA) provide funding and scientific expertise to help protect, manage, and restore coastal and marine habitats. Under NOAA, the Coastal Services Center has developed a guidance document entitled "Beach Nourishment: A Guide for Local Governments" to help state and local organizations make knowledgeable decisions regarding beach nourishment (see http://www.csc.noaa.gov/opis/html/descrip.htm). Additional publications regarding beach restoration are: Nordstrom 2000; MMS 2001; Greene 2002; and Dean 2003.

Mudflats, on the other hand, are restored primarily to support seagrass, mangrove, and marsh vegetation that might have been degraded due to human activities such as dredging. In some cases when mudflats are eroded or otherwise degraded, marsh vegetation found in these habitat types also declines. Once marsh vegetation is reduced, the number of organisms that feed on grass species or shorebirds occupying grass areas is also reduced. Efforts to restore the mudflat depend on the reason for degradation and goals of the project. An important goal is to restore the hydrological functionality of the habitat. This may involve raising the elevation of the flat, increasing tidal flow to support plant growth which in turn supports many other

[7] A term for coarse beach material, a mixture of gravel, pebbles and larger material.

organisms, and planting vegetation on degraded mudflat areas.

Assuming that all the physical conditions affecting the site remain the same, successful restoration relies on increasing sediment availability. A key question for success in relation to bird usage is the speed and type of colonization by invertebrates and plants, notably *Zostera* spp. Where there is abundant sediment either naturally or as a result of sediment recharge, physical structures can be employed to increase the rate of sedimentation. The methods applied, to some extent, depend on whether the aim is to move the habitat seaward, maintain the existing position of the flats (by raising the level of the surface), or to allow re-creation on former tidal land. Each method chosen for restoration purposes may be used separately or in combination with other approaches designed to improve sea defenses (through beach nourishment) and/or re-create saltmarshes by managed realignment. In addition to re-creating the tidal flats, the extent of recolonization by invertebrates and seagrass species such as *Zostera* can be enhanced. This design may be done mainly to improve seagrass usage by wintering and migratory waterfowl in marshes, mudflats, and sandy beaches (Doody 2003).

The three principle approaches to restoring sandy beaches, sandflats, and mudflats are:

- Moving the habitat seaward by encouraging the accumulation of sediment on the foreshore through a variety of techniques, including the construction of polders[8]
- Maintaining the existing shoreline using various methods including beach nourishment, and
- Retreating the habitat landward by altering a flood-protected area to allow flooding (i.e., managed realignment)

MONITORING

In order to obtain the support of government agencies (local, state, and federal) and community members for restoration of soft shoreline habitats, practitioners must develop an understanding of the ecological role of the various plants and animals within the habitat. Once the practitioner has obtained this information through monitoring and review of previous studies of the area, it can be presented to government agencies and the community to gain their support (discussed further in Chapter 14).

Before restoration is performed, monitoring should be performed not only to understand the ecological role of plants and animals present in the habitat, but also to gather baseline information on the habitat's conditions. This helps to determine whether the habitat is suitable for restoration and what factors may affect progress of the project. For example, some mudflat or sandy areas may not be suitable for restoration if the original impacts that degraded the habitat are ongoing and cannot be mitigated through restoration efforts. Monitoring is also performed during restoration to allow practitioners to detect any changes that may have occurred such as whether the habitats are stable, whether erosion or alteration are occurring due to human-induced or natural pressures, and whether modifications can made to improve the project. Post-restoration monitoring is done to determine whether the project accomplished the goals that were set. Surveys should be considered when performing any coastal restoration monitoring, as these surveys can provide detailed information on threatened coastal areas and help identify measures to be incorporated into the restoration plan (Wise and Kraus 1993; Tyler and McHattie 1999).

[8] An area of low-lying land that has been reclaimed from a body of water and is protected by dikes.

STRUCTURAL CHARACTERISTICS OF SOFT SHORELINE HABITATS

This section presents the structural characteristics of soft shoreline habitats that may be applicable to restoration monitoring. The characteristics described below refer to the physical and hydrological features of the habitat. They may be potential parameters to gather baseline information and monitor restoration efforts as they may influence soft shoreline restoration projects. Not all of these structural characteristics, however, are expected to be measured or monitored in every restoration project. Additional information is provided to help educate the reader on the ecology of soft shoreline habitats.

Structural characteristics of these habitats include:

Physical

- Habitat created by soft substrates
- Topography/Geomorphology
- Sediment grain size
- Wind speed and direction
- Organic content
- Turbidity

Hydrological

- Waves
- Coastal and littoral currents
- Tides/Hydroperiods
- Water sources

As these structural characteristics can influence soft shoreline restoration efforts, practitioners should first monitor them to ensure conditions are favorable for restoration success and determine how these parameters can potentially affect restoration progress.

PHYSICAL

Habitat Created by Soft Substrates

Sandy beaches, as previously mentioned in the introduction, are land areas covered by loose material (sand) extending over a wide range of area (Brown et al. 1990; Finkl 2004). Beaches and other soft shoreline habitat types range from intertidal beaches to mudflats that are comprised generally of unconsolidated sediment (Finkl 2004). Beaches are formed when sand or other loose materials are deposited along the shore by waves or currents that are influenced by winds. Sand particles may be suspended in seawater and transported by currents flowing parallel to the beach as waves break at the shore. The shape of a beach is influenced by both constructive and destructive waves, and whether the material is sand or other materials, such as shingle (Bascom 1980). Constructive waves transport material further up the beach shore, whereas destructive waves transport beach material down the beach and out to sea. The backwash of the waves continuously removes material, thus forming a gently sloping beach (Bascom 1980).

Mudflats (Figure 9) and sandflats however form along slightly sloping coastal areas where sediment is available and wave energy is low. Sediment deposited above high tide (i.e., the supratidal zone) is often inundated during spring or storm tides in both mudflats and sandflats. This zone can be divided into vegetated and non-vegetated intertidal mudflats and/or sandflats (Morelock 2000). The ecological community of mudflats may rely on other habitats such as saltmarshes because bacteria and fungi affiliated with marshes break down marsh plants and help replenish mudflat sediments. In return, mudflats disperse wave energy, which helps prevent erosion of saltmarshes and flooding in low-lying areas. Mudflats contain high biological productivity and an abundance of organisms, but low diversity with few rare species (Reise 1985).

Sampling and Monitoring Methods

Digital Shoreline Mapping System - There are various methods to map shorelines to

Figure 9. Tidal mudflat with *Spartina*. Photo courtesy of South Florida Water Management District. http://www.sfwmd.gov/org/wrp/wrp_ce/2_wrp_ce_info/photos/hires/sl_inlet_spartina.jpg

show their past and present conditions. The Digital Shoreline Mapping System (DSMS) for example, has been used to determine historical shorelines from maps and provide clarity in aerial photographs (Thieler and Danforth 1994). This system allows researchers to quantify and analyze various sources of error during the mapping procedure. It also allows baseline information to be gathered on the habitat's condition before restoration is performed. This helps to determine whether restoration will be suitable at a potential site (Thieler and Danforth 1994). It also allows for one person to perform shoreline mapping in a small lab using computer hardware and software. The DSMS produces shoreline position data that correspond with geographic information systems (GIS).

Digital Shoreline Analysis System - The Digital Shoreline Analysis System (DSAS) is used to calculate shoreline rates-of-change from a sequence of shoreline data in a GIS. Using this system at selected times throughout the restoration project can help track changes and identify factors that may prevent restoration progress towards achieving a naturally sustainable habitat. The combined use of DSMS and DSAS can provide accurate shoreline positions and erosion rates (Thieler and Danforth 1994). The use of mathematical models along with referred tools can also help in the prediction of shoreline evolution.

Other field methods, data collection, and analysis procedures for monitoring changes in soft shoreline physical features include: aerial photography, satellite imagery, profile surveys, and bathymetric (hydrographic) records (Gorman et al. 1998). Aerial photographs and satellite images can serve as base maps to interpret landform changes and quantify shoreline movement, both of which can help track restoration progress over time.

Profile surveys, which can be obtained from government agencies and universities, can be used to assess shoreline changes along and across the shore (Gorman et al. 1998).

Bathymetric data for a specific project may be plotted using State Plane coordinates[9], while hydrographic data from federal agencies such as the United States Geological Survey (USGS), United States Army Corps of Engineers (USACE), and NOAA may be provided in latitude/longitude coordinates.

Long-term data collected using methods discussed previously can be used to evaluate natural and human-induced changes to a coastal system that can affect restoration progress including storm history, seasonality, wave climate and engineering changes (i.e. large and small scale landform changes) (Gorman et al. 1998).

[9] A coordinating system that separates the U.S. states, Puerto Rico, and U.S. Virgin Islands into over 120 numbered zones. Each zone has a designated code number that identifies the projection parameters for the region.

Topography/Geomorphology

Although soft shoreline habitats are usually flat, strong wind-induced waves and currents transporting sediment (mud or sand) can cause substrates to accumulate and form mount-like characteristics such as sand bars and mud banks (Purandara et al. 1996). Sandy shores, however, have a gradual slope as a result of constant wave action. For example, sandy beaches have a relatively smooth profile and are basically straight or gently curved (Russell 1958). Geomorphic features (Figure 10) relating to processes that form and shape beaches (Finkl 2004) include:

- Berm - the near horizontal part of the beach landward of the sloping foreshore
- Berm crest - the seaward limit of the berm
- Beach face - berm crest to low tide waterline, in the swash zone[10]
- Trough - extended depressions or sequence of depressions along the lowered beach or in the offshore zone that may be exposed at low water, and
- Longshore bar - an elongate, partially submerged, and sand ridge or ride which may be exposed at low water (Finkl 2004)

Muddy shores on the hand, appear relatively flat most of the time (Eltringham 1971) and form during calmer wave periods (Pethick 1996). Changes in frequency of wave events, the tidal regime, and sediment availability can affect the habitat's elevation and the pattern of its profile. If sediment availability decreases, lower deposition rates will result. Therefore, mudflats do not completely recover from erosion before the next wave activity occurs. This can result in a decrease in surface elevation (Pethick 1996). If erosion occurs, vegetation such as mangroves may withdraw along the coastline when landward sand is transferred, covering the mudflat, and smothering vegetation (Cohen

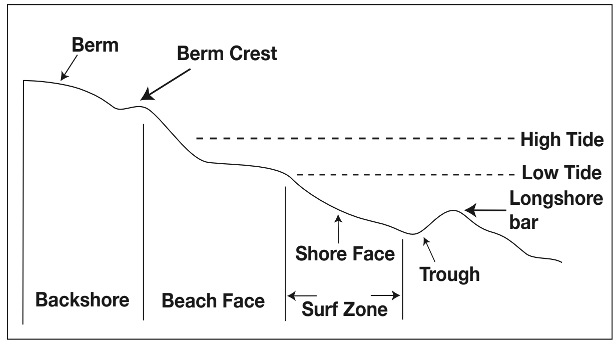

Figure 10. Geomorphic features of a beach. Diagram courtesy of Felicity Burrows, NOAA National Centers of Coastal and Ocean Science

and Lara 2003). As part of a soft shoreline restoration plan, practitioners must devise a strategy that will successfully restore the habitat structure to a naturally sustainable habitat supporting vegetation growth and a large number of organisms. Human activities may also cause changes in soft shoreline habitats (discussed in "Human Impacts to Soft Shoreline Habitats" section of this chapter). For instance, dredging of canals may alter water flow and cause an increase or decrease in the slope of the mudflat, which may in turn disrupt benthic communities.

Sampling and Monitoring Methods

Environmental Sensitivity Index (ESI) - In the United States, NOAA's ESI mapping is commonly used to map and gather information on coastal sensitivity, biological resources, and human use of these habitat types (Finkl 2004). The maps identify sensitive resources and are used to create mitigation plans prior to an oil or chemical spill to minimize the damage if such an event occurs. The ESI maps also include geomorphology of shoreline types which can assist in identifying hazards during a spill event affecting progress towards restoring soft shoreline habitats. These maps are assembled in both paper and digital formats to be easily accessed by various coastal managers and restoration practitioners. The maps provide a consistent approach for mapping coastal

[10] The area of a beach where water rushes up following the breaking of a wave.

geomorphology as well as consistent color schemes and symbolization for coastal habitats (Finkl 2004).

Airborne (Light Detection and Ranging) LIDAR - A LIDAR device may also be used to map and monitor shoreline topography through surveys (Gibeaut et al. 2001; Woolard et al. 2003). For restoration purposes, this method may be used in pre-monitoring and post-monitoring of soft shoreline geomorphology. LIDAR surveys integrate a scanning laser, a device that records aircraft motion, and global positioning system (GPS) receivers. LIDAR can be used to survey beaches and collect data points less than one meter apart from one another. These devices also help create detailed beach topographic models and soft shoreline characterizations. Many organizations, such as NOAA's Coastal Services Center, use LIDAR to map coastal topography in the United States by using a GPS reference frame to obtain LIDAR data. Collected data is used not only to determine coastal topography and elevation, but also to assess erosion, storm damage, inlet migration, beach nourishment, and shoreline stabilization (Gibeaut 2001; Fitzgerald et al. 2003).

Video digital imagery - Charge-Coupled-Device (CCD) video digital imagery can be used to assess beach width, bluff erosion, geomorphology, and seismic structures (Rindell and Hollarn 1998). The CCD images can help to identify changes from events such as landslides. This system can rapidly be constructed for natural disaster assessment following storms, floods, or other coastal disturbances that can affect restoration progress (Rindell and Hollarn 1998). Video digital imaging systems can provide continuous and automated data collection on beach bathymetry as well. Shoreline features are identified using an automated system with full-color imagery and an objective discriminator function to define the boundary of the shoreline. Shoreline elevation is calculated in a model using concurrent tide and wave information. The model combines the effects of wave set-up[11] and water movements (Aarninkhof et al. 2003). In some cases, video imagery may be more time- and cost-efficient than aerial photography.

Sediment

Grain size

Sediment grain size is a distinct feature of soft shoreline habitats. Sandy habitats contain substrate that may be calcareous or terrigenous in origin and coarser than mud. Sandy sediments dominate in relatively high energy environments. Muddy habitats contain some sand particles but are composed mainly of silt and clay and found in waters with low energy (Sanders 1958; Cowardin et al. 1979). Silt contains very fine inorganic particles that are normally held in place at the surface of the mud with minimum water movement (Eltringham 1971). Clay is basically hydrated aluminum silicate with iron and other impurities (Eltringham 1971). Because mud sediments are composed of fine grains, they can be easily transported and deposited by low energy waves.

Both sand and mud environments support a number of species of organisms that prefer different grain sizes. For example, meiofauna in intertidal sandflats are mainly small interstitial organisms (i.e., they prefer spaces between particles). The interstitial spaces provide oxygenation to deeper sediments so that meiofauna can live at broader sediment depths (McIntyre 1969). In mudflats, however, meiofauna are larger than those species limited to surface sediments and found burrowed just below the surface (McIntyre 1969; Peterson and Peterson 1979). These burrowing animals help aerate the sediment and increase the flow of seawater by creating holes that act as passage ways. Changes in grain size which may result from coastal activities such as dredging can disrupt ecological communities in soft shoreline habitats and affect restoration progress in these areas.

[11] When waves break on a beach and produce a rise in the mean water level above the still-water elevation of the sea.

Basin for materials

Sand and mud particles may act as sinks for not only nutrients but pollutants. As the particles in mud are much finer than those in sand, mud particles are able to retain pollutants for longer periods. Land runoff and industrial discharges can seep into sediments and alter the benthic community by killing some of the organisms. Collecting sediments and analyzing metals, organics, other substances, and benthic organisms within the sediment can help determine factors affecting the habitat's ecological communities and whether restoration efforts would be appropriate for a particular area.

Sampling and Monitoring Methods

Push corer instruments - Push corer instruments (Figure 11) can be used to collect both sand and mud samples because they can easily penetrate through soft sediments (USEPA 1984; USEPA 1998). The practitioner places the instrument on the surface of the sediment and drives it into the sediment to the point marked on the push core where gravity sucks the sample into the container and the sample is then pulled from the surrounding sediment. A vacuum device may also be attached to the push core to extract sediment deeper than two meters. Push core tubes can then be cut at the water-substrate interface and sealed to prevent disruption of the sediment (USEPA 1984; USEPA 1998). Piston corer samplers also use both gravity and hydrostatic pressure to collect sediment samples. As the instrument penetrates the sediment, an internal piston remains at the level of the sediment-water interface to prevent sediment compression (USACE 1996).

Remote Sensing - To quantify sediment grain size distribution, remote sensing methods can be used prior to restoration in order to gather baseline information on the grain size of the habitat (Rainey et al. 2003). In some cases, remote sensing can also be done during and after restoration to determine whether there was

Figure 11. A push corer being inserted in the sediment using the manipulator arm of *Alvin*, a remotely operated vehicle (ROV) from Woods Hole Oceanographic Institution. Similar plastic tubes can be introduced manually in the sediment by diving or simply walking in an intertidal flat. Photo courtesy of NOAA Ocean Explorer.

any change in grain size distributions that might influence the functioning of that habitat (e.g., ability to support plant and animal communities). Remote sensing platforms can take measurements within the short-wave infrared (SWIR) band that generally ranges from 0.8-1 microns (µm). The timing of image attainment with regard to tidal cycles and sediment moisture content is considered significant for identifying spectral differences between sand and mud particles, therefore providing precise mapping of estuarine sediment distributions (Rainey et al. 2003).

A more common instrument to assess sediment grain size is a sieve. Sieve methods include press sieving and wet sieving (USEPA 2001). Press sieving involves pressing down on sediments using paddles and then recording visible matter such as organisms, shell fragments, gravel, and debris collected on the screen (USEPA 2001). Wet sieving involves rotating sediments and water within a sieve. Water is added to the sieve to assist in separating larger and smaller particles. The particles are then sieved and retained for measurement. In most cases, sand particles may not have to be sieved because they are composed of larger, coarser grains. After being retrieved from the shoreline, sand and mud samples are deposited into sample containers. The weight of sediment preserved on each sieve is measured and converted into a percentage of the total sediment sample (USEPA 2001).

Wind speed and direction

Winds plays a role in transporting sand and mud particles and can influence the geomorphology of the soft shoreline. Once winds transport sediment from one position to the next, the original sediment location becomes relatively flat or eroded while the new location is elevated. The direction and speed of the wind can also play a significant role in geomorphological changes. For example, high-speed winds continuously blowing in the same direction can result in severe erosion of a particular area. Winds can also influence wave movement and affect the stability of animals living in soft shoreline habitats (Norkko et al. 2002). Waves, combined with winds, are significant to the formation of habitats, particularly on sandy shores. In sandy habitats, for example, the greater the wind speed, the higher the waves, and the greater the angle when waves hit a beach, the more sand is transported. Once sand is transported during high–speed winds and intense wave action (e.g., during storms), the area on the beach from where sand was transported becomes flat. Sand will eventually re-accumulate on the shore over time, but at a slow and gradual rate.

Sampling and Monitoring Methods

Cup anemometer and windwane - Monitoring wind speed and direction allows practitioners to assess the frequency and rate at which soft substrate is transported. Two instruments used to measure wind speed and direction are a cup anemometer and a windvane. These instruments are usually placed at about 6.5 meters high (Abuodha 2000) and data can be recorded, processed, and stored in a programmable datalogger.

Other commercial instruments such as a wind direction sensor can provide a single output of the wind direction angle. The advantage to using a wind direction sensor is that it reduces errors and minimizes friction.

Organic content

Organic content in sediment greatly influences the plant, animal, and microorganism populations. For instance, decomposed organic material provides nutrients to benthic organisms. Microorganisms utilize the organic matter and recycle nutrients so that they can provide food for other organisms (Trimmer et al. 1998). In high energy regions where sandy habitats such as beaches and sandflats) are typically found, organic matter levels are relatively low (Eagle 1973) and consist mainly of detritus resulting from decayed macroalgae, feces, and animal remains (Hayward 1994). Since organic content is low in these areas, very few species of animals are found there.

In intertidal mudflats, however, organic content is much higher than in sandy habitats (Rae and Bader 1960; Cowardin et al. 1979). As mudflats are found in relatively low energy regions, these habitats accumulate large quantities of organic matter and therefore experience higher rates of biomass decomposition. Sources of organic material in mudflats include:

- Human sources (effluent, runoff, food and waste from aquaculture, and degraded petroleum hydrocarbons)
- Natural sources (plankton and detritus), and
- Organic material such as benthic microalgae (diatoms and euglenoids)

As a result, plant and animal species abundance is greater in mudflats than in sandy habitats.

Sampling and Monitoring Methods

There are various methods to sample sediments, many of which are discussed in the "Sediment: *Sampling and Monitoring Methods*" section of this chapter. Methods to assess total phosphorus involve extracting the phosphorus from sediments with 1 N (i.e., one mole per liter) hydrochloric acid after ignition at high temperatures (550ºC) or by digesting the sample with sulphuric acid-potassium persulphate at 135ºC in a sealed pressure vessel (Aspila et al. 1976). Organic phosphorus can be determined by the difference in phosphorus content of the 1 N hydrochloric acid extract measured before and after ignition of the dry sediments at 550ºC (Aspila et al. 1976). The level of orthophosphate - a salt of phosphoric acid - is determined by using a standard technical AutoAnalyzer II. These methods can successfully measure inorganic, organic, and total phosphorus in sediments (Aspila et al. 1976).

Another technique used to analyze organic content in sediment, particularly nutrients such as carbon and nitrogen, is acidification**.** The sediment samples are dried and acidified with 10 percent hydrochloric acid to eliminate all carbonates. The samples are then dried again and analyzed for carbon and nitrogen. Data collected from organic/nutrient analyses of sediment samples can indicate whether organic levels have increased or decreased significantly over time. For example, an increase in nutrients may be an indication of agricultural runoff, causing increased algal growth which then reduces oxygen levels.

Turbidity

Turbidity is a water quality parameter referring to the water clarity, or the amount of light penetrating through the water column. The greater the amount of total suspended solids or sediments (TSS) in the water, the more muddy or cloudy the water appears and the higher the measured turbidity. Clay, silt, and sand particles from soils of soft shoreline habitats are common suspended solids. Wave energy circulates the sediments throughout the water column which eventually settle to the bottom. When there is frequent strong wave action along a soft shoreline, the water column is generally turbid because sediments are in constant motion. The water column in muddy habitats, however, is generally more turbid than sandy habitats because the mud grains are finer and easily distributed throughout the water. Thus, the turbidity of the water can be an indication of the sediment type that creates the soft shoreline habitat (i.e., sand creates less turbid waters than mud). Changes in turbidity may also affect the ecological community of soft shoreline habitats. Macroalgae in turbid waters, for instance, receive minimum sunlight and therefore may be unable to photosynthesize. As a result, productivity is low which in turn, affects the animal community that relies on macroalgae as a food source.

Measuring and Monitoring Methods

Secchi disc - The depth of light penetration in the water column can be measured using a secchi disc (Figure 12). It is a painted disc attached to a cord. The disc is lowered slowly from the water's surface. As light travels through the water column, some of it is absorbed by phytoplankton and dissolved material. The remaining light reflects off the secchi disc and travels back through the water column where more is absorbed. The deeper the disc is lowered in the water, the harder it is to see the disc as an increasing amount of light is absorbed. The depth at which the disc can no longer be seen is the depth at which the light is being completely absorbed as it passes down and back up through the water column. Three measurements are usually recorded at each location.

Turbidimeter - There are also many commercial instruments that can be used to measure turbidity. A turbidimeter, for example, measures water turbidity by passing a beam of light

Figure 12. A Secchi disc is taken out of the water after a depth reading in a study of Poplar Island, Maryland. Photo courtesy of Chris Doley, NOAA Restoration Center.

through the sample and measuring the quantity of light scattered by particulate matter (Rogers et al. 2001). The turbidity measurements are then displayed in nephelometer turbidity units (NTUs) (USEPA 1983; Rogers et al. 2001).

HYDROLOGICAL

Waves

Soft shoreline habitats, particularly those composed of sand, are influenced by wave height and period, as well as fetch[12] of the wave. The height and period of a wave correlate with the strength and fetch of the wind that produces it. For instance, the longer the fetch, the greater the increase in wavelength and period (Brown et al. 1990). Short fetches cause waves to be higher, whereas longer fetches cause lower wave heights.

Wave energy (from minor to extreme) also influences soft shoreline characteristics and is primarily responsible for sediment transportation. The movement of waves is driven primarily by kinetic and potential energy (Brown et al. 1990). Kinetic energy refers to the energy of particle motion; potential energy is the displacement of the sea surface in relation to wave height (Brown et al. 1990). Wave energy is considered directly proportional to wave height. The total wave energy per unit area is represented as:

$$E = 125\ H^2 \text{ ergs. cm}^{-2}$$

E = energy in ergs
H = height
ergs = unit of energy

In shallower waters, wave energy is dissipated through friction with bottom sediments and additional energy is lost as waves break on shorelines or other objects. In contrast, waves that approach the shore in deeper waters retain greater energy which can cause shoreline erosion.

Although wave energy is generally low in muddy shores, when storms or other forces increase wave action, mud banks may form

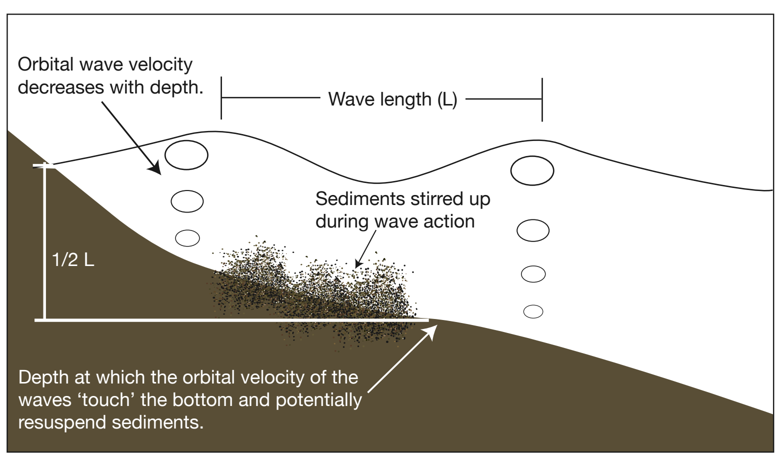

Figure 13. Wave in motion stirs up sediments as it approaches the shore, causing an increase in turbidity. Diagram courtesy of Felicity Burrows, NOAA National Centers for Coastal and Ocean Science.

[12] The distance over open water wind travels to generate waves.

as sediment accumulates. Differences in wave energy levels also influence what species of plants and animals are found in these habitats, depending on their ability to tolerate high or low wave exposure. For example, the substrate material on sandy shores is exposed to extreme washing action of waves which reduces organic content, thus organisms in this area must be able to tolerate and survive under low organic content conditions (Norkko et al. 2002). Because wave energy can influence the physical characteristics of these habitat types, their plant and animal communities, and restoration efforts, monitoring wave energy should be considered during the project planning process.

Waves influence not only sediment transport and shoreline geomorphology, but also the distribution of pollutants. The effects of wave and tidal occurrences on spilled oil penetration on tidal flats and the influence of the penetrated oil on seawater infiltration were studied with the use of a tidal flat simulator (Cheong and Okada 2001). Oil penetrated sediments by tidal movement only, whereas seawater infiltrated sediments by wave action and tidal fluctuation. In addition, infiltration of seawater was lessened by penetrated oil. Furthermore, penetrated oil may reduce seawater infiltration in sediments, causing oxygen, nutrients, and organic matter reductions, which affect the abundance of benthic organisms in tidal flats (Cheong and Okada 2001).

Measuring and Monitoring Methods

Pressure gauges - Bottom-mounted pressure gauges can be used to measure wave pressure and direction (Smith 2002), and sensors can be used to measure wave height. Pressure gauges may be mounted on platforms to measure the depth from the sea surface to the gauge and determine wave directions (Smith 2002).

Wave buoys - Wave buoys (Figure 14) fixed at certain locations in the ocean use electronic sensors to measure wave height, wave direction, and time period between waves (Davies 1996). As this monitoring method may be relatively expensive for restoration practitioners, information about wave conditions may be obtained in some instances from other research efforts in proximity to the restoration site. This encourages collaborative efforts between researchers and practitioners. In areas where wave energy is low, such as sand and mudflats, the measurement of wave energy should not be a priority when assessing restoration progress. Other sources that describe methods for measuring wave energy as well as wave direction, height, and periods include: Draper et al. 1974; Middleton et al. 1978; Fu et al. 1987; Brumley et al. 1983; AshokKumar and Diwan 1996; Tortell and Awosika 1996; Terray et al. 1999; and Yang et al. 2004.

Coastal and Littoral Currents

Coastal currents are offshore currents that flow generally parallel to the shoreline in the deeper

Figure 14. A three-meter NOAA buoy collects weather data by measuring wave height and period, as well as other weather parameters such as wind speed and direction. Photo courtesy of NOAA National Data Buoy Center.

water beyond and near the surf zone. They are not related intrinsically to waves and the resulting surf, but may relate to tides, winds, or the distribution of large oceanic circulations. In contrast, littoral (i.e., relating to the seashore, especially the intertidal zone) currents occur in the littoral zone and result primarily from wave action such as long shore currents or rip currents (USACE 1984).

Littoral processes include the interaction of waves, currents, winds, tides, sediments, and other materials near the shoreline. These currents flow either parallel to the shoreline (longshore currents) or perpendicular to the shoreline (rip currents or undertow) and travel in one primary direction. For example, in the Fire Island National Seashore Park in Patchogue, New York, littoral currents generally run in an east-west direction (NPS 2004). Together with waves, winds, and tides, littoral currents transport coastal materials towards and away from beaches. Such materials, collectively referred to as littoral drift, include sand, gravel, other sediments, and organic material. Littoral transport is the movement of littoral drift in the littoral zone by waves and currents. Depending on the rate and direction of littoral transport, beaches erode, accrete (i.e. expand), or remain relatively stable.

Structures that extend perpendicular to shorelines interfere with natural littoral processes and sediment transport. For example, groins are constructed to control or modify littoral transport. Such structures block the nearshore movement of littoral materials and cause "up-current" beaches to accrete. Although groins may increase deposition on up-current beaches, they effectively steal sediments from down-current beaches, intensifying erosion in those areas. Coastal currents may also displace high quantities of sand along the shoreline. It is important to know the direction of those currents and measure the amount of sand transported throughout the year.

Measuring and Monitoring Methods

Current profilers - Commercial instruments such as current profilers have generally been used to obtain information about the speed and direction of currents. The most commonly-used current profilers are acoustic Doppler current profilers (ADCPs) (Figure 15). This instrument uses underwater sound to measure vertical profiles of horizontal currents. The ADCPs are generally moored in the open sea, but they can also be mounted aboard survey vessels.

Tides/Hydroperiods

Mudflats and sandflats are mostly exposed to very low tides compared to sandy beaches, but each of these habitat types is inundated during high tides (Cowardin et al. 1979). Hydroperiods (i.e., fluctuating water levels) play a significant role in modifying the physical structure of soft shorelines and in the distribution and abundance of plant and animal communities. As a result of changes in water level fluctuations and increased inundation periods, mobile animals that are used to lower water fluctuations may migrate to more suitable locations, thus opening a niche for other species preferring the more inundated conditions. In other cases,

Figure 15. Image of a typical four-beam acoustic Doppler current profiler (ADCP) sensor head. The ADCP measures the speed and direction of ocean currents using the principle of "Doppler shift." Photo courtesy of NOAA Ocean Explorer.

inundated waters may cause animals and plants to die because they are not able to tolerate flooded conditions. During restoration of some habitats (e.g., mudflats), hydroperiods may be restored in order to support plant and animal communities that were initially found in that particular area. Continuous flushing of nutrients and other materials by fluctuating water levels is necessary to distribute nutrients and make them available to organisms. Flushing can also help prevent the accumulation of nutrients and other materials that may contaminate the habitat and disrupt the habitat's ecological community. However, if flushing is increased in areas such as mudflats that are accustomed to low energy wave action, animal and plant abundance may decline.

Sediment transport and accretion are also influenced by fluctuating waters. Slower water fluctuations reduce sediment transportation rates, particularly for coarser grains. Since grain size in muddy shores is finer, less energy is required to suspend and transport silt and clay materials. Sediment accretion due to water level fluctuation may also affect the survival and growth of some vegetative species such as mangroves. For instance, when mangrove seedlings are planted on mudflats they may experience an increase in mortality rates with increasing sediment accretion. As a result, mangrove growth declines (Terrados et al. 1997).

Measuring and Monitoring Methods

Tide gauges - A tide gauge is a mechanical device that is usually placed on piers or pilings to record water levels (IOC 1985; Emery and Aubrey 1991). This instrument may consist of a datalogger that reads and stores data from different sensors and a modem that communicates with a computer (IOC 1985). The elevation of the water level sensor should be determined from a stable bench mark and calibrated at regular intervals to ensure accurate water level measurements.

Water Sources

Water quality is a significant parameter that affects soft shoreline plant and animal communities. The source of water inflow can influence nutrient concentrations, toxins, and ultimately the number of organisms living there. The chemical concentration and physical characteristics of water near soft shoreline habitats can be influenced by various environmental factors, including:

- Tides/hydroperiods
- Currents
- Groundwater, and
- Human inputs (e.g., runoff from upstream land use)

In some cases when runoff - which may include freshwater, nutrients, sediment, or pollutants - from upland areas enters soft shoreline habitats, it can reduce the number of organisms occupying the habitat or alter behavioral patterns of some organisms (Levings and McDaniel 1976; Mohd Long 1987; Rao 1987; Lercari and Defeo 2003). In other cases, groundwater flowing through sandy beaches (and in some cases, mudflats) to coastal waters is considered a source of nutrients that supports the biological productivity of coastal waters (Nakasone et al. 1998). Also in several areas, freshwater flowing over intertidal, estuarine mudflats may attract waterbirds, especially ducks and geese, probably because the water source for preening and drinking is near their feeding grounds (Ravenscroft and Beardall 2003). Freshwater inflows, however, may not be utilized by some organisms and may cause ecological changes to occur in soft shoreline habitats. Large amounts of freshwater discharges may also form deeply-cut creeks in narrow mudflats that may not be suitable for most waterbirds (Ravenscroft and Beardall 2003).

Measuring and Monitoring Methods

Water quality measurements and water source evaluation should be considered when developing a restoration monitoring plan because these factors can have a tremendous impact on restoration success. If polluted runoff continues to enter soft shoreline habitats, the quality of the habitat deteriorates. In most cases, restoration practitioners may not be able to correct this problem but should, at a minimum, be able to identify factors that contributed to unsuccessful restoration.

Monitoring methods that may be used directly in the field to obtain immediate measures include commercial pH meters, oxygen meters, and turbidity readers. Samples should be taken at designated locations to ensure that certain parameters that cannot be measured in the field are measured or determined in the laboratory (e.g., nutrient concentrations, heavy metals, etc.). Samples should also be properly contained, transported, and stored in the laboratory for preservation purposes.

A good reference for monitoring water sources is the *Standard Methods for the Examination of Water and Wastewater*, a joint publication by the American Public Health Association, American Water Works Association, and Water Environment Federation that covers all aspects of water and wastewater analysis techniques. The United States Environmental Protection Agency (USEPA) approved the 20th Edition of this manual for regulatory applications (Clesceri et al. 1998).

CHEMICAL

Salinity levels can influence the distribution of plants and animals in sandflats and mudflats. For example, mangroves are considered salt-tolerant plants. Hypersaline conditions (greater than 35 ppt) can, however, affect productivity by preventing mangrove terminal buds from developing (Koch and Snedaker 1997) (see Chapter 9 - Restoration Monitoring of Mangroves). Also different species of seagrasses tolerate different salinity levels (Lirman and Cropper 2003). Those species of seagrass that tolerate relatively lower salinity levels may result in low productivity if salinity levels increase significantly. Some factors that may be responsible for increase in salinity levels include industrial and agricultural inputs (see Chapter 7 - Restoration Monitoring of Submerged Aquatic Vegetation). Because of the effect salinity may have on plants and animal distribution, it should be monitored in tidal areas exposed to changes in salinity levels.

Sampling and Monitoring Methods

Hydrometer - A hydrometer can be placed into a tall flask containing the water sample. Salinity is determined by taking a reading of the position of the water surface at the bottom of the meniscus (Rogers et al. 2001). Hydrometers are typically calibrated for use at a specific temperature and a conversion chart is usually provided in order to estimate salinities at different temperatures (Rogers et al. 2001).

Refractometer - A refractometer is a hand-held instrument that measures the bending of light between dissolved salts as it passes through the water sample. To measure salinity, one or two drops of the sample are put onto the prism. The observer holds the cover down, faces the instrument toward the light and looks at the scale through the eye piece to determine the salinity (Rogers et al. 2001).

FUNCTIONAL CHARACTERISTICS OF SOFT SHORELINE HABITATS

In most cases, the goal of many restoration projects is to restore the habitat to a functioning and naturally sustainable state which supports plants and animals. These functions include:

Biological

- Providing habitat and shelter for plants, fish, and invertebrates
- Providing breeding and feeding grounds for many marine species
- Assisting in providing food for marine organisms by contributing to primary productivity
- Providing refuge from predation for benthic invertebrates

Physical

- Affects transport of suspended/dissolved material
- Alters turbidity

If the health of the habitat is degraded in any way, it can affect the functioning of the habitat. Understanding how the habitat functions is important to restoring it successfully. Monitoring should be performed to determine whether the habitat is functioning efficiently and to track progress throughout the restoration project.

In the section below, some of the biological and physical functions performed by soft shoreline habitats are discussed. Also provided are methods to sample, measure, and monitor several functional parameters affiliated with the functional characteristics described. Not all of these functional characteristics, however, are expected to be measured for every restoration project. This information is provided to illustrate the importance of the habitat and the role each characteristic plays. The methods discussed here are just a few of the methods that can be used.

BIOLOGICAL

Provides Habitat and Shelter

Different types of shoreline habitats support various plant and animal species that can tolerate a constantly changing environment. Tidal flats, for instance, whether they are accreting or not, are important in contributing to the productivity of estuaries. They help support the food web within the tidal embayment and therefore play a critical role in both fisheries and wildlife conservation. The high productivity associated with tidal waters and flats also helps to support spawning and juvenile stages of many important commercial and recreational fish species such as flounders, snappers, and groupers.

Vegetation commonly found along soft shorelines includes mostly herbaceous vascular, plankton, and algal species that are washed in with tides. For example, eelgrass (*Zostera marina*) (Figure 16) is an important plant found in mudflats and sandflats and, commonly lives in the mid-upper shore. Eel grass provides important grazing for a variety of herbivores including ducks and geese. It also contributes to the stability of tidal flats, a characteristic which they share with another species of seagrass called widgeon grass (*Ruppia maritime*) that is found in the intertidal zone. Seagrass species, in general, play an important role in coastal wetlands by providing oxygen, food, shelter, and nursery areas for a wide variety of marine species, and by helping to stabilize shorelines.

Not only are species of grass found in soft shoreline habitats but other vascular plants such as mangroves (e.g., *Rhizophora* spp.) (Figure 17) are commonly found along mudflats.

On sandy beaches, however, there is typically very little vegetation found as it is hard for plants

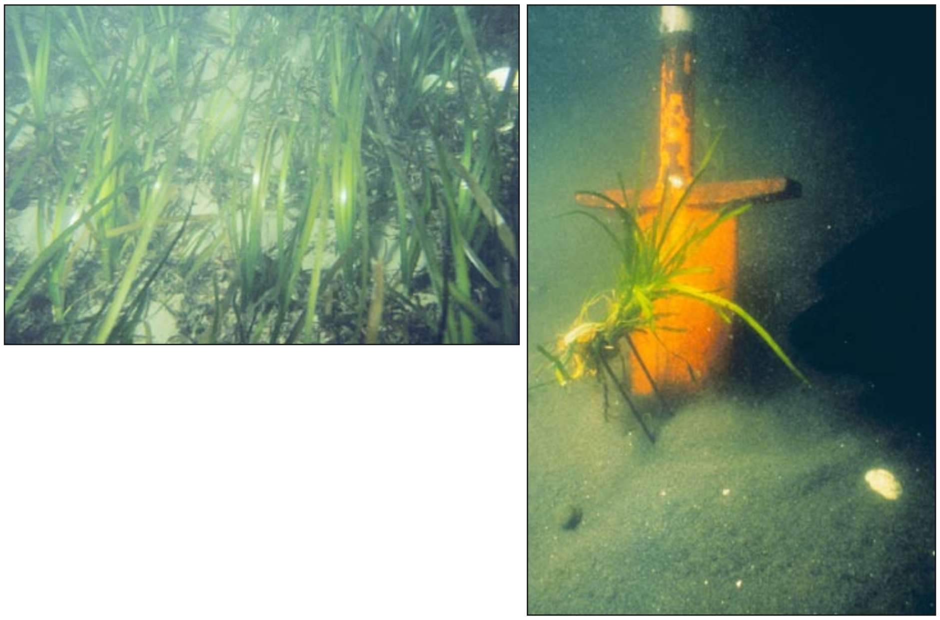

Figure 16. Left: Bed of eelgrass (*Zostera marina*). Photo courtesy of USEPA Dive Team. Right: A plug of eelgrass (*Zostera marina*) just before it is transplanted. Note the u shaped "staple" that is used to secure it to the bottom. Photo credit: Jay Preshoso. Photo courtesy of NOAA Narragansett Bay Eelgrass Restoration Project.

to establish themselves and seeds have difficultly settling in the sand. There are, however, a few species of amphipods, crustaceans, polychaetes, and bivalves adapted to this habitat type.

Some vegetative species that are seen in areas near sandy beaches, especially in dunes immediately linked to the beach, are:

- Beach wild rye (e.g., *Leymus mollis*)
- Beach bur (e.g., *Franseria chamissonis*)
- Beach salt bush (e.g., *Atriplex leucophylla)*
- Dune beach grass (e.g., *Ammophilia spp.)* (Figure 18)
- Lizard tail (*Eriophyllum confertiflorum)*
- Saw palmetto *(*e.g., *Serenoa repens),* and
- Sea fig (e.g., *Carpobrotus edulis)* (Slattery 1996)

In the United States, European beachgrass (*Ammophila arenaria*) has been used in beach and dune restoration. This species, however, is invasive and has outgrown other native plants in dunes throughout the East coast, Great Lakes, Washington, and Oregon. *Carpobrotus edulis* (known as hottentot fig or highway ice plant or sea fig) is also considered an invasive plant along dunes and beaches in California. It is therefore important to consider invasive species when monitoring restoration efforts particularly if non-local plants are used. Successful management of coastal sand dunes in the United States requires the control of aggressive species such as European beachgrass. The spread of this and other invasive species can be controlled

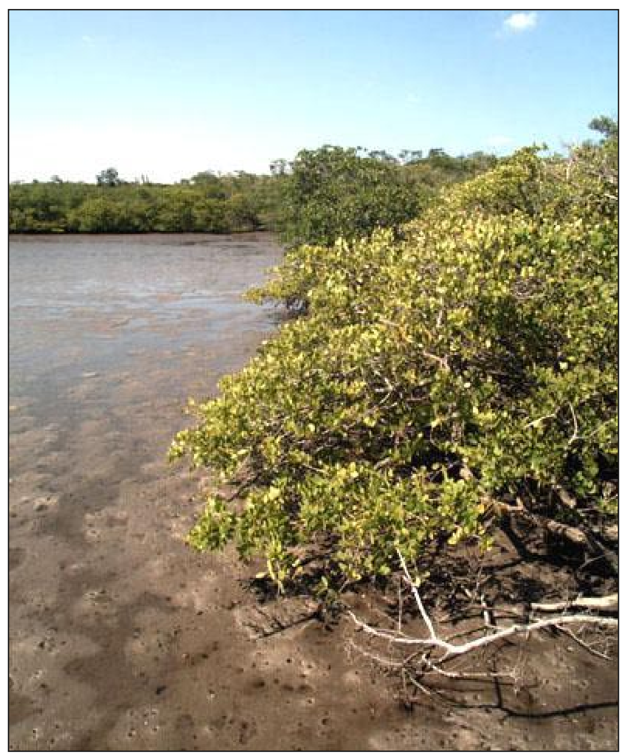

Figure 17. Mangroves bordering a mudflat. Photo courtesy of United States Geological Survey, South Florida. http://sofia.usgs.gov/virtual_tour/images/photos/wlak/ak_mangroves.jpg

Figure 18. Dune beach grass (*Ammophilia spp.*). Photo courtesy of S. Muller, NOAA National Estuarine Research Reserve Collection. http://www.photolib.noaa.gov/nerr/nerr0786.htm

by manually removing the plant. This type of control requires ongoing treatment and is labor intensive. Control should be emphasized until eradication techniques are refined.

Animals found along the soft shoreline may vary depending on the sediment texture and grain size such as fine-grained mud or coarse-grained sand. Mudflats and sandflats support a large number of invertebrates such as amphipods, polychaetes, bivalves, and oligochaetes in the sediment surface. Typical densities on predominantly muddy shores for mud snails (*Hydrobia* sp.) and burrowing amphipods (*Corophium volutator*) may be up to 100,000 and 60,000 individuals per square meter, respectively (Barnes 1974). Segmented worms such as ragworm (*Nereis diversicolor*) and lugworm (*Arenicola marina*), which are found on more sandy shores, are also often abundant and particularly important as prey for wintering wading birds.

Other animals found in soft shoreline habitats include:

- Crustaceans (e.g., amphipods, mysids, ghost shrimp, and crabs) (Figure 19)
- Invertebrates (e.g., mud snails, oligochaetes, and polychaetes)
- Molluscs such as bivalves (e.g., oysters, *Crassostrea;* clams *Corbicula;* and zebra mussels, *Dreissena polymorpha*)
- Shorebirds (e.g., sandpiper, *Calidris pusilla* and red knot, *C. canutus*), and
- Fishes

(Note: Species distribution will vary based on salinity. For instance, zebra mussels, oligochaetes, and some species of ghost shrimp are found primarily in freshwater.)

Provides Breeding Grounds

Organisms such as crustaceans such as American horseshoe crab (*Limulus polyphemus*) and birds such as piping plover (*Charadrius melodus*) use soft shoreline habitats as breeding grounds. The male American horseshoe crab courts with females by attaching themselves to the back of the female's shell using pincher-like appendages called pedipalps. The female crab then drags the attached male up the beach and constructs holes in the sand to lay eggs. Male crabs then fertilize the eggs. Waves at high tide wash up the shore and distribute eggs all along the shoreline where they lay exposed (Rudloe 1980). Other species of crabs, such as fiddler crabs (*Uca* spp.), also use soft shoreline habitats as breeding grounds (Figure 20). Male fiddler crabs attract females to the mudflats by waving their claws, signaling females in the breeding grounds (Oliviera et al. 2000). The female crab then approaches the

Figure 19. Female blue crab (*Callinectes sapidus*) occupying soft shoreline. Photo courtesy of Mary Hollinger, NOAA National Oceanographic Data Center. Publication of NOAA Central Library. http://www.photolib.noaa.gov/coastline/line0838.htm

male and burrows underground to mate. After the mating process, the female crab remains underground for approximately two weeks to incubate the eggs.

Birds such as piping plovers seek a suitable nesting territory just before breeding. Once a site has been selected, the male and female birds then perform courtships with each other. The two birds develop depressions in the sand near the high beach for nests (USFWS 1997). The eggs and the young are camouflaged by grasses and sand present to lessen the chance of predation. In some cases, however, nests are disturbed by storm tides, predators, or intruding humans before the eggs can hatch (USFWS 1997).

Provides Feeding Grounds

Soft shoreline habitats, especially mudflats, are important feeding grounds for many animals because they provide greater biomass resources than sandy habitats. Bacteria and diatoms present between sand grains support the soft shoreline habitat food web by recycling nutrients and providing food for microscopic protozoans, crustaceans, invertebrate larvae, and roundworms (Berrill and Berrill 1981). Crustaceans such as fiddler crabs, for example, use their claws to scrape the surface of the sediment while placing sediment particles into their mouth to retrieve organic matter.

Figure 20. Male fiddler crab (*Uca* spp.) inhabiting a mudflat. Photo courtesy of USGS, South Florida. http://sofia.usgs.gov/virtual_tour/images/photos/wlak/ak_malefidcrab.jpg

Sandy beaches, mudflats and sandflats are especially important in providing feeding areas for a variety of waterfowl, particularly migratory waders. These waders depend on the availability of suitable invertebrate prey that live in or on the surface of the sediment. In the low intertidal zones of beaches where there is protection against intense heat and freezing temperatures, concentrations of small invertebrates such as amphipods, isopods, polychaete worms, and clams are very high (Larsen and Doggett 1990). Shorebirds (Figure 21) also feed on invertebrates (e.g., clams and polychaetes), molluscs (e.g., snails), as well as crustaceans (e.g., crabs) by picking or probing in the mud or sand along the water's edge.

Sea turtles, fishes, and other animals feed on other small animals (e.g., polychaetes), seagrasses (e.g., *Zostera*) found in these habitats, and algae which may be washed ashore by tides and waves. Seagrass beds can provide food for a smaller number of herbivores, most notably grazing ducks and geese (discussed in Chapter 9 "Restoration Monitoring of Submerged Aquatic Vegetation"). The importance of the habitat for waterfowl is reflected in the number of sites identified as nationally and internationally significant for this group of species. Seagrasses in soft shoreline habitats are also an important source of food and shelter for the young stages of many fish and crustacean species, some of which serve as food for commercially-valuable fishery species (Doody 2003).

Provides Refuge from Predation

Many organisms such as crustaceans and other invertebrates seek refuge within sediments to avoid being preyed upon by larger organisms such as birds and fish that primarily capture prey on or just beneath the sediment surface. For example, the staghorn sculpin fish (*Leptocottus*

Figure 21. Sandpiper searching for food along a Gulf of Mexico beach in Biloxi, Mississippi. Photo courtesy of Mary Hollinger, NOAA National Oceanographic Data Center. Publication of NOAA Central Library. http://www.photolib.noaa.gov/coastline/line2589.htm

armatus), known as opportunistic feeders, prey mainly on ghost shrimp (*Callianassa californiensis*) and blue mud shrimp (*Upogebia pugettensis*). These shrimps avoid being preyed upon by burrowing in sediments to depths deep enough where predators cannot reach them (Armstrong et al. 1995). Migratory shorebirds also forage over intertidal shores, preying on crabs and worms. For example, the American golden plover (*Pluvialis dominica*), black-billed plover *(P. squatarola*), ruddy turnstone (*Arenaria interpres*), and whimbrel (*Numenius phaeopus*) have been seen foraging on species of fiddler crabs (*Uca uruguayensis*) in soft shoreline habitats (Iribarne and Martinez 1999). Similar to shrimps and other types of crustaceans and invertebrates, crabs burrow into the sediment to avoid predation once they sense a threat. In some cases, prey may still be captured because the sediment is soft, as predators such as birds are able to probe into the sediments to obtain prey, or the prey may be captured before they can burrow into the sediment.

Sampling and Monitoring Methods

Birds - Aerial surveys can be used to determine bird numbers. Practitioners observe and record the numbers, location, and species of birds. The data collected from multiple surveys can be compared to determine whether any changes have occurred in species type or bird numbers (i.e., the number of birds nesting, breeding, and feeding patterns) over time (King and Michot 2002). Nesting sites of colonial waterbirds can be identified using color infrared aerial photography (Kingsbury 2001). The sites are displayed by digital imagery in GIS software such as ESRI's ArcView. This method allows researchers to perform temporal and aerial assessments of colonial waterbird breeding activities. ArcView allows the user to query, analyze, and view information about the colonial waterbirds. Practitioners can customize the software to observe the information at different scales to show species distribution, areal extent of the nesting areas, and population trends for long periods (Kingsbury 2001).

Transect methods can also be used for monitoring birds along the shoreline. Transect counts may vary depending on species type and whether an index of relative abundance or absolute abundance is needed (Mannan and Meslow 1980). A relative abundance index represents the number of birds per kilometer of transect, while an absolute abundance represents the density of birds per square kilometer. To determine a relative abundance index, practitioners travel along the transect beside the shoreline for a particular distance and count the number of individuals detected. The resulting index represents the number of detections per unit distance traveled (Gibson 1971). Absolute abundance can be measured using fixed-width transects in which practitioners move along a transect and count the birds detected within a fixed-width strip on either side of the transect (Government of British Columbia 1997). Bird densities may be determined by dividing the number of birds detected by the area of the transect strip.

Invertebrates - A multiple tube sampler can be used to sample benthic and pelagic invertebrates (Euliss et al. 1992). This sampling device consists of clear acrylic tubes that are arranged in the shape of a square and placed 25 centimeters apart from one another. Each tube is sharpened so that it can penetrate into the sediment (Euliss et al. 1992). The device is lowered into the water and pushed about 10-15 centimeters into the sediment. The sediment type will, however, influence the depth in which this device will be inserted. A standard five centimeter pressure plug is then used to cover the tube with an air-tight seal. Once sealed, the tubes are shaken back and forth to separate sediment (Euliss et al. 1992).

Invertebrates can also be sampled using a standard core sampler or collected by hand within quadrats (Boer and Prins 2002). Organisms assessed using quadrats are usually large enough to be seen by the naked eye. Parameters measured generally include:

- Composition
- Biomass
- Abundance
- Density or percentage of target species
- Predator to prey ratio
- Target species size
- Species richness
- Species-rank abundance, and
- Biomass/abundance ratio

Quadrat replicates may be taken along a transect or various transects at fixed intervals along the shore. Other instruments used to sample sediment and macrofauna include dredge (Figure 22), sled, or grab samplers (Brown et al. 1990).

Fish - There are various types of nets that can be used to sample fish, such as seine nets, lift nets and gill nets. Seine nets are composed of a bunt (i.e., bag or lose netting) and long ropes used to pull it out of the water. The nets contain floats to keep the top part afloat and weights to keep the bottom of the net submerged to prevent the fish from escaping from the net-enclosed area. Fish caught in the net are then identified and counted (Hart and Reynolds 2002).

Lift nets consist of a bag-shaped structure with the opening facing upwards while the bottom of the bag remains submerged. Fish that swim over the opening of the bag are then enclosed as persons holding the net lift it out of the water.

Figure 22. Hand dredging on a mudflat in Metal Bank site, Philadelphia, Pennsylvania. Photo courtesy of NOAA Office of Response and Restoration.

Gill nets can also be used to sample fish. The mesh size of the net varies depending on the size of the targeted fish species. Fish are captured when they swim into the invisible mesh net and struggle to escape. As they struggle, they become entangled within the net (Hart and Reynolds 2002). Practitioners then separate the fish from the nets so that they can be identified and counted.

Contributies to Primary Productivity

Primary productivity in both mud and sandy shores is primarily from benthic macrophytes, benthic macroalgae, and phytoplankton biomass and supports many animals (Peterson and Peterson 1979). Chlorophyll concentration is measured to determine the abundance of phytoplankton which contributes to most plant production in estuaries and oceans. This measurement allows practitioners to determine whether the vegetative species growing in these habitats are productive. Low productivity in a habitat that usually has substantial vegetation can be an indication of insufficient nutrients to support plant growth and therefore can affect animal abundance. Mudflats particularly receive organic input from other coastal vegetation that have high rates of primary production. These include marsh plants such as *Spartina, Juncus*, seagrasses such as *Halodule, Zostera*, and mangroves. (Odum 1959; Keefe 1972). In some areas, higher levels of primary production vary between benthic algae and phytoplankton (Marshall et al. 1995). In the Chesapeake Bay, near intertidal mudflats, for example, higher primary productivity was due primarily to benthic algae (Marshall et al. 1995). Whether benthic algae, benthic macrophytes, or phytoplankton is the main source of high primary productivity, each of these vegetative species provides a large supply of nutrients to benthic fauna occupying soft shoreline habitats.

Sampling and Monitoring Methods

Fluorometer - A sample fluorometer can be used to estimate phytoplankton biomass by measuring chlorophyll. This is an underwater instrument that projects a beam of blue light into the water column and then measures the amount of red light absorbed by chlorophyll in the suspended algae (Moldaenke et al. 1992; Xia et al. 1997). Chlorophyll concentrations are measured by first collecting water samples and extracting chlorophyll in 90 percent acetone along with the help of a mechanical tissue grinder (Arar and Collins 1997). The chlorophyll concentration is then determined from the absorbance of light measured in a spectrophotometer and compared to estimates made using the sample fluorometer.

PHYSICAL

The primary physical functions of soft shoreline habitats include alteration of turbidity and, transportation of sediment and dissolved materials by means of waves, currents, tides and hydroperiods. These parameters have been discussed with the associated structural characteristics in this chapter.

PARAMETERS FOR MONITORING STRUCTURAL/FUNCTIONAL CHARACTERISTICS

The following matrices present the structural and functional characteristics of soft shoreline habitats suitable for restoration monitoring. These matrices are not exhaustive, but represent those elements most commonly used in restoration monitoring strategies. These parameters have been recommended by experts in soft shoreline habitat restoration as well as in the literature on soft shoreline restoration and ecological-monitoring literature. The closed circle (●) denotes a parameter that should be considered in monitoring restoration performance. Parameters with an open circle (❍) may also be measured depending on specific restoration goals.

Parameters to Monitor the Structural Characteristics of Soft Shoreline Habitats

Structural Characteristics

Parameters for Monitoring	**Physical**	Sediment grain size	Topography/ Geomorphology	**Hydrological**	Tides/ Hydroperiod	Wave energy	**Chemical**	pH, salinity, toxics, redox, Dissolved oxygen
Hydrological								
Physical								
Shear force at sediment surface						❍		
Water level fluctuation over time					●			
Chemical								
Salinity (in tidal areas)					❍			❍
Soil/Sediment								
Physical								
Basin elevations			❍					
Geomorphology (slope, basin cross section)			●		●			
Organic content		●			●			
Percent sand, silt, and clay		●						
Sedimentation rate and quality		❍	❍		❍			

Parameters to Monitor the Functional Characteristics of Soft Shoreline Habitats

Functional Characteristics

Parameters	Biological: Contributes to primary production	Biological: Provides breeding grounds	Biological: Provides feeding grounds	Biological: Provides refuge from predation	Physical: Affects transport of suspended/dissolved material	Physical: Alters turbidity
Geographical						
Acreage of habitat types	●	●	●	●	●	●
Biological						
Plants						
Species, composition, and % cover of:						
Algae	❍	❍	❍	❍	❍	❍
Herbaceous vascular	❍	❍	❍	❍	❍	❍
Invasive species		❍	❍	❍		
Interspersion of habitat types		❍	❍	❍	❍	❍
Plant health (herbivory damage, disease[13])			❍			
Biological						
Animals						
Species, composition, and abundance of:						
Birds		●	●	●		
Fish		❍	❍	❍		
Invasive species			❍	❍	❍	❍
Invertebrates		●	●	●		
Hydrological						
Physical						
Fetch					❍	❍
Shear force at sediment surface					❍	❍
Trash			❍		❍	❍
Water level fluctuation over time		●	●	●	●	●
Chemical						
Chlorophyll concentration	❍		❍		❍	❍
Salinity (in tidal areas)	❍	❍	❍			
Toxics		❍	❍			
Soil/Sediment						
Physical						
Geomorphology (slope, basin cross section)		●	●	●	●	●
Sediment grain size (OM[15]/sand/silt/clay/gravel/cobble)					❍	❍
Sedimentation rate and quality					❍	❍
Chemical						
Organic content in sediment			❍		❍	❍
Pore water salinity (in tidal areas)	❍					

[13] Organic matter.

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APPENDIX I: SOFT SHORELINE HABITATS ANNOTATED BIBLIOGRAPHY

This annotated bibliography contains summaries of restoration case studies and basic ecological literature. It is designed to provide restoration practitioners with examples of previous restoration projects as well as overviews of papers from the ecological literature that offer more detail than that covered in the associated chapter. Entries are presented from both peer reviewed and grey literature. They were selected through extensive literature and Internet searches as well as input from reviewers. They are not, however, a complete listing of all of the available literature. Entries are arranged alphabetically. Wherever possible, web addresses or other contact information has been included in the reference to assist readers in easily obtaining the original resource. Summaries preceded by the terms '*Author Abstract*' or *'Publisher Introduction*' or similar descriptors were taken directly from their original source. Summaries without such descriptors were written by the authors of the associated chapter.

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Author Abstract. The purpose of this study is to clarify the effects of wave and tidal actions on the penetration of spilled oil stranded on tidal flats and to evaluate the influence of the penetrated oil on seawater infiltration using tidal flat simulator. A simulator used was composed of tidal flat, wave maker, tide controlling device, temperature controlling system, and computer controlling system. The infiltrations of seawater and fuel oil C into tidal flats were visualized using transparent glass beads as tidal flat sediments. Penetration behaviour of the spilled oil into the sediments was significantly different from that of seawater. Seawater infiltrated into the sediments both by wave action and tidal fluctuation, while fuel oil C penetrated by tidal movement only. The infiltration of seawater was reduced by penetrated oil. This result indicates that the penetrated oil diminishes infiltration of seawater into the sediments and thus results in the reduction in the supply of oxygen, nutrients, and organic matter to the benthic organisms in tidal flat.

Collins, M. 1996. The high-frequency in situ measurement of coastal zone processes, p. 521. In Duursma, E. (ed.), Conference on the Coastal Change, Bordomer-95. Proceedings Jointly Organized by the Intergovernmental Oceanographic Commission of UNESCO (IOC) and Bordomer organization (France), Bordeaux (France), 10-16 February 1995 Workshop Report. Intergovernmental Oceanographic Commission. Paris 105 Supplemental. UNESCO, Paris, France.

Author Abstract. The understanding of coastal zone processes has been approached (by oceanographers, geologists, and engineers) on a variety of scales, both temporally and spatially. Hence, on the one hand, beach stability constitutes part of an overall sediment transport system incorporating: riverine inputs, sometimes ephemeral; the onshore-offshore transport of material, and the loss of sediment through submarine canyons, intercepting the adjacent continental shelf or shoreline. At the same time, there is a need to understand the response of beach profiles to extreme events such as short-term effects. Such process-response mechanisms, on the basis of scale extrapolation, control the evolution and development of the associated coastal morphology. Sediment transport mechanisms, at various scales, have been investigated using a variety of techniques including field measurements and (1D, 2D and 3D) numerical modelling. In some cases, conventional instrumentation and modelling has been used; in others, specifically-designed experimentation or instrumentation has been utilized. Against a background of the development of regional course-grain (conceptual) sediment transport model for a section of the coastline and inner continental shelf of southern England, a bottom-mounted tripod system (TOSCA) has been developed. The system was designed to examine the movement of shingle, under combined wave and current activity, in water depths of up to 20 m. Hydrodynamic conditions were monitored using electromagnetic meters (currents) and pressure sensors (waves). Movement of the sediment particles was detected using SGN self-generated noise), caused by interparticle collision. For comparison, regional patterns of movement were identified on the basis of: sea bed sampling; geophysical (side-scan sonar) surveying; and the numerical modelling of hydrodynamic conditions. A high-frequency monitoring system, similar to TOSCA, has been used on adjacent sandy beaches. The resuspension of sand has been related here to the presence of "wave groups" and, in comparable laboratory studies, to pore pressure fluctuations. Following the description of integrated fieldwork, modelling and laboratory programmes, designed to understand process-response processes and parametise the boundary conditions for models, consideration will to be given to: (i) the utilization of site-specific measurements to large-scale sections of the coastline; and (ii) extrapolation of short-term measurements of extreme events to long-term coastal evolution. The scientific objectives described affect utilization of the coastal zone with particular reference to the artificial replenishment of beaches and dredging activities.

Danufsky, T. and M. A. Colwell. 2003. Winter shorebird communities and tidal flat characteristics at Humboldt Bay, California. *Condor* 105:117-129.

Author Abstract. We examined winter (November-January) shorebird use at 19 sites around Humboldt Bay, California, an important site for nonbreeding shorebirds. We analyzed species richness (number of species), species densities, and incidences (presence/absence) in relation to habitat characteristics (tidal flat width, channelization, standing water, timing of tidal ebb, and sediment particle size). We included site area in analyses of incidence, and site area and substrate heterogeneity in the species richness analysis. We observed a total of 19 species, 8-16 at individual sites, and this variation correlated with substrate heterogeneity. Substrate particle size correlated positively with Sanderling (*Calidris alba*) incidence and negatively with American Avocet (*Recurvirostra americana*) incidence. Amount of standing water correlated positively with Whimbrel (*Numenius phaeopus*) and negatively with dowitcher (*Limnodromus griseus* and *L. scolopaceus*) incidence. Width of tidal flat correlated negatively with Whimbrel incidence. Sites at which tides ebbed earliest had higher incidences of Whimbrel and Sanderling and higher densities of Long-billed Curlew (*Numenius americanus*), but lower yellowlegs (*Tringa melanoleuca* and *T. flavipes*) densities. The amount of channelization correlated positively with curlew densities. These habitat relationships suggest that alteration of tidal flats at Humboldt Bay and elsewhere in coastal habitats has the potential to adversely affect patterns of shorebird distribution.

Dernie, K. M., M. J. Kaiser, E. A. Richardson and R. M. Warwick. 2003. Recovery of soft sediment communities and habitats following physical disturbance. *Journal of Experimental Marine Biology and Ecology* 285-286:415-434.

Author Abstract. Physical disturbance in soft sediment habitats disrupts the sediment structure and can lead to the death or emigration of resident biota. Current methods used to quantify the response of benthic assemblages to physical disturbance are time consuming and expensive, requiring the analysis of a time series of samples to ascertain the time taken for a disturbed area to converge on a condition similar to that found in adjacent control areas (the recovery time). Researchers designed an experiment that studied the effects of two intensities of physical disturbance on both the habitat and fauna of a sheltered sand flat to ascertain whether the recovery of the biota could be predicted from physical attributes of the habitat. Benthic community recovery from the lower intensity disturbance occurred within 64 days of the disturbance, whereas recovery after higher intensity disturbance did not occur until 208 days post-disturbance at this site. Sediment granulometry and percentage organic content did not alter as a result of the disturbance in either treatment. However, the depth of water that remained in the disturbed pits decreased with time, and correlated with the temporal changes in community structure. Although this was the most crude physical parameter measured it best described the recovery process of the fauna and may encapsulate the entire suite of other more subtle habitat changes that occur at the same time. By quantifying the persistence of physical features in different soft sediment habitats it might be possible to develop a more amenable and rapid framework for assessing the longevity of the effects of physical disturbance.

Dolphin, T. J., T. M. Hume and K. E. Parnell. 1995. Oceanographic processes and sediment mixing on a sand flat in an enclosed sea, Manukau Harbour, New Zealand. *Marine Geology* 128:169-181.

Author Abstract. Studies of oceanographic and sedimentary processes on intertidal sandflats in an enclosed sea were undertaken to gain better understanding of the factors controlling the mixing and dispersal of sediment bound contaminants. Understanding interactions between wave action and sediment transportation will aid in restoration monitoring techniques for soft shoreline habitats. Field investigations included a 90-day process experiment during which wind, waves, tidal currents, tides, depth of disturbance, and sand flat morphology were measured, and 27 months of sand flat profile monitoring. Sediment entrainment by strong spring tidal currents is restricted to the middle and lower regions of the sand flat which are inundated during the peak tidal flows. The upper 2-3 cm of sediment is re-worked across the middle and upper sand flat by mild storm wave events (H sub(s) = 70 cm), which occurred four times during the 90-day experiment. Numerous ridges and runnels in the upper sandflats are wave-formed features and are maintained by the lack of currents of sufficient magnitude to re-work the features. The ridge and runnel morphology is testimony to large infrequent storm events which re-work the sediment to depths of 20 cm. Such storms are an important mechanism for the release of contaminants and were recorded on 3 occasions in the 27 month profile record.

Dugan, J. E., D. M. Hubbard, D. L. Martin, J. M. Engle, D. M. Richards, G. E. Davis, K. D. Lafferty and R. F. Ambrose. 2000. Macrofauna communities of exposed sandy beaches on the southern California mainland and Channel Islands, pp. 339-346. In Browne, D. R., K. L. Mitchell, and H. W. Chaney (eds.), Proceedings of the Fifth California Islands symposium. United States Department of the Interior, Minerals Management Service, Pacific OCS Region, Camarillo, CA.

Author Abstract. Exposed sandy beaches are important intertidal habitats and coastal resources in southern California. A high proportion of the mainland coast (74%, 93%, and 66% of Santa Barbara, Ventura, and Los Angeles counties, respectively) is sandy beach, much of which is heavily used by humans. Lower proportions of the California Channel Island coasts are sandy (52%, 33%, and 14% of San Miguel, Santa Rosa, and Santa Cruz islands, respectively). Island beaches receive little direct human disturbance and some are important rookeries for pinnipeds and nesting birds. Recent studies used similar methods to sample macrofauna and other factors on 36 sandy beaches of the southern California mainland and Channel Islands. Monitoring of physical characteristics, macrophyte wrack, and selected macrofauna species occurs only on Santa Rosa Island beaches. The beaches sampled were primarily modally intermediate morphodynamic types. Species richness, abundance, and biomass of macrofauna inhabiting exposed sandy beaches in southern California were high compared to values reported for similar beaches of other regions. Species richness was higher on mainland beaches than on island beaches. Species richness and abundances of selected taxa were positively correlated with macrophyte wrack cover. Beach grooming practices that remove wrack may have significant impacts on macrofauna communities. Understanding how sandy beaches support macrofauna as well as other species of the ecological community will aid in the development of restoration monitoring plans.

Dugan, J. E. and A. McLachlan. 1999. An assessment of longshore movement in *Donax serra* Roeding (Bivalvia: Donacidae) on an exposed sandy beach. *Journal of Experimental Marine Biology and Ecology* 234:111-124.

Author Abstract. Peak abundances of intertidal populations of a donacid bivalve, *Donax serra*, occur 10-23 km from major river mouths along exposed sandy beaches of log-spiral bays on the coast of southeast Africa. Post-settlement eastward movement of *D. serra* from areas of spat settlement by prevailing longshore currents has been suggested as the mechanism which results in the observed population distributions. To estimate the net rates of longshore movement in intertidal *D. serra* on one of these exposed beaches, we developed and used a novel technique. A metal detector was used to track net change in the positions of intertidal juvenile and adult clams (37-67 mm shell length, 1-3 + years) with aluminum tags glued to the shells over a 3-month period during the austral fall and winter. Estimated net longshore movement of tagged clams ranged from 0.19 to 0.80 m day^{-1}. The net movement of tagged clams was primarily to the east along the beach but the direction of longshore movement varied during the study. Net rates of longshore movement were not correlated with clam size. The burrowing rates and the condition of recaptured tagged individuals were not significantly different from untagged clams after 2 months. The results of this study suggest that average longshore movement rates of intertidal clams, > 1 year of age, along the beach are low and the animals are relatively sedentary. The technique developed and used here to estimate net longshore movement rates in *D. serra* allowed us to successfully recapture and track tagged individuals with very minimal disturbance to the intertidal habitat and associated fauna. Use of this novel technique could potentially enhance investigations of post-settlement movement, growth, zonation, competitive interactions and other aspects of the ecology of mobile soft sediment macrofauna. Understanding faunal use of sandy beaches will be useful for developing efficient management and restoration monitoring plans.

Fischer, R. L., K. R. Slocum, J. E. Anderson and J. E. Perry. 1998. Use of Digital Multispectral Video for Littoral Zone Applications. NTIS, Springfield, VA. NTIS accession number: ADA354816.

Author Abstract. Digital multispectral videography was obtained over Parramore Island, VA in an effort to extract information concerning vegetation communities, micro elevation changes, soil texture, and soil moisture conditions. These information categories would then be used to assist in tactical near-shore decisions, such as cross country mobility, avenues of approach, bivouac sites, and landing areas, and to also provide greater insight concerning environmental management activities within installation natural resource communities. Flightlines extending from the open ocean to the bayside lagoons were collected at both 0.25 meter and 0.5 meter ground spatial resolution. Through image analysis and ground truth verification, the multispectral videography was successful in separating the basic ecological communities of seaside beach, undulating dune-ridge/valley complex, maritime forest, salt marsh, tidal flat, and bays.

Frid, C. L. J., W. U. Chandrasekara and P. Davey. 1999. The restoration of mud flats invaded by common cord-grass (*Spartina anglica*, CE Hubbard) using mechanical disturbance and its effects on the macrobenthic fauna. *Aquatic Conservation: Marine and Freshwater Ecosystems* 1:47-61.

Author Abstract. The growth of the common cord-grass, *Spartina anglica,* across many temperate coastlines has resulted in a reduction in the extent of tidal flats. Its colonization has reduced the abundance of macrobenthic fauna and hence has had a direct effect on the feeding of shorebirds. Although the use of chemical methods has proven successful in controlling *Spartina* swards on tidal flats, factors such as environmental and human health concerns have stimulated a search for alternative control methods. However, any such control method must not impact the macrobenthic fauna. The effectiveness of a physical disruption to control *Spartina* swards on tidal flats was investigated in the saltmarsh at Lindisfarne NNR, UK. The sediment was disturbed by a light-weight tracked vehicle until the *Spartina* swards were dislodged and buried within the sediment. The post-disturbance dynamics of the infauna in the disturbed area was investigated 1, 12, 31, 92 and 384 days after the disturbance. In spite of the drastic change brought about in the flora, there was no evidence that the infauna were impacted by the disturbance at any sampling time. Two possible mechanisms to explain the absence of changes in the abundance of the infauna are discussed with special reference to the unconsolidated nature of the sediment and the high mobility of the adult infauna. The abundance of *Spartina* swards in the disturbed area was lower than that in the undisturbed area. Physical disturbance to *Spartina* swards by the tracked vehicle seems to be an appropriate method for its control in tidal flats which obviates the need, with associated financial costs and environmental risks, of chemical control.

Garcia-Mora, M. R., J. B. Gallego-Fernandez and F. Garcia-Novo. 2000. Plant diversity as a suitable tool for coastal dune vulnerability assessment. *Journal of Coastal Research* 16:990-995.

Author Abstract. The investigation reported here is concerned with the use of plant diversity measures for coastal dune monitoring. The original set of recorded plant species on dune systems was broken into 3 functionally homogeneous groups, which allow ecological comparisons among foredune vegetation on a much wider sense than traditional taxonomic approaches. Plant diversity was measured both, as species richness and as the rate of species number increase with area. Plant diversity values were tested as a dependent variable of a coastal dune vulnerability index. Increasing coastal dunes vulnerability, caused by natural or human events, lowered the rate of species increase with area within the plant functional type associated to prograding foredunes. Results suggest that plant diversity within this functional type, measured as the slope of the species-area curve, may be used as a management tool for predicting coastal dune vulnerability.

Govender, Y. and M. R. Jury. 2000. Long-term Monitoring of South Africa's Coral Coast as Part of C-Goos, p. 1. The Tenth Southern African Marine Science Symposium (SAMSS 2000): Land, Sea and People in the New Millennium, Abstracts.

Author Abstract. To improve management of the north coast of South Africa where coral reefs are present, a long-term monitoring project is proposed to quantify and understand the: diversify of marine species in the coral reefs; dynamic behaviour of sandy beaches; diversify of vegetation in the coastal dune forests; human uses and impacts; and potential for limited development. The bi-annual observational program at Mabibi will include measurement of: sand height along three transects; near-surface wind profiles; near-shore currents using drifting drogues; sea and air temperature and soil moisture; swell height and period bio-diversify assessment of coral species; bio-diversify assessment of dune vegetation; vehicular, pedestrian, and snorkeling traffic. In addition soil and water samples will be collected for analysis of fertility and pollution. Demographic surveys of local communities, visiting tourists, conservation officers and private developers will be conducted. The following Key Questions will be addressed: is the near-shore ocean circulation wave, wind, or current driven? And does the net longshore drift display seasonal, synoptic, and tidal cycles; how is dune vegetation de-stabilized and overtopped by blown sand from the incessant NE winds; how will human pressure arising from local consumption, visitors from Sodwana and coastal developments alter the ecosystem.

Irish, J. L. and C. Truitt. 1995. Beach fill storm response at Longboat Key, Florida: Sand wars, sand shortages and sand-holding structures, pp. 103-117. In Tait, L. S. (ed.), Proceedings of the 1995 National Conference on Beach Preservation Technology. Florida Shore and Beach Preservation Association, Tallahassee, FL, USA.

Author Abstract. Over two million cubic meters of compatible sand were placed in the spring of 1993 to restore the severely eroded Gulf beaches of Longboat Key, Florida. The fill section begins just north of New Pass and extends north for over 14 km. The source of the borrow material was the ebb shoal at New Pass on the south and at Longboat Pass on the north end of the Key. The conditions imposed as part of the several regulatory permits for the project defined an overall monitoring program which included periodic beach profile surveys. The surveys were performed using conventional hydrographic surveying techniques. Three additional surveys were performed to supplement the required monitoring and to evaluate an alternate surveying technique. These surveys were conducted using the Scanning Hydrographic Operational Airborne Lidar Survey (SHOALS) system, developed by the United States Army Engineer Waterways Experiment Station. The SHOALS system collected very detailed bathymetry along an 8 km section of the restored beach, producing a 4 m by 4 m uniform horizontal grid with measured depths from 1 m to 9 m. The initial fill adjustment during the first project year appeared to be dominated by storm events. A goal of the present effort was to evaluate the beach response to the wave climate during the second year monitoring. Directional wave information was collected throughout the period in order to quantify any significant storm activity and relate any observed beach changes.

Jackson, N. L. 1999. Evaluation of criteria for predicting erosion and accretion on an estuarine sand beach, Delaware Bay, New Jersey. *Estuaries* 22:215-223.

Author Abstract. Predicting erosion and accretion of sand beaches in estuaries is important to managing shoreline development and identifying potential relationships between biological productivity and beach change. Wave, sediment, and profile data, gathered over twenty-nine days on an estuarine sand beach in Delaware Bay, New Jersey, were used to evaluate the performance of four criteria that predict beach erosion and accretion due to wave-induced cross-shore sediment movement. Each criterion defines a relation, between a wave and sediment parameter, and includes a coefficient that discriminates beach erosion and accretion events. Relations, based on small-scale laboratory and field data, were evaluated for predicting erosion or accretion at the study site. Significant wave heights at the study site, monitored near high water, ranged from 0.08 to 0.52 m with periods of 2.4 to 12.8 s. Median grain sizes of sediments on the beach foreshore, gathered at low water, ranged from 0.33 to 0.73 mm. All four criteria showed a clustering of erosion and accretion events. Relations derived from small-scale laboratory data were better predictors of erosion on the profile at the field site than those derived from field data gathered on exposed ocean environments. The planar profile and dominance of incident waves of low height and short period are similar to laboratory conditions characterized by initial planar beach slopes and monochromatic waves. Decreasing the value of the empirical coefficient to account for the differences in the magnitude of wave energy and grain size increases the performance of the criteria tested to predict erosion of the profile.

Jaramillo, E., A. McLachlan and J. Dugan. 1995. Total sample area and estimates of species richness in exposed sandy beaches. *Marine Ecology Progress Series* 119:311-314.

Author Abstract. Recent studies have shown that macroinfaunal species richness of exposed sandy beaches increases from reflective to dissipative conditions. To analyse if this trend is affected by sampling strategies (primarily area sampled), we compared results from surveys carried out in different beach types of South Africa, Australia, and Chile. Total area sampled in those surveys was 4.5 m^2. The percentage of species predicted for each beach increased in relation to an increase in total sampling area. Only at a total sample area of 4 m^2 were most (> 95%) of the species present collected. Sampling areas of 1 m^2 and 2 m^2 result in average underestimations of nearly 40% and 20% of the species, respectively. Beaches harbouring the highest number of species (the most dissipative ones) need to be sampled more extensively to collect most of the species, as compared with beaches having lower species richness. A bibliographic survey showed that most of the studies carried out on sandy beaches have been based upon sampling areas considerably smaller than 4 to 4.5 m^2, suggesting that in many of the studies the sandy beach macrofauna was under-sampled.

Jutte, P. C., R. F. Van Dolah and P. T. Gayes. 2002. Recovery of benthic communities following offshore dredging, Myrtle Beach. South Carolina *Shore & Beach* 70:25-30.

Author Abstract. The Myrtle Beach Renourishment Project placed more than 6 million cu yd of sand on approximately 25 miles of beaches in the northern portion of South Carolina. The project was divided into three phases due to its large size. Nearshore dredging for the first phase occurred in 1996. More than 2.6 million cu yd of sandy sediments were removed to approximately 1 m below grade by a hopper dredge. Replicate benthic infaunal and sediment samples were collected quarterly from the borrow area and an undredged reference area from November 1995 until February 1998, with supplemental sampling occurring in February 1999. Sediment measurements were made of silt/clay, sand, $CaCO_3$, and organic matter content. Sediment composition at the borrow area underwent significant changes in sand, silt/clay, and $CaCO_3$ following dredging activity. Organic matter content at the borrow site was elevated after dredging occurred, with effects persisting throughout the study period. Biological effects at the dredged site, based on temporal and spatial comparisons, included altered diversity indices (H', J', and species richness), shifts in general taxonomic composition, and changes in numerically dominant species. The benthic infaunal assemblage in the borrow area recovered to pre-dredging conditions, showing signs of enhancement, within 27-30 months after dredging. The relatively rapid recovery of the dredged area was attributed to the use of hopper dredges that leave shallow dredged furrows separated by relatively undisturbed areas of sediment and biota.

McLachlan, A. 1996. Physical factors in benthic ecology: Effects of changing sand particle size on beach fauna. *Marine Ecology Progress Series* 131:205-217.

Author Abstract. This paper reports on the disposal of diamond mine tailings on a Namibian sandy beach. Coarse sand in the tailings greatly increases the grain size of the affected parts of the beach and thereby provides the opportunity to assess the effects of changing sand grain size on a beach when other physical variables are kept constant. Elizabeth Bay (Namibia) is 4 km long and was originally composed of fine sand which, exposed to moderate to heavy wave action, produced a log spiral bay with a dissipative beach. Tailings disposal in the centre of the bay has increased mean sand particle size from original values of 110 to 160 mu m to present values of 500 to 800 mu m with a concomitant conversion of beach morphodynamic state from dissipative to intermediate. Surveys of the 2 ends of the bay, which are relatively unaffected by disposal, and of an undisturbed similar bay nearby revealed intertidal benthic macrofauna communities with 15 to 20 species occurring in high abundance (24,120 to 129,276/m). In 3 transects in the affected area, species richness was 8 to 12 per transect and abundance was 640 to 4,710/m. Beds of the large sand mussel *Donax serra* have disappeared from the affected sector of the bay and peracarids typical of finer sands have been replaced by a more robust species. Regression analysis revealed significant correlations between community parameters (species richness and abundance) and both beach slope and particle size; ANOVA confirmed the significantly lower abundances of fauna in the affected areas. Smothering effects appeared to be localised and limited. This study has supported the hypothesis that an increase in sand particle size (on a beach where tide range and wave energy have remained constant) results in a change in beach state and a decrease in species richness and abundance.

Miller, D. L., M. Thetford and L. Yager. 2001. Evaluation of sand fence and vegetation for dune building following overwash by hurricane Opal on Santa Rosa Island, Florida. *Journal of Coastal Research* 17: 936-948.

Author Abstract. Santa Rosa Island, a barrier island located in the panhandle of Florida, was severely impacted by hurricane Opal's 3-4 m tidal surge in October 1995. Rapid reestablishment of the fragmented dune system through sand accumulation and stabilization is essential for many wildlife and plant species and protection of coastal structures against storm surge. Comparisons of sand accumulation rates for two biodegradable materials, three-fence orientations and non-fenced controls were assessed in a secondary dune position. Effect of winter and spring planting without supplemental water on survival and growth of nursery-grown sea oats and bitter panicum was monitored within the dunes. Wood and Geojute material sand fences in three orientations were installed at six sites. Sand accumulation associated with these fence material/orientation combinations and non-fenced controls was measured twice a year (1996-99). There were no significant differences in sand accumulation between Geojute and wood fences at most positions for the first eight months. Following this, Geojute degraded and its accumulated sand was no more than that of the controls 18 months after installation. Sand accumulation did not differ significantly among wood fence configurations at most distances from the fence. Through time the straight-conventional wood and perpendicular-wood fence treatments had consistently higher sand accumulation values compared to unfenced controls. While survival of transplanted sea oats and bitter panicum was not effected by season of planting, growth varied with planting season.

Moragwa, G. and J. Seys. 1995. Monitoring Waterbirds as Indicators of Ecosystem Health. Sustainable Development of Fisheries in Africa, Kenya, 211 pp. FISA, Nairobi Kenya.

Author Abstract. The universality and high mobility of birds makes them very easy to monitor since their presence or absence can act as an early warning system in assessing ecosystem health. From January 1994 to March 1995, regular counts of wetland birds were conducted in six major creek systems between Gazi-bay and the Sabaki river mouth. Spatial patterns showed that shorebirds were best represented (23) followed by large wading birds (15) then gulls and terns (10). Of these species, twenty were common in all the studied areas, while the rest had a more restricted distribution. In total, sixty species were encountered. Mida creek and Sabaki River mouth (Kenya) were the most important bird areas with 79% of the total numbers and 80% of the species respectively. In the marine environment, birds are on top of the food web and thus can indicate the presence of lower trophic groups. Local fishermen have been known to use sea gulls and terns to locate the presence of large schools of fish. Temporal patterns carried out in Mida Creek and Gazi Bay using boat surveys showed that piscivores were dominant in Gazi Bay, while benthivores were dominant in Mida Creek. Abiotic and geomorphological characteristics of the creeks were found to determine the relative abundance of different trophic groups of birds. The tidal flats exposed during low tide had the highest densities due to the feeding activity of many shorebirds and large waders. Food availability in terms of small benthic organisms (Mollusca, worms) tended to be higher in fine sediments than in coarse ones while sands banks were favorite habitats for certain crab species which are prey for birds such as crab plovers *Dromas ardeola*. Mangroves played a critical role for the safety of many species during high tide.

Nel, R., A. McLachlan and D. Winter. 1999. The effect of sand particle size on the burrowing ability of the beach mysid *Gastrosaccus psammodytes* Tattersall. *Estuarine, Coastal and Shelf Science* 48:599-604.

Author Abstract. Laboratory studies on the burrowing rates of the mysid shrimp, *Gastrosaccus psammodytes*, in a series of well-sorted sediments, determined whether (1) burial times were dependent on grain size and (2) if natural population distribution may be influenced by grain size on beaches. Assessing sediment particle size in relation to fauna activity will help practitioners understand soft shoreline use and contribute to developing an effective restoration monitoring plan. Burial times were tested in nine well-sorted sediments with grain size ranging from 90 to 2000 mu m. Large individuals (i.e., gravid females) were used. *G. psammodytes* burrowed fastest in 125-1000 mu m sand with mean burial times less than 1.6 s. Burial time increased to approximately 2 s in 90-125 mu m sand. *G. psammodytes* could not burrow in grain sizes coarser than 1000 mu m. *G. psammodytes* has been reported to occur on beaches with grain sizes ranging from 90 to 500 mu m but are uncommon on beaches with coarser sand. It appears that population distribution may be influenced by grain size that is probably not related to the animals' burial time ability, but rather their inability to burrow completely into coarse sand. Indirectly, grain size may also influence the morphodynamic state of a beach and therefore food availability since coarse-grained beaches tend to be reflective with little surf production.

Ohsaka, Y. and Y. Koshiishi. 1998. Effects of covering a tidal flat with sand for stock enhancement of tonguefish: A feasibility study at Ariake Sound in Kyushu, Japan, pp. 105-114. In. Howell, W. H., B. J. Keller, P. K. Park, J. P. McVey, K. Takayanagi, and Y. Uekita (eds.), Nutrition and Technical Development of Aquaculture.

Author Abstract. Ariake Sound is characterized by a high tidal range of about 6 m at the innermost part, and is known to have high productivity of commercially important species. However, the production of certain species has shown decreasing trends due to overfishing and deterioration in environmental conditions. Tonguefish are important species for gill net and trawl fisheries in this sound because of their high commercial values, but the annual catch of *Cynoglossus abbreviatus* has been decreasing markedly during the last decade. We assumed that covering the muddy tidal flat with sand as a means of habitat restoration would enhance the stock of these fish. In order to study the effects of sand covering on growth and survival of tonguefish *C. abbreviatus* and *C. joyneri* juveniles, we carried out periodic samplings by small beam trawl at the innermost part of the sound. A sand-covered area made in 1991, at about the lowest low water level, to increase the production of short-neck clams was selected as the survey area. The gear was towed along the lines set on the sand-covered area and a nearby muddy area as a control. The periodic samplings revealed that occurrence of *C. abbreviatus* in the sand-covered area increased with growth, but was not the case for *C. joyneri.* Since the larger juveniles of *C. abbreviatus* changed their prey animals from copepods to gammarids and mysids which were known to be abundant in the sandy area, it was suggested that covering the mud with sand provided beneficial effects at least for the growth and survival of this species.

Parikh, A. and N. Gale. 1998. Vegetation monitoring of created dune swale wetlands, Vandenberg Air Force Base, California. *Restoration Ecology* 6:83-93.

Author Abstract. A monitoring program was established on San Antonio Terrace at Vandenberg Air Force Base to compare vegetation development at two created wetland sites and six nearby natural wetlands. The reference wetlands were chosen to represent a range of habitats in dune swale wetlands on the Terrace. Vegetation in the reference wetland plant communities varies from low-growing herbaceous marsh species with open canopies to closed canopies dominated by shrub or tree species. Transects and plots for long-term vegetation monitoring were established in all the wetlands, stratified by plant communities in the reference wetlands and by geomorphic location in the newly created wetlands. Quantitative vegetation and environmental data were collected at all the sites; measures included species distributions, species cover, and topographical elevations. Over the first three years of monitoring, variations in groundwater depth at different geomorphic locations in the created wetlands resulted in a variety of physical conditions for plant growth. In the first year, more than 100 plant species were observed, the majority being natives. During the next two years, species richness at the created wetland sites remained relatively stable and was higher than at the reference sites. Statistical comparisons of vegetation parameters by analysis of variance and hierarchical clustering exhibited patterns of increasing similarity between the created and reference wetlands. Long-term monitoring will be continued to track the progress of vegetation at the created sites, and to assess their development relative to the reference wetlands.

Pickart, A. J., L. M. Miller and T. E. Duebendorfer. 1998. Yellow bush lupine invasion in northern California coastal dunes: Ecological impacts and manual restoration techniques. *Restoration Ecology* 6:59-68.

Author Abstract. We studied the ecological effects of the invasion of coastal dunes by *Lupinus arboreus* (yellow bush lupine), an introduced species, and used the results to develop manual restoration techniques on the North Spit of Humboldt Bay. Vegetation and soil data were collected in five vegetation types representing points along a continuum of bush lupine's invasive influence. We collected data on the number and size of shrubs, vegetation cover, and soil nutrients. One set of plots was subjected to two restoration treatments: removal of lupine shrubs only, or removal of all nonnative vegetation and removal of litter and duff. Treatments were repeated annually for four years, and emerging lupine seedlings were monitored for three years. Prior to treatment, ammonium and nitrate were found to increase along the lupine continuum, but organic matter decreased at the extreme lupine end. Yellow bush lupine was not the most significant variable affecting variation in soil nutrients. After four years, nonnative grasses, including *Vulpia bromoides, Holcus lanatus* (velvet grass), *Bromus* spp. (brome), and *Aira* spp. (European hairgrass), were significantly reduced in those restoration plots from which litter and duff was removed. Native species increased significantly in vegetation types that were less influenced by lupine. By the third year, soil variables differed among vegetation types but not by treatment. Bush lupine seedling emergence was higher, however, in plots receiving the litter and duff removal treatment. Based on these results, we conclude that bush lupine invasion results in both direct soil enrichment and indirect enrichment as a result of the associated encroachment of other nonnative species, particularly grasses. Although treatment did not affect soil nutrients during the period of this study, it did reduce establishment of nonnative grasses and recruitment of new bush lupine seedlings. Restoration should therefore include litter and duff removal. In areas that are heavily influenced by lupine and contain few native propagules, revegetation is also required.

Piehler, M. F., V. Winkelmann, L. J. Twomey, N. S. Hall, C. A. Currin and H. W. Paerl. 2003. Impacts of diesel fuel exposure on the microphytobenthic community of an intertidal sand flat. *Journal of Experimental Marine Biology and Ecology* 297:219-237.

Author Abstract. This study employed simulated spills of weathered diesel fuel and measured the initial effects on the intertidal sand flat microphytobenthic (MPB) communities. The goals were to examine the impacts of short-term (hours) and longer-term (days) exposure to petroleum on the native sand flat MPB in coastal North Carolina and to assess recovery of the community following the exposure. We assessed changes in biomass (chlorophyll a), primary productivity ^{14}C bicarbonate incorporation), photophysiology (P vs. I curves) and species composition (microscopy) and compared diesel exposed samples to unamended controls. We found that short-term impacts of diesel fuel pollution were confined to primary productivity and photophysiology of sand flat MPB. Short-term effects were only detected at relatively high concentrations that are not common outside of a major spill event. In the longer term, diesel fuel was again found to have effects on primary productivity, but at higher concentrations than would be likely to occur in industrialized coastal areas. However, negative impacts on photophysiology were detected at diesel fuel concentrations slightly above typical ambient conditions in coastal waters in industrialized areas. Biomass as measured by chlorophyll a was not affected by any concentration in the longer-term exposure to diesel fuel. Cell counts in the longer-term experiments found cyanobacteria had larger negative impacts from diesel fuel exposure than did diatoms. The recovery portion of this study showed the sand flat MPB communities were fairly resilient following both additions of diesel fuel. However, photophysiology and cell counts did not return to conditions equivalent to the control. Data from this study indicate that the effects of petroleum pollution on the MPB community of tidal sand flats should be considered alongside effects on other coastal microalgae in ecological and damage assessments.

Prandle, D., R. A. F. Flather, M. Regener, K. Duwe, W. Rosenthal, H. Gerritsen, G. Chapelain, J. Monbaliu, J. Ozer, J. Carratero, E. Alvarez, A. Jenkins and H. Wensik. 1999. Coastal Evolution Extending Short Term Simulations, pp. 307-308. In Barthel, K. G., H. Barth, M. Bohle-Carbonell, C. Fragakis, E. Lipiatou, P. Martin, G. Ollier, and M. Weydert (eds.), Third European Marine Science and Technology Conference (MAST conference), Lisbon, 23-27 May 1998: Conference Proceedings. European Commission DG 12 Science, Research and Development, Luxembourg.

Author Abstract. The objectives of this study were to (1) to identify how modeling and monitoring capabilities need to be developed and combined to provide estimates of coastal-nearshore sediment exchanges; and (2) to consider limits to long term predictability. Traditionally shoreline evolution has focused on coastal engineering aspects of the response of beaches to waves. This focus has recently been extended to include coastal-nearshore sediment exchange, reflecting concerns arising from acceleration in: climate change (sea level and storminess), offshore aggregate extraction, steepening of cross-shore slopes, adoption of soft-defense strategies (inc. beach nourishment) and recognition of large-scale interdependencies. Such large-scale sediment exchanges cannot be measured directly and the longer term impact on bathymetry may only be evident in shallow water. Thus models are required, linking dynamical simulations of tide, surge, wave and turbulence to 'dispersion' modules representing the erosion, transport, and deposition of a range of sediment types. The associated dynamical coupling of model components and subsequent evaluation against observations emphasizes the need for a Pre-Operational modeling approach. Monitoring is required to verify the sediment algorithms locally and the integrated depth changes in areas of rapid accretion/ erosion. In the MAST 111 program PROMISE, the North Sea was adopted as a focus because of the existence of forecasting systems for tides, surges and waves. Wave models were adapted for fine-scale application in near-shore shallow regions. Likewise the turbulence models were developed to incorporate wave-tide-surge interactions. Extensive data sets were then assembled to assess these various modules independently and overall. Parallel applications of the above models in the MAST 3 program SCAWVEX have indicated that existing models accurately simulate both currents and waves in the near-shore zone. Likewise the interaction between these parameters can be reproduced together with their impact on turbulence intensity and locally re-suspended sediments. Thus the dynamics and associated erosion, deposition and suspension of sediments can be accurately simulated (at least at such low sediment concentrations). Longer term (and thereby larger scale) simulations of sediment transport are bedeviled by the chronology of sediment availability and the resultant evolution of bed form etc. Likewise there are inaccuracies in specifying meteorological forcing and 'initial' bathymetry.

Rakocinski, C. F., R. W. Heard, S. E. LeCroy, J. A. McLelland and T. Simons. 1996. Responses by macrobenthic assemblages to extensive beach restoration at Perdido Key, Florida, USA. *Journal of Coastal Research* 12:326-353.

Author Abstract. In this study, we examine and monitored complex responses by macrobenthic assemblages to extensive beach restoration affecting 7 km of open shoreline at Perdido Key, Florida. Beach restoration consisted of two phases, beach nourishment and profile nourishment, each phase lasting roughly one year. Macrobenthic responses using an optimal impact study design incorporating ten macrobenthic surveys completed over a three-year period were examined. This study is important because of its geographical region, its relatively large spatial scale, its long duration, and its consideration of both nearshore assemblages from high energy sandy beaches and diverse assemblages from stable offshore habitats. The physical environment was altered by beach restoration through changes in depth profiles and sediment composition as well as through sediment dynamics. Various macrobenthic responses attributable to beach restoration included: decreased species richness and total density, enhanced fluctuations in those indices, variation in abundances of key indicator taxa, and shifts in macrobenthic assemblage structure. One long-term impact of beach nourishment at nearshore stations included the development of macrobenthic assemblages characteristic of steep depth profiles. Two long-term negative impacts of beach restoration at offshore stations included one from beach nourishment and another from profile nourishment. After beach nourishment, the macrobenthic assemblage structure changed markedly across a considerable offshore area in concert with increased silt/clay loading. Macrobenthic impacts from silt/clay loading were still evident at the end of the study, more than two years after beach nourishment. Macrobenthic populations fluctuated widely at the farthest seaward stations from apparent sediment disturbance, both during and after profile nourishment. These fluctuations involved total densities, species richness, and densities of key indicator taxa. Macrobenthic fluctuations continued through the end of the study, although profile nourishment was completed for more than one year prior to that time. Considerable macrobenthic recovery was apparent during the study, although macrobenthic recovery remained indeterminate in some places. Long-term macrobenthic impacts at several offshore stations supported the hypothesis that diverse offshore assemblages may be less resilient than contiguous nearshore sandy-beach assemblages.

Ray, G. L. 2000. Infaunal assemblages on constructed intertidal mudflats at Jonesport, Maine, USA. *Marine Pollution Bulletin* 40: 1186-1200.

Author Abstract. Dredged materials have been used to construct two mudflats near Jonesport, Maine (USA). A flat at Sheep Island was constructed in 1989 and along with an adjacent reference area (REF) has been monitored for infaunal assemblage development and sediment texture since 1990. The second site, Beals Island, an example of a much older constructed flat (CF), has been monitored since 1991. Infaunal taxa richness, total numerical abundance, species composition, and diversity values were similar between the Sheep Island natural and constructed sites within two years of construction. At Beals Island, taxa richness and other diversity measures were similar between sites, however, abundance and total biomass values were lower at the constructed site. Although total biomass was also lower at the Sheep Island CF than its REF, biomass values at both constructed sites (Sheep Island and Beals Island) were within the range of values previously reported for natural flats.

Rooney, J. J. B. and C. H. Fletcher. 2001. Climate variability and shoreline change along the Kihei Coast of Maui, Hawaii. Coastal Geotools '01. In Proceedings of the 2nd Biennial Coastal Geotools Conference. United States National Oceanic and Atmospheric Administration, NOAA Coastal Services Center, Charleston SC.

Author Abstract. It is difficult to overemphasize the importance of sandy beaches as a resource in the Hawaiian Islands. Despite their importance, beaches on all the main Hawaiian Islands have been degraded. On the island of Maui it has been estimated that one third of the original sandy beach has been lost or narrowed. Given the need for improved management of beach and coastal resources, this project is an effort to improve our understanding of these changes. It has examined movement of the shoreline over the last century at an erosion "hotspot" on the Kihei coast. The techniques and methods developed at this site are now being applied to all significant sandy shoreline areas on the island. To elucidate historical patterns of shoreline change we use soft-copy photogrammetric techniques to rectify available NOS T-sheets and aerial shoreline photographs. Years of coverage include T-sheets from 1900 and 1912 and photographs from 1949, 1960, 1963, 1975, 1987, 1988, and 1997. The landward boundary of the beach (vegetation line) and shoreline (beach step crest) are digitized on orthorectified photomosaics for each year of coverage. Historical movement of these features is measured along shore-normal transects spaced 20 m apart. Average annual erosion hazard rates (AEHRs) are determined for each transect with a reweighted least-squares regression applied to the most recent trend in shoreline position. AEHRs are used to calculate and plot the position of the 30-year erosion hazard line. A model was developed using seasonal beach profile data to estimate volumetric change for each transect, and area-wide rates of net longshore sediment transport (LST). Our data show that between 1900 and 1997 there was severe erosion at the southern end of the site but roughly three times more accretion to the north. Production and delivery of sand to the beach from the fringing reef fronting the site is estimated to account for 6% of the net gain. These changes began prior to 1912 and a major portion of the total change had occurred by 1949, prior to significant western perturbation of the coastline. This suggests that natural rather than anthropogenic forcing is primarily responsible. However, impoundment of sediment behind coastal armoring along one third of the site has contributed to littoral sediment deficiencies since about 1975. Kona storms are large, low-pressure systems approaching the islands from the southwest or west and accompanied by rain-bearing winds. Occasional large kona storms have been shown to cause significant erosion and northward LST along the Kihei coast. Genesis of kona storms changes in response to variations in ENSO activity, which in turn is modulated by the Pacific Decadal Oscillation (PDO). We find that patterns of the PDO cycle, kona storm activity, and LST are similar at multi-decadal time scales. We hypothesize that the general agreement in these records suggests a cause-and-effect relationship between the PDO and LST along the Kihei coast. If further research confirms this hypothesis, PDO-driven shoreline dynamics will be an important consideration in the successful management of Hawaii's south and west facing shorelines.

Samuelson, G. M. 2001. Polychaetes as indicators of environmental disturbance on subarctic tidal flats, Iqaluit, Baffin Island, Nunavut Territory. *Marine Pollution Bulletin* 42:733-741.

Author Abstract. The polychaetes of the tidal flats near the town of Iqaluit, Baffin Island were analyzed along gradients of environmental disturbance resulting from human activity. Sources of environmental disturbance include a sewage lagoon, garbage sites; and an area of the tidal flat that is cleared by bulldozer. Sampling of the tidal flats included 300 biological sediment cores taken from 75 sites along seven transects. Environmental disturbance has resulted in four zones of polychaete communities with increasing distance. The heavily disturbed zone is closest to the disturbances and is devoid of polychaetes. The disturbed zone follows and is characterized by low diversity the result of increased densities of a few opportunistic species such as, *Capitella capitata* sp. The moderately disturbed zone is characterized by increased species diversity due to organic enrichment from the disturbances. The undisturbed zone, located the furthest from the sources of disturbance, is characterized by moderate levels of diversity compared to the other three zones. Methods used in this study can contribute to monitoring whether disturbances have occurred during restoration and how disturbances impact species that are present.

Schoeman, D. S., A. Mclachlan and J. E. Dugan. 2000. Lessons from a disturbance experiment in the intertidal zone of an exposed sandy beach. *Estuarine, Coastal and Shelf Science* 50:869-884.

Author Abstract. Exposed sandy beaches are important, sensitive, and widespread coastal habitats. Although they have been studied for more than 50 years, investigators have been reluctant to attempt manipulative experiments due to the dynamic nature of these environments. Consequently, the ecology of exposed sandy beaches remains relatively poorly understood. We conducted a community-level, manipulative experiment involving a simulated anthropogenic disturbance on an exposed microtidal sandy beach in the Eastern Cape, South Africa; the first of its kind and scale. This study comprised pre- and post-impact sampling at an experimental site and two control sites. The impact involved excavating and removing a 200 m^2 quadrat of sand from the mid-intertidal of the experimental site to a depth of 0.3 m. The intention was to address the prediction that anthropogenic disturbances would be detectable if appropriate spatial and temporal scales were investigated. The following variables were monitored: transect gradient; species richness; macrofaunal abundance; and both the abundance and biomass of the dominant infaunal species, the beach clam *Donax serra* Roeding. Analyses revealed significant differences in temporal patterns of all response variables amongst sites. Some evidence linked these changes to the experimental disturbance, although impacts appear temporary, being ameliorated within, at most, one semi-lunar cycle. This confirms that it is possible to successfully conduct manipulative experiments on exposed sandy beaches. However, the uncontrollable, natural dynamics of the beach face, as expressed by intertidal gradient, contributed significantly to the description of spatio-temporal variation in biotic response variables. It is concluded that to isolate treatment effects from those of natural variation, two advances are necessary on the current research approach. First, experimental designs must take cognizance of the fact that exposed, microtidal sandy beaches have little in common with other intertidal habitats; and second, large-scale treatments must be replicated in space.

Tanner, C. D., J. R. Cordell, J. Rubey and L. M. Tear. 2002. Restoration of freshwater intertidal habitat functions at Spencer Island, Everett, Washington. *Restoration Ecology* 10:564–570.

Author Abstract. In November 1994 dikes were breached around Spencer Island, restoring tidal inundation and connections to the Snohomish River estuary, Washington. Approximately 23.7 ha (58.5 ac) of palustrine wetlands previously dominated by *Phalaris arundinacea* (reed canary grass) now experience diurnal tides and are in the process of transition to a freshwater tidal system. It was expected that brackish water would accompany the return of tidal influence to the site, but post-project monitoring has revealed little evidence of salinity. Pre- and post-project monitoring of changes in habitat function included aerial photography, vegetation and fish sampling, and benthic prey studies. To date site changes include (1) die back of pre-project vegetation, development of tidal mudflat, and emergent wetland habitats, with recruitment of vegetation typical of freshwater tidal wetlands; (2) presence of juvenile coho, chum, and chinook salmon that feed on invertebrate prey typical of the site; (3) presence of three distinct benthic invertebrate assemblages in the project area; and (4) some invasion by *Lythrum salicaria* (purple loosestrife). The unexpected freshwater conditions, the lack of published information about tidal oligohaline marshes in the Pacific Northwest, the use of the site by endangered salmonid species, and the invasion by an undesired plant species underscore the importance of long-term monitoring at the site.

APPENDIX II: SOFT SHORELINE HABITATS REVIEW OF TECHNICAL METHODS MANUALS

This Review of Technical Methods Manuals includes a variety of sampling manuals, Quality Assurance/Quality Control (QA/QC) documents, standardized protocols, or other technical resources that may provide practitioners with the level of detail needed when developing a monitoring plan for a coastal restoration project. Examples from both peer reviewed and grey literature are presented. Entries were selected through extensive literature and Internet searches as well as input from reviewers. As with the Annotated Bibliographies, these entries are not, however, a complete list. Entries are arranged alphabetically by author. Wherever possible, web addresses or other contact information is included in the reference to assist readers in easily obtaining the original resource. Summaries preceded by the terms '*Author Abstract'* or *'Publisher Introduction*' or similar descriptors were taken directly from their original source. Summaries without such descriptors were written by the authors of the associated chapters.

Cook Inlet Keeper. 1998. Volunteer training manual. Contact information: Cook Inlet Keeper, P. O. Box 3269, Homer, AK 99603, Phone # (907) 235-4068 and Fax # (907) 235-4069. http://www.inletkeeper.org/training.htm.

This Manual provides Cook Inlet Keeper volunteers with information needed to monitor water quality in the Cook Inlet watershed. It also provides guidelines for monitoring procedures that are currently included in the Keeper's Citizens' Environmental Monitoring Program (CEMP). Outlined in this document are safety and access issues; a monitoring overview which discusses areas such as water quality test methods, test parameters and sampling schedule; monitoring procedures which include: field procedure checklist, field observations, collecting the samples, testing procedures, sample custody and completing data sheets; equipment care and waste disposal; data management and reporting; and quality control. Additional information for methods and procedures used can be obtained from this manual.

Davies, J., J. Baxter, M. Bradley, D. Connor, J. Khan, E. Murray, W. Sanderson, C. Turnbull and M. Vincent. 2001. Marine Monitoring Handbook. UK Marine Science Project, and Scottish Association of Marine Science. Joint Nature conservation Committee, English Nature, Scottish Natural Heritage, Environment and Heritage Services. http://www.jncc.gov.uk/marine/mmh/Introduction.pdf.

The UK Marine Science Project developed this hand book to provide guidelines for recording, monitoring, and reporting characteristics and conditions of marine habitats. However, based on location and other environmental conditions methodologies will have to be modified to suit the structural characteristics of the habitat. This manual addresses the fundamentals and procedures for monitoring different parameters in marine habitats, management tools, and benefits and costs for developing a monitoring project. Topics presented in this document include establishing marine monitoring programs highlighting what needs to be measured and methods to use; provides guidance when developing a monitoring program; selecting proper monitoring techniques to attain precision and accuracy; and procedural guidelines for monitoring a specific marine habitat. Detailed information on the tools needed for monitoring marine habitats are described within the marine monitoring handbook.

Davis, G. E., K. R. Faulkner and W. L. Halvorson. 1994. Ecological Monitoring in Channel Islands National Park, California, pp. 465-482. In Halvorson, W. L. and G. J. Maender (eds.), The 4th California Islands Symposium: Update on the Status of Resources.

Author Abstract. Natural resource managers need to understand the natural functioning of and threats to ecosystems under their management. They need a long-term monitoring program to gather information on ecosystem health, establish empirical limits of variation, diagnose abnormal conditions, and identify potential agents of change. The approach used to design such a program at Channel Islands National Park, California, may be applied to other ecosystems worldwide. The design of the monitoring program began with a conceptual model of the park ecosystem. Indicator species from each ecosystem component were selected using a Delphi approach. Scientists identified parameters of population dynamics to measure, such as abundance, distribution, age structure, reproductive effort, and growth rate. Short-term design studies were conducted to develop monitoring protocols for pinnipeds, seabirds, rocky intertidal communities, kelp forest communities, terrestrial vertebrates, land birds, terrestrial vegetation, fishery harvest, visitors, weather, sand beach and coastal lagoon, and terrestrial invertebrates (indicated in priority order set by park staff). Monitoring information provides park and natural resource managers with useful products for planning, program evaluation, and critical issue identification. It also provides the scientific community with an ecosystem-wide framework of population information.

McCobb, T. D. and P. K. Wieskel. 2003. Long-Term Hydrologic Monitoring Protocol for Coastal Ecosystems. United States Geological Survey Open-File Report 02-497. 94 pp. http://water.usgs.gov/pubs/of/2002/ofr02497/

The United States Geological Survey (USGS) and the National Park Service have designed and tested monitoring protocols implemented at Cape Cod National Seashore. The monitoring protocols are divided into two parts. Part one of the protocol discusses the objectives of the monitoring protocol and presents rationale for the recommended sampling program. The second part describes the field, data-analysis, and data-management, and variables that are to be taken into consideration when monitoring (e.g., sea level rise, climate change and urbanization). This protocol provides consistency when monitoring changes in ground-water levels, pond levels, and stream discharge. The monitoring protocol not only establishes a hydrologic sampling network but provides reasoning for measurement methods selected and spatial and temporal sampling frequency. Data collected during the first year of monitoring and hydrologic analyses for selected sites are presented. Long-term hydrologic monitoring procedures performed at the Cape Cod National Seashore may also assist set a template for deciphering findings of other monitoring programs.

Morton, R. A., M. P. Leach, J. G. Paine and M. A. Cardoza. 1993. Monitoring beach changes using GPS surveying techniques. *Journal of Coastal Research* 9: 702-720.

Author Abstract. A need exists for frequent and prompt updating of shoreline positions, rates of shoreline movement, and volumetric nearshore changes. To effectively monitor and predict these beach changes, accurate measurements of beach morphology incorporating both shore-parallel and shore-normal transects are required. Although it is possible to monitor beach dynamics using land-based surveying methods, it is generally not practical to collect data of sufficient density and resolution to satisfy a three-dimensional beach-change model of long segments of the coast. The challenge to coastal scientists is to devise new beach monitoring methods that address these needs and are rapid, reliable, relatively inexpensive, and maintain or improve measurement accuracy. The adaptation of Global Positioning System (GPS) surveying techniques to beach monitoring activities is a promising response to this challenge. An experiment that employed both GPS and conventional beach surveying was conducted, and a new beach monitoring method employing kinematic GPS surveys was devised. This new method involves the collection of precise shore-parallel and shore-normal GPS positions from a moving vehicle so that an accurate two-dimensional beach surface can be generated. Results show that the GPS measurements agree with conventional shore-normal surveys at the 1 cm level, and repeated GPS measurements employing the moving vehicle demonstrate a precision of better than 1 cm. In addition, the nearly continuous sampling and increased resolution provided by the GPS surveying technique reveals alongshore changes in beach morphology that are undetected by conventional shore-normal profiles. The application of GPS surveying techniques combined with the refinement of appropriate methods for data collection and analysis provides a better understanding of beach changes, sediment transport, and storm impacts.

Oregon Watershed Enhancement Board. 1999. Oregon Aquatic Habitat: Restoration and Enhancement Guide. Salem Oregon, 97301, Phone # (503) 986-0178. http://www.oweb.state.or.us/publications/habguide99.shtml

This guide was developed to provide guidance on restoration and enhancement measures that would assist in aquatic ecosystem recovery. The guide is divided into five sections: An overview of restoration activities, activity guidelines, overview of agency regulatory functions and sources of assistance, grants and assistance, and monitoring and reporting. The purpose of this document is to provide information that will assist in developing effective restoration projects; to define standards and priorities that will be approve by state and receive funding or authorized restoration projects; to identify state and federal regulatory requirements and receive assistance in restoration projects. Additional information on monitoring techniques for salmonid restoration and guidelines and considerations for reporting restoration progress over time are described within the document.

Pohle, G. W. and M. L. H. Thomas. 2001. Monitoring Protocol for Marine Benthos: Intertidal and Subtidal Macrofauna. A Report by the Marine Biodiversity Monitoring Committee (Atlantic Maritime Ecological Science Cooperative, Huntsman Marine Science Centre) to the Ecological Monitoring and Assessment Network of Environment Canada. Contact information: Gerhard Pole, arc@sta.dfo.ca. http://www.eman-rese.ca/eman/ecotools/protocols/marine/benthics/intro.html.

This document provides methods used for sampling and monitoring intertidal and subtidal macrofauna. The information presented here is for monitoring and sampling in hard bottoms and soft bottoms habitats. The tools for monitoring these habitats allow changes in fauna abundance and diversity to be detected with regard to natural variability, and what elements are responsible for altering the habitat conditions. Depth and sediment grain size significantly affects species composition of benthic macrofauna therefore should be sampled at comparable depths and measured within a narrow scope size of grain size. Methods that are recommended for sampling intertidal and subtidal soft bottom areas and described in this document include subtidal grab sampler or corer methods for quantitative sampling and dredge and trawls for qualitative sampling in subtidal areas. Methods of analysis for data collected include: univariate (measures species richness), multivariate, graphical, indicator species and taxonomic reductions. Additional information on methods used for sampling is described in this document.

Raposa, K. B. and C. T. Roman. 2001. Monitoring Nekton in Shallow Estuarine Habitats. A Protocol for the Long Term Monitoring Program at Cape Cod National Seashore. 39 pp. Narragansett Bay National Estuarine Research Reserve, Prudence Island, RI and National Park Service, Graduate School of Oceanography, University of Rhode Island, Narragansett, RI. Contact information: Kenny@gso.uri.edu. http://www.nature.nps.gov/im/monitor/protocoldb.cfm

Author Abstract. Long term monitoring of estuarine nekton has many practical and ecological benefits but efforts are hampered by a lack of standardized sampling procedures. This study develops a protocol for monitoring nekton in shallow (<1m) estuarine habitats for use in the Long Term Coastal Monitoring Program at Cape Cod National Seashore. Sampling in seagrass and salt marsh habitats is emphasized due to the susceptibility of each habitat to anthropogenic stress and to the abundant and rich nekton assemblages that each habitat supports. Extensive sampling with quantitative enclosure traps that estimate nekton density is suggested. These gears have a high capture efficiency in most habitats and are small enough (typically 1m^2) to permit sampling in specific microhabitats. Other aspects of nekton monitoring are discussed, including seasonal sampling considerations, sample allocation, station selection, sample size estimation, parameter selection, and associated environmental data sampling. Developing and initiating long term nekton monitoring programs will help track natural and human-induced changes in estuarine nekton over time and advance our understanding of the interactions between nekton and the dynamic estuarine environments.

Shelton, L. R. 1994. Field guide for collecting and processing stream-water samples for the National Water Quality Assessment Program. U.S. Geological Survey Report 94-455, Sacramento, CA. http://ca.water.usgs.gov/pnsp/pest.rep/sw-t.html

Author Abstract. The U.S. Geological Survey's National Water-Quality Assessment program includes extensive data-collection efforts to assess the quality of the Nation's streams. These studies require analyses of stream samples for major ions, nutrients, sediments, and organic contaminants. For the information to be comparable among studies in different parts of the Nation, consistent procedures specifically designed to produce uncontaminated samples for trace analysis in the laboratory are critical. This field guide describes the standard procedures for collecting and processing samples for major ions, nutrients, organic contaminants, sediment, and field analyses of conductivity, pH, alkalinity, and dissolved oxygen. Samples are collected and processed using modified and newly designed equipment made of Teflon to avoid contamination, including nonmetallic samplers (D-77 and DH-81) and a Teflon sample splitter. Field solid-phase extraction procedures developed to process samples for organic constituent analyses produce an extracted sample with stabilized compounds for more accurate results. Improvements to standard operational procedures include the use of processing chambers and capsule filtering systems. A modified collecting and processing procedure for organic carbon is designed to avoid contamination from equipment cleaned with methanol. Quality assurance is maintained by strict collecting and processing procedures, replicate sampling, equipment blank samples, and a rigid cleaning procedure using detergent, hydrochloric acid, and methanol.

Trippel, E. A. 2001. Marine Biodiversity Monitoring: Protocol for Monitoring of Fish Communities. A Report by the Marine Biodiversity Monitoring Committee (Atlantic Maritime Ecological Science Cooperative, Huntsman Marine Science Centre) to the Ecological Monitoring and Assessment Network of Environment Canada. http://www.eman-rese.ca/eman/ecotools/protocols/marine/fishes/intro.html#Rationale

This document presents a monitoring protocol for estimating species diversity of bottom dwelling or demersal fish species inhabiting the Canadian continental shelf regions. Monitoring protocols presented in this document can be used to monitor and evaluate fish communities in regions other than the Canadian continental shelf. Methods used to estimate the abundance of different demersal fish species include random stratified sampling and fixed station sampling. Using these standardized procedures helps to maintain precision. Some factors taken into consideration when monitoring fish communities include depth, temperature, salinity, seasonal shifts and diurnal behavior patterns. Additional information found in this document includes size of area and sampling intensity, sampling gear, sampling procedures, and treatment of data.

United States Environmental Protection Agency (USEPA). 1992. Monitoring Guidance for the National Estuary Program. United States Environmental Protection Agency, Office of Water, Office of Wetlands, Washington D.C. EPA Report 842-B-92-004.

This document provides guidance on the design, implementation, and evaluation of the required monitoring programs. It also identifies steps to be taken when developing and implementing estuarine monitoring programs and provides technical basis for discussions on the development of monitoring program objectives, the selection of monitoring program components, and the allocation of sampling effort.

Some of the criteria listed for developing a monitoring program and described in this document include: monitoring program objectives, performance criteria, establish testable hypotheses, selection of statistical methods, alternative sampling designs, use of existing monitoring programs, and evaluate monitoring program performance. Additional information on guidelines for developing a monitoring program is described in this document.

United States Environmental Protection Agency (USEPA). 1997. Volunteer Stream Monitoring: A Methods Manual. United States Environmental Protection Agency, Office of Water 4503F, Office of Wetlands, Washington D.C. EPA Report 841-B-97-003. http://www.epa.gov/volunteer/stream/stream.pdf.

This document has been developed to provide guidance for project managers when developing monitoring programs and describes the importance of volunteer monitoring. Described in the document are parameters that are monitored in stream habitats but will vary depending on project goals as well as methods used for sampling and conducting surveys.

Some methods described in this document include a watershed survey which is a visual assessment that describes the geography, land and water use, and potential and current pollution sources, history of the stream and its watershed; biological monitoring of macroinvertebrates which involves collecting, processing and analyzing aquatic organisms which can help determine health of the habitat. Surveys may be performed by using the rock rubbing method which involves randomly picking a rock from the bed and removing organisms from the rock surface or the stick picking method which collects several sticks from the stream, place in water and then remove it to examine organisms present on the stick over a pan; and water quality examination by measuring stream flow, temperature, turbidity, dissolved oxygen, pH, fecal bacteria, nutrients, total solids, conductivity and alkalinity. Additional information on methods and parameters used for monitoring stream habitats are described in detail in this document.

United States Environmental Protection Agency. 2002. National Beach Guidance and Required Performance Criteria for Grants. United States Environmental Protection Agency, Office of Water, Washington D.C. http://www.epa.gov/waterscience/beaches/grants/guidance/all.pdf

In order to be funded under the Beaches Environmental Assessment and Coastal Health Act (BEACH Act) coastal and Great Lakes state, local, and tribal governments must meet the performance criteria provided in the Act for implementing coastal recreation water monitoring and public notification programs. Performance criteria provides guidelines for monitoring and assessing coastal recreation waters adjacent to beaches so that water quality standards for pathogen indicators are achieved; and warning the public of increasing or likelihood of increasing water quality standards for pathogens indicators for coastal recreation. The document also outlines procedures that are used for sample handling, water sample collection, laboratory analysis, and predictive models to estimate indicator levels. Performance criteria requirements described in this document include: developing a risk-based beach evaluation and classification plan; developing a monitoring plan; providing reports on data collected; describing methods and assessments to be used; designing a public warning and risk communication plan; present measures that will be followed to alert EPA, local governments and the public; and public evaluation of the program. Additional information on performance criteria guidelines for beaches as well as methods and procedures used are described in this document.

United States Environmental Protection Agency (USEPA). 2002. Assessing and Monitoring Floatable Debris. EPA-842-B-02-002, Oceans and Coastal Protection Division, U.S. Environmental Protection Agency, Washington, D.C.

Assessing and Monitoring Floatable Debris document is devised to assist states, tribes, and local governments in producing assessment and monitoring programs that suit their needs for floatable debris in coastal waters. Floatable debris can negatively impact both wildlife and humans. For example, birds, fish, crustaceans negatively affected mainly by entanglement and ingestion whereas debris can endanger human health and safety through disease transmission or sharp objects which can result in injury. This document provides information on monitoring and assessment programs in the United States that address the impact of floatable debris, as well as some mitigation activities with reference to floatable debris. Also provided are: the types of floatable debris and their origins such as street litter, medical items, debris from industrial activities, sewage-related items, and a few others; a variety of plans and programs that have been created and implemented to evaluate and monitor floatable debris; recommendations for creating assessment and monitoring programs that can be found in the Marine Debris Survey Manual, created by the National Oceanic and Atmospheric Administration, and Chapter 16 of EPA's Volunteer Estuary Monitoring: A Methods Manual (USEPA, 1993) and; provides various examples of future prevention and mitigation activities affiliated with floatable debris. This document should provide the basis for monitoring debris that can affect the soft shoreline ecologically, economically, and recreationally.

Wenner, E. L. and M. Geist. 2001. The National Estuarine Research Reserves Program to Monitor and Preserve Estuarine Waters. *Coastal Management* 29:1-17.

The National Estuarine Research Reserve (NERR) sites in 1992 coordinated a program that would attempt to identify and track short-term variability and long-term changes in representative estuarine ecosystems and coastal watersheds. Water quality parameters that were monitored include: pH, conductivity, temperature, dissolved oxygen, turbidity, and water level. Standardized protocols were also used at each site so that sampling, processing, and data management techniques were consistent among sites. Statistical techniques are being used to identify periodicity in water quality variables. Periodic regression analysis indicated that diel periodicity in dissolved oxygen is a larger source of variation than tidal periodicity at sites with less tidal amplitude. Authors of this document stress how understanding the functions of estuaries and how they change over time will help predict how these systems respond to change in climate and anthropogenic sources.

APPENDIX III: LIST OF SOFT SHORELINE HABITAT EXPERTS

The experts listed below have provided their contact information so practitioners may contact them with questions pertaining to the restoration or restoration monitoring of this habitat. Contact information is up-to-date as of the printing of this volume. The list below includes only those experts who were 1) contacted by the authors and 2) agreed to submit their contact information. Some of those listed also reviewed the associated habitat chapter. In addition to these resources, practitioners are encouraged to seek out the advice of local experts as well faculty members and researchers at colleges and universities. Engineering, planning, and landscape architecture firms also have experts on staff or contract out the services of botanists, biologists, ecologists, and other experts whose skills are needed in restoration monitoring. These people are in the business of providing assistance in restoration and restoration monitoring and are often extremely knowledgeable in local habitats and how to implement projects on the ground. Finally local, state, and Federal environmental agencies also house many experts who monitor and manage coastal habitats. In addition to the National Oceanic and Atmospheric Administration (NOAA), the Environmental Protection Agency (EPA), the Army Corps of Engineers (ACE), Fish and Wildlife Service (FWS), and the United States Geologic Survey (USGS) are important Federal agencies to contact for assistance in designing restoration and monitoring projects as well as potential sources of funding and permits to conduct work in coastal waterways.

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CHAPTER 9: RESTORATION MONITORING OF SUBMERGED AQUATIC VEGETATION

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INTRODUCTION

Submerged aquatic vegetation (SAV - referred to as Aquatic Bed in Cowardin et al. 1979) is a habitat created by vascular[4] plants that grow below the surface of the water. The plants are usually completely inundated throughout the growing season. Some SAV habitats may also contain a mix of open water and rooted, floating-leaved, and short-emergent vegetation. The distribution of SAV in a particular area is dependent on water depth, turbidity, and wave energy, the presence of grazers, and characteristics of the sediment. Salinity can also be important in tidal areas. Plant species diversity is greater in freshwater SAV habitats than marine habitats. Approximately 500-700 plant species in 50 genera (Sculthorpe 1967) have been cataloged for freshwater areas compared to just 50 species in 12 genera for marine settings (den Hartog, 1970 cited in Stevenson 1988).

SAV (freshwater, brackish, and marine) can greatly alter the physical, chemical, and biological nature of the water column that supports them. Dense stands of SAV slow water velocity, reducing turbidity and increasing sedimentation and nutrient cycling. Through the processes of photosynthesis and respiration of SAV themselves, their attached epiphytes, and the respiration of the animals they attract, SAV beds can have a tremendous influence on the pH, carbon dioxide (CO_2), and dissolved oxygen (DO) concentration of the water column (Wetzel 1983). Even in tidal areas, such as the Potomac River, that are subject to strong physical mixing forces, SAV can strongly influence DO, pH, and temperature differences within the water column of the bed at times of high biomass production (Dale and Gillespie 1977; Carter et al. 1988). The presence of SAV also increases the overall productivity of the water column, compared to unvegetated areas, as SAV brings nutrients up from the sediment into the water column where they can eventually be used by phytoplankton[5]. SAV are often colonized by epiphytes (algae and bacteria) that compete with their host plant for light but may also provide a better food source for herbivores than the host macrophytes[6]. SAV also helps to increase the overall species diversity of the area by creating low energy microhabitats in what might otherwise be a higher energy environment (Carpenter and Lodge 1986 and literature cited therein).

The structural and functional characteristics of SAV presented in this chapter have been compiled using literature from studies in marine, brackish, and freshwater habitats. While the particular plant and animal species that inhabit SAV habitats around the United States and its protectorates are very different, many of the core structural and functional characteristics and the parameters and techniques used to monitor them are quite similar. Light availability, turbidity, water velocity, wave energy, sediment grain size, basin topography, water source, hydroperiod, and nutrient chemistry make up the main structural

[1] 2205 Commonwealth Boulevard, Ann Arbor, MI 48105.
[2] 1305 East West Highway, Silver Spring, MD 20910.
[3] 101 Pivers Island Road, Beaufort, NC 28516.
[4] Some non-vascular plants such as the algae muskgrass (*Chara* spp.) are also often considered SAV.
[5] Algae suspended in the water column.
[6] Literally means 'large plants'. This term is often used as a general term for SAV since it incorporates both vascular and non-vascular plants visible with the naked eye.

characteristics of SAV beds and have similar influences on plant communities regardless of salinity[7]. In our review of the literature, we found occasional gaps in the literature for certain habitat types. By combining the literature we are able to provide the reader with a more comprehensive picture of all the characteristics that may be relevant in a restoration monitoring effort. As used in this chapter, the terms 'SAV' or 'macrophytes' refer to any submerged aquatic vegetation in marine, brackish, or freshwater settings. When information applies to a specific type of SAV and is *not* generally applicable to other forms, specific terms such as 'seagrass' or 'freshwater SAV' will be used. In addition, the term 'seagrasses' is also used to refer to those species found in higher salinities. The term 'freshwater SAV' includes those species that are generally found in freshwater (salinity < 0.5 ppt) as well as brackish areas (salinity 0.5 to 18.0 ppt), as many species can tolerate a wide range in salinity.

When preparing a restoration project and associated monitoring program, practitioners are encouraged to begin monitoring well in advance of implementing a restoration effort (i.e., collect baseline information). Pre-restoration monitoring can be used to select sites most conducive to successful restoration, determine which species to plant, what depths to plant at, which planting methods are most appropriate, whether or not exclosures to limit herbivory are needed, and what is the best time of year to plant. Post-restoration monitoring allows practitioners to document habitat functions and gage progress toward project goals. Without one or two years (or sometimes more) of pre-restoration data on water quality and the locations and abundance of any SAV already growing in or near the restoration site, practitioners cannot accurately evaluate post-implementation project performance.

ORGANIZATION OF INFORMATION

Following the rest of the Introduction, the primary structural characteristics of SAV relevant to restoration monitoring are presented. These characteristics will determine whether or not SAV is able to grow in a particular area or not and how well. Structural characteristics will often be the first ones monitored during a restoration project. Once the proper set of structural characteristics is in place and SAV are growing, functional characteristics (covered later in the chapter) may be added to the monitoring program. At the end of the chapter, readers will find two matrices that will help connect these structural and functional characteristics to the actual parameters that can be used to monitor them. Wherever possible, parameters from this list have been used in the text to help explain how they are used and any potential problems with using them. Following the discussion of each characteristic, sampling suggestions or tips directing practitioners to addition resources or examples are provided. When selecting methods and equipment for a monitoring project, careful consideration of the project goals and data required to assess them needs to take place before any equipment is purchased. Local or regional experts can assist in this process and should be consulted as to the precise method and equipment that could or should be used in any given location. An annotated bibliography of restoration-related SAV literature and a review of technical methods manuals are provided in Appendices I and II respectively to direct practitioners to more detailed information as needed.

HUMAN IMPACTS TO SAV HABITATS

Various human activities impact the survival and health of SAV populations and their ecological communities. Examples of impacts include:

[7] Salinity (in tidal areas) also helps determine which particular species can grow in a particular area and affects many of the functional characteristics common to SAV habitats as well. Unless extremely high levels are reached, however, salinity does not determine whether or not submerged aquatic vegetation can grow in an area.

- Heavy-metals carried in run-off from urban or industrial areas can be absorbed in plant roots and sicken or kill the plants
- Siltation smothers plants and increases turbidity
- Climate change causing erosion by rising sea level, increased storms, and increased ultraviolet irradiance
- Eutrophication increases the growth of algae that competes with SAV
- Mechanical damage from fishing, anchoring, and dredging as part of port or marina construction and maintenance directly removes SAV and increases turbidity, starving the plants of light
- Oil spills (particularly seagrasses), and
- Salinity levels altered due to development and associated changes in hydrology leading to changes in species composition or even death if levels get too high (Hervey Bay Dugong and Seagrass Monitoring Program 1997; Duarte 2002)

Quantitative assessments of SAV loss are hard to find as area estimates are simply not available or, when present, combine SAV and marsh habitats. A few regional examples, however, can be used to illustrate the severity of losses. In 1938, about 715 ha of SAV habitat were present in the Patuxent Estuary of the Chesapeake Bay. By 1990, SAV beds had either been completely destroyed or only small ephemeral beds were present (Stankelis et al. 2003). As of 2003, the Chesapeake Bay as a whole is estimated to have lost approximately 68% of its seagrass acreage (Blankenship 2004). In coastal wetlands along Lake Erie from the Detroit River to Vermillion, Ohio[8] marsh and associated SAV acreage was reduced from 4,000 km^2 (1,544 mi^2) in 1850 to 150 km^2 (58 mi^2) by the late 1980's (Herdendorf and Krieger 1989).

Recreation and commercial watercraft can also impact SAV beds and even lead to their complete destruction (Sargent et al. 1995). Propellers, anchors, trawl nets, and dredge equipment can damage the leaves, stems and roots of plants when dragged across the beds. Boats passing through an area may disturb sediments and increase turbidity or possibly smothering plants completely (Hervey Bay Dugong and Seagrass Monitoring Program 1997). Slow growing species such as turtle grass (*Thalassia testudinum*) do not recover rapidly after physical disturbance to rhizomes (Zieman 1976). Rhizomes are often disturbed by motorboat propellers, not through physical damage but from resuspension of sediments. The resuspension and removal of fine sediments can reduce light levels and lower pH and Eh[9] of the remaining sediment, thus altering conditions that are suitable for seagrass growth. This type of damage is common in shallow areas, between islands and keys, and other areas where boat traffic is high.

Oil spills can also impact SAV by reducing primary productivity and changing associated animal communities (Thorhaug et al. 1986). Thorhaug et al. (1986) studied various concentrations of oil on several seagrass species that dominate the Atlantic subtropical Greater Caribbean basin. The extent of impact varied between seagrass species. While all species tested showed reduced productivity, shoal grass (*Halodule wrightii*) and Manatee grass (*Syringodium filiforme*) were more vulnerable to oil exposure, while turtle grass was more tolerant. Oil spills can also impact other components of the community that depend upon seagrass habitats. For example, oil spills can negatively affect, and in some cases kill, juvenile fish and fish eggs. Fish moving through seagrass habitats that were exposed to very high concentrations of oils may experience acute toxicity resulting in death. The actual level of impact from oil spills varies depending on the type and amount of oil and the plant or animal species exposed.

[8] Approximately 1/3 of the lake's coastline on the U.S. side.
[9] Redox potential, the ability of the soil to perform certain chemical transformations. Covered in detail in Chapter 10.

Eutrophication, often caused by high nutrient inputs from agricultural and urban runoff, is another threat to SAV habitats (Duarte 2002). High nutrient concentrations affect SAV by causing epiphytes that cover the surface of plants and phytoplankton in the water column to grow rapidly, preventing sunlight from reaching submerged macrophytes. As SAV growth decreases the whole community may ultimately be destroyed. Increases in certain nutrients such as ammonium and nitrite can result in increased mortality, stunting, decreased density, and shoot patchiness for seagrasses such as posidon grass (*Posidonia oceanica)* (Pergent-Martini et al. 1995).

Some of the most common impacts to SAV beds have been the draining and diking of coastal wetlands for agriculture, heavy industry, and recreation (Jude and Pappas 1992; Edsall and Charlton 1997). Such practices can completely alter the hydrology and related functions of these systems. Fish, for example, can be cut off from historic spawning and nursery habitats. In addition, material export and nutrient and sediment dynamics can often become disrupted (Wilcox 1995). Sediments and nutrients that were historically filtered through coastal wetlands are then discharged directly into estuaries and other receiving water bodies. As a result, SAV beds can be smothered and the water quality of receiving bodies decreased (Minc 1998).

Water level management of some of the Great Lakes and shoreline stabilization around coastal development have also had an effect on vegetation communities in coastal wetlands, including SAV beds (Jude and Pappas 1992; Wilcox 1995). Stabilizing water levels to facilitate recreational and commercial shipping concentrates the erosive energy of wind and waves at one particular elevation along the shoreline. Although aquatic vegetation can dissipate erosive energy, prolonged erosion at one elevation can eventually overpower SAV and wash it away, leaving shoreline sediments unprotected. In addition, armoring both marine and Great Lakes coastlines with riprap or sea walls to protect urban or residential development only directs the erosive energy of waves downward (Johnson 1991; Tsai et al. 1998; Davis and Streever 1999), leading to the erosion of plants, less mobile animals, sediments, seed banks, and reducing the possibility of regeneration of aquatic vegetation.

RESTORATION EFFORTS

Various coastal restoration projects have been initiated throughout the United States in an effort to increase the amount of SAV acreage and maintain SAV functions in support of coastal ecosystems (Fonseca 1992; Fonseca et al. 1998). Restoration can be done by taking transplants from healthy habitats, using seeds or other propagules, or by natural recolonization once the habitat has suitable environmental conditions (Fonseca 1992; Granger et al. 2002). Transplanting SAV can be very successful if the habitat requirements of SAV are also met. Examples of successful seagrass projects using eelgrass (*Zostera marina*) include projects by Thayer et al. (1985) and Orth et al. (1999). In both projects, restoration efforts involved transplanting shoots with rhizomes by hand into the sediment. Eelgrass habitats were successfully restored based on significant increases in percent cover and shoot density. In addition, the abundance of animals also increased significantly in these areas. Transplanting individual plants by hand, however, can be time consuming and, unless plants are separately grown for the task, requires that plants come from donor areas. Thus impacting these areas as well. The use of seeds and vegetative propagules in marine and freshwater habitats can also be used to re-introduce SAV to new areas without some of the constraints of using transplants alone (Orth et al. 1994; Lundholm and Simser 1999; Rybicki et al. 2001; Granger et al. 2002).

Restoration practitioners interested in learning more about specific SAV restoration projects can find them at NOAA's Restoration Center database of restoration projects. This online, searchable database can be used to help those interested in planning a restoration project contact others in their area and share information. Individual projects or a description of all restoration efforts in the database can be downloaded from: http://restoration.noaa.gov/. The Environmental Protection Agency also maintains a restoration project database at http://yosemite.epa.gov/water/restorat.nsf/rpd-2a.htm. This database, however, is not exclusively devoted to coastal habitat restoration projects and includes descriptions for restoration projects in inland waterways and terrestrial habitats as well.

STRUCTURAL CHARACTERISTICS OF SUBMERGED AQUATIC VEGEGATION

Habitat restoration is the process of re-establishing a self-sustaining habitat that closely resembles a natural condition in terms of structure and function (Pinit and Bellmer 2000). In order to improve restoration efforts and sustain SAV communities, one must consider site selection, which species to plant, the type of propagules to use, the proper care and handling of plant material, the ecological functions performed by the habitat, and any social and economic values associated with it. When planning a program to monitor a restoration effort, however, one of the first steps is to understand the basic structural characteristics of the system and their relationship to project goals. For SAV, these basic structural characteristics include:

Biological
- Habitat created by plants

Physical
- Light availability
- Turbidity
- Temperature
- Sediment
  - Grain size
  - Nutrient concentration
  - Organic matter
- Topography/Bathymetry
  - Geomorphology
  - Elevation/Slope

Hydrological
- Current velocity
- Water sources
- Wave energy, and
- Tidal regime or hydroperiod

Chemical
- Salinity
- Nutrient concentration

Since the physical, hydrological, chemical characteristics of an area determine where SAV can grow; practitioners must first monitor these structural characteristics to ensure conditions are suitable for SAV restoration. Once plants are established, the focus of monitoring can change to the functions SAV habitats perform such as providing fish habitat and improving water quality. This change in monitoring focus from structural to functional characteristics as the restoration matures, dictates where monitoring will take place. Pre-restoration monitoring, to determine baseline conditions, will often occur in areas where SAV is absent or degraded. Post-restoration monitoring will occur within and above the SAV bed with results compared to associated, unvegetated areas or other reference conditions[10] to show the effects of the restoration. The focus of this section is on the structural characteristics of SAV, examples of parameters that can be used to measure these structural characteristics are also provided. A more complete list of suggested parameters for monitoring the structural characteristics of SAV can be found at the end of this chapter and in abbreviated form in *Volume One*. Sampling methods for suggested parameters can be found using resources in the second appendix of this chapter the *Review of Technical Methods Manuals*.

BIOLOGICAL

Habitat Created by Plants

SAV beds provide important feeding, spawning, and nursery grounds for fish, aquatic invertebrates, and many species of waterfowl (Wilcox and Whillans 1989; Wilcox 1995). The ability of a particular SAV bed to perform these functions depends upon the architecture,

[10] See Chapter 15 for a discussion of methods to selection reference conditions for restoration monitoring programs.

diversity, and density of the plant species present (Orth et al. 1983). A few examples of common, dominant species, the types of habitat created by seagrasses and other SAV, and how those habitats are used by various animal species, are provided here. A more thorough description of habitat-related functions and methods to monitor animal use of SAV habitats is given in the Functional Characteristics section below.

Seagrasses

Seagrasses are very productive vascular plants that provide habitat for many other marine plant and animal species such as epiphytes, crabs, fish, and benthic invertebrates. Although seagrasses are found in a variety of locations throughout the coastal United States, southern Florida with 14,633 km^2 of seagrasses is home to one of the largest beds in the world (Fourqurean 2002). These flowering plants typically grow in soft sediments submerged in shallow waters of estuaries, bays and lagoons. Some species of surfgrass (*Phyllospadix* spp.), however, attach to rocky habitats on the Pacific coast. Seagrass ecosystems also protect coastal shorelines and improve water quality. Many species of seagrass have extremely wide ranges and are found throughout the world. A few examples of seagrass species and their geographic range are given below. This list is only of a few examples of common species and is by no means a complete listing, many other species are also found throughout the coastal areas of the United States and its protectorates (Hemminga and Duarte 2000; Green and Short 2003).

Eelgrass (*Zostera marina)* North Atlantic, Mediterranean Sea, western and eastern Pacific
Shoal grass (*Halodule wrightii)* Caribbean
Turtle grass (*Thalassia testidinum)* Caribbean
Dwarf eelgrass (*Zostera japonica)* temperate west Pacific
Manatee grass (*Syringodium filiforme)* Caribbean
Johnson's seagrass (*Halophila johnsonii)* coastal waters of southeastern Florida
Surfgrass (*Phyllospadix japonicus)* temperate west Pacific

Other plants that may be present in seagrass habitats can include *Caulerpa taxifolia,* an invasive, marine, green algae found in the Mediterranean Sea and off the coast of California. *Caulerpa* spreads by fragmentation as pieces of the plant break off and become established in new areas. This species is able to dominate seagrass habitats by secreting a toxic substance that prevents sea urchins and other large herbivores from feeding on it. As a result, it is able to out-compete native seagrasses to the detriment of fisheries and other marine organisms dependent upon seagrass habitats (Williams and Grosholz 2002).

Freshwater SAV

Submerged species that dominate freshwater areas include the algae muskgrass (*Chara* spp.) and vascular plants such as:

Pondweeds (*Potomageton* spp.)
Waterweed (*Elodea* spp.)
Naiads (*Najas* spp.)
Bladderworts (*Utricularia* spp.), and
Coontails (*Ceratophyllum* spp.) (Cowardin et al. 1979)

Some species such as Sago pondweed (*Stuckenia pectinata*) are also tolerant of brackish conditions up to 20 ppt. Invasive species such as Eurasian water-milfoil (*Myriophyllum spicatum* hereafter milfoil) and *Hydrilla verticillata*[11] (hereafter hydrilla) are also common in many freshwater and brackish systems. These non-native species

[11] Exotic species such as milfoil and hydrilla were once considered nuisances and subject to extensive control measures but are now generally tolerated in the mid-Atlantic region (Orth, 1994). This may have more to do with the inability to establish native species in these areas than a new found love for these exotics. A similar phenomenon is occurring in marshes on the coast of Louisiana with *Phragmites australis*. In addition, some invasives such as milfoil have started to naturalize and cause less disturbance than before. Methods to eradicate invasives can also be extremely damaging to native plants as well.

can form dense canopies preventing most other species from growing in an area. They can be a nuisance to boaters and swimmers and can alter the structure and diversity of habitat available to fish, invertebrates, and waterfowl.

Freshwater SAV beds can often have much greater structural complexity than marine systems. This is due to the greater diversity of plant species adapted to freshwater conditions and to lower amounts of physical energy found in freshwater areas compared to marine environments. Lower tidal and wave energy in freshwater habitats means less stress for plants. Freshwater SAV can therefore contribute less energy to root structures and repairing damage than marine species typically need to (Stevenson 1988) and put more energy into above-ground growth where it can be more readily utilized by other organisms. Due to increased stress associated with tides and waves, marine species typically have basal growth[12], ribbon-like or roseate leaves and grow in 'meadows' lower in the water column (Figure 1). Many freshwater species, on the other hand, have a more complex, dissected leaf structure, apical[13] growth, and lie on or reach near the surface of the water to maximize photosynthesis[14] (Wetzel 1983; Stevenson 1988). This leads to the formation of complex underwater canopies in freshwater SAV beds much like those of terrestrial forests (Stevenson 1988). This structural complexity increases the number and types of habitats available to fish and invertebrates.

Figure 1. This lush meadow of ribbon-like seagrass from the Philippines consists mostly of *Thalassia hemprichii* and *Syringodium isoetifolium*. Photo courtesy of Ronald C. Phillips, NOAA Coastal Services Center.

The presence and abundance of all SAV communities can be extremely variable over time. Dominant species and entire plant communities can appear and disappear in response to changes in structural characteristics such as upstream land use, climate, water quality, exotic species introductions, disease, herbivores, sediment deposition, and turbidity (Bates and Smith 1994; Carter and Rybicki 1994; Titus 1994). This high level of natural variation in SAV communities highlights the need for monitoring reference sites in conjunction with restoration projects to determine which post-restoration observations result from restoration activities and which are caused by natural variability beyond the control of the restoration practitioner.

Seeds and other propagules

One characteristic of SAV that may be of use in restoration projects is their tendency to grow from vegetative propagules as well as from seed. Vegetative propagules such as dislodged plants, stems, rhizomes, and tubers may be carried into new areas with currents, settle on the sediment, and become established. For example, Rybicki et al. (2001) studied the availability and survivability of SAV propagules in freshwater tidal areas of the Potomac River. They found that some unvegetated areas were subject to a relatively consistent supply of propagules and seeds from adjacent or upstream areas. Due to poor water quality, improper sediment grain size, or low nutrient availability, plants did not always become established in areas so supplied. Knowing where propagules are naturally

[12] Apical growth can also occur in some species, often during flowering.
[13] From the tips of the plants.
[14] Wild celery, a common freshwater plant, is an exception to this pattern of growth as it has ribbon-like leaves and basal growth.

available could help guide the selection of sites for restoration projects (Rybicki et al. 2001). In areas that have an existing supply of propagules but where plants have not become established, other factors such as poor water quality or sediment nutrient concentration may be limiting SAV growth. These areas should not be the focus of additional planting efforts as plants are unlikely to survive until factors limiting growth can be addressed. In unvegetated areas without an existing source of propagules but with sufficient light and nutrient availability for SAV to grow, planting may be an appropriate way to bring about a successful restoration (Rybicki et al. 2001).

Another freshwater example comes from a SAV regeneration study in Cootes Paradise, a Great Lakes coastal marsh on the Canadian shore of Lake Ontario (Lundholm and Simser 1999). Submerged vegetation in the area had been repressed by the presence of carp foraging for plant tissues and associated increases in turbidity. Once carp were excluded from the system, dense beds of SAV regenerated despite the fact that earlier seedbank studies had shown little viable seed present in the sediment (Whillans 1996; Westcott et al. 1997). Perennial SAV species had regenerated through vegetative structures buried in the sediment that had not been previously observed. Although little is known about the longevity, viability, or species diversity of these vegetative structures (Lundholm and Simser 1999), they may provide a cost effective means of revegetating an area without new planting. Species composition in these regenerated areas may, however, be skewed to those plants that are more tolerant of disturbance and/or have longer-lived vegetative propagules. Depending on the goals of the restoration project, the regeneration of species with these characteristics may or may not be acceptable. In any event, this study provides an excellent example of a successful restoration project where the cause of degradation (i.e., carp) was eliminated, allowing the system to regenerate on its own.

In marine areas, seagrasses rely on both vegetative growth (through rhizome elongation) and propagation from seedlings to maintain and expand existing beds and colonize new areas. Seeds of some species such as eelgrass, however, do not travel far (less than a few meters) before settling out and becoming incorporated in the sediment (Orth et al. 1994). Seeds from eelgrass plants and other similarly heavy-seeded species can be collected and stored for use in restoration projects (Granger et al. 2002).

Sampling

Sampling some characteristics of SAV such as percent cover, stem density, or productivity can be challenging. In areas where plants do not grow all the way to the water's surface and sufficient light is available, divers can collect information on species presence and percent cover (Figure 2). Diving or snorkeling in areas where plants form a complete canopy to the surface of the water, however, is not recommended as swimmers and equipment can become seriously entangled. In these situations, it may be possible to estimate percent cover from the surface with the use of a glass bottom boat or a 'fish eye'[15]. Both of these methods eliminate the glare off the surface of the water and make it easier to see the plants and animals below. When

Figure 2. A diver sampling a seagrass bed. Photo courtesy of NOAA Center for Coastal Monitoring and Assessment, Silver Spring, MD.

[15] Also called an aqua scope, it is a large, hollow tube with a piece of glass on one end that is placed in the water.

Figure 3. Searching for SAV in the Tred Avon River with a bamboo shrub rake. Part of an annual Bay-wide ground-truthing effort. Photo from the NOAA Photo Library.

plant samples are needed for identification or estimating productivity[16], divers can cut plants or plants can be collected with a rake (Figure 3) or with a grab sampler (Dromgoole and Brown 1976). Readers interested in specific methods to monitor vegetative characteristics are referred to the second appendix of this chapter, a *Review of Technical Methods Manuals*.

PHYSICAL

Light Availability

Light availability is the single greatest factor affecting SAV growth (Carter and Rybicki 1990; Carter and Rybicki 1994). Knowing the amount of light available at different depths allows practitioners to select those depths at which certain species can be planted (Miller and McPherson 1995). The amount of light available to SAV is affected by a variety of inter-related phenomena[17] including:

- Tidal regime
- Hydroperiod
- Day length
- Cloud cover
- Nutrient loads
- Suspended sediment and particulate loads
- Dissolved organic material
- Chlorophyll-*a* concentration in the water column
- The presence of epiphytes growing on SAV
- The amount of fetch, and
- The frequency of large storms (Carter and Rybicki 1994; Orth 1994)

SAV growth in response to light availability varies by species and location. Generally somewhere between 5% and 25% of the amount of light available at the water's surface is required for SAV to grow. Bulthuis (1983) reviewed the light requirements of freshwater and marine SAV and found that the minimum amount of light required for growth and survival ranged from 5% to 15% of the total amount of light available at the water's surface. If measured precisely, this corresponds to approximately 100 – 250 $\mu E\ m^{-2}\ s^{-1}$ [*] (Carter and Rybicki 1990 and literature cited therein). Other researchers found that seagrasses needed 15% - 25% of light available at the water's surface to survive (Kenworthy and Haunert 1991; Dennison et al. 1993). In a study of subtropical and tropical waters, Fourqurean et al. (1995) found that turtle grass dominated waters where the percent of light at the surface was greater than 10% and shoal grass dominated darker areas where the percent of light was less than 10% of that at the surface.

By measuring the amount of light available, practitioners can also assess whether or not their plants are receiving enough light or if other factors might be responsible for poor plant performance. In a study of the growth and survival of transplanted eelgrass and environmental conditions in a southwestern tributary of the Chesapeake Bay, Moore et al. (1996) observed no long-term survival of

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[16] Methods to measure productivity are discussed in the Functions section below.

[17] Monitoring of these parameters, in conjunction with measurements of available light may help practitioners better interpret their light availability data and discover cause-and-effect relationships impacting a restoration project.

[*] Irradiance is measured in units called einsteins. In English, the notation given here translates to 100 – 250 micro einsteins per square meter per second. Most quantum sensors provide output in einsteins.

transplants at any restored sites. Transplants died due to high turbidity and associated low light levels. Maintaining good water clarity and quality is critical to long-term eelgrass survival and successful recolonization (Moore et al. 1996). This highlights the need to obtain pre-restoration monitoring data to ensure that conditions are conducive to SAV establishment and growth before placement of additional plant materials is attempted (Batiuk 1992; Batiuk et al. 2000).

Turbidity

Although not a direct measure of all light available for photosynthesis, turbidity does affect the amount of light available to SAV. Thus helping to determine the presence and abundance of plants. Turbidity is a combination of:

- The color of the water, which changes with varying amounts of dissolved organic matter
- The concentration of suspended sediments and particles, and
- The concentration of phyto- and zooplankton, which also varies seasonally (Sculthorpe 1967)

Many freshwater SAV plants are canopy formers and have the ability to morphologically adapt to conditions of high turbidity and low light availability. Under these conditions, some plants such as milfoil and hydrilla elongate more quickly in an attempt to reach higher in the water column where light availability is greater (Barko and Smart 1981a; Barko et al. 1991). Other common dominant plants such as wild celery (*Vallisneria americana*) do not elongate rapidly under low light circumstances (Barko et al. 1991). For restoration purposes then, wild celery may not be the best choice for planting in areas with high turbidity and low light availability. Many canopy formers (including milfoil and hydrilla), however, are exotic in the United States and thus should not be used in restoration projects. A native canopy former that has been planted with success in some Chesapeake Bay projects is redhead grass (*Potamogeton perfoliatus*).

Changes in land use from forested to agriculture or urban cover types can lead to increases turbidity and changes in the species composition of SAV beds (Minc 1998). Native, canopy-forming plants such as waterweed and pondweed are intolerant of high turbidity. Plants such as coontail, milfoil, and hydrilla are well adapted to turbid conditions and displace less tolerant species (Minc 1998). These changes in dominant vegetation change the vertical structure of the habitat available to invertebrates and fish and thus alter faunal species composition (Wilcox and Meeker 1992; Brazner 1997; Grenouillet and Pont 2001; Valley and Bremigan 2002).

In addition to increases in turbidity caused by humans, animals can also affect the amount of turbidity and light available for SAV. Filter feeders, such as mussels and oysters, can help keep turbidity levels low to the benefit of SAV. For example, one of the effects of the invasive zebra mussel (*Dreissena polymorpha)* in the Great Lakes has been an increase in the amount of submerged aquatic vegetation in shallow areas such as Saginaw Bay (Skubinna et al. 1995). As the mussel colonies filter out vast quantities of suspended organic matter, the water gets less turbid and light is able to reach greater depths, thus providing energy for photosynthesis to a larger area of the lake bottom than before (Knapton and Scott 1999). The loss of historical oyster populations in the Chesapeake Bay has been linked to increased turbidity and the decline of SAV in the Bay. Other species, such as the common carp, can stir up sediments through their feeding behavior, also increasing turbidity and limiting the amount of light available to SAV (Wilcox 1995).

The duration of high turbidity levels can also affect SAV growth. In a study comparing two locations on a Chesapeake Bay tributary where seagrasses were planted, Moore et al. (1997) found that turbidity levels were low during winter at both upriver and downriver locations and eelgrass was growing well. After eight months of continuous growth, however, eelgrass transplants at the upriver site declined and eventually died as turbidity increased during summer months. Interestingly, turbidity increases on the downriver site were more severe but of shorter duration than at the upriver site and transplants survived. Plants were apparently able to tolerate very high yet short-term pulses of turbidity but more moderate increases in turbidity over longer periods of time resulted in the loss of vegetation (Moore et al. 1997).

Submerged aquatic vegetation not only benefits from low turbidity but it helps to maintain it by reducing water velocity, thus promoting settling of suspended solids, and through a complex relationship with phyto- and zooplankton. The effect SAV has on phytoplankton concentration comes from the lowering of water velocity[18] and by providing refuge for zooplankton that feed on phytoplankton (Jones 1990). When fish that feed on zooplankton are not present, small phytoplanktivores such as the freshwater *Daphnia* live out in the water column, feeding on suspended phytoplankton. When zooplanktivorus fish are present, however, zooplankton hide in the complex canopy created by SAV (Daldorph and Thomas 1995; Perrow et al. 1999). These relationships are discussed in greater detail in separate sections on invertebrate and fish use of SAV as refuge and feeding grounds in the Functional Characteristics section of this chapter below.

Sampling

PAR - The amount of light available for photosynthesis can be directly measured as photosynthetically available radiation (PAR) or indirectly by measuring turbidity or water clarity. PAR is the portion of visible light between 400 and 700 nm (Kirk 1994). The exact wavelengths used for photosynthesis will vary among different species. PAR can be measured using a device called a quantum sensor at the water surface and throughout the water column to determine how much light is absorbed by the water column and is then left available for SAV growth (Miller and McPherson 1995; Batiuk et al. 2000). Quantum sensors can be connected to dataloggers[19] and left in place allowing for the continuous measurement of PAR over time. This has the benefit of measuring random events such as storms or large river flows that can temporarily increase turbidity and that might be missed with less-frequent, manual sampling. For continuous deployments, a spherical (4 Pi) PAR sensor must be used to reduce fouling from settling sediments, while for measurements taken by lowering the sensor from a boat or pier, a flat (2 Pi) sensor is normally used to minimize the amount of light reflected off the boat that reaches the sensor. PAR measurements made by the two types of sensors are not directly comparable because they receive light from different angles. Estimates of light extinction (see equation below) that result from PAR measurements will also vary depending on the depths at which measurements are taken. There is no known single agreed protocol for the depths at which PAR is measured.

PAR can also be measured manually at various depths by using Beer's law (Carr et al. 1997):

$$PAR = I_o * e^{(-kz)}$$

Where I_o equals PAR at the surface, k is the light extinction coefficient of the water and associated dissolved material, and z is the depth. Unless referenced to mean tidal level (see chapter 8 in Batiuk et al. 2000), continuous monitoring of water level fluctuation in tidal and Great Lake areas subject to seiches may be required if PAR is to be determined in this manner. These hydrodynamic processes change a key input to the equation, depth (z). They may also affect

[18] Moving water helps keep phytoplankton suspended in the water column.
[19] An electronic device that continually records data over time.

values for *k* as well by changing the amount and type of dissolved material in the water, thus requiring additional monitoring of dissolved materials over time.

Turbidity - A simple, inexpensive way to measure turbidity is with a secchi disc, a weighted black and white circle, typically made of plastic, lowered slowly from the shady side[20] of a boat or dock (Figure 4). As light travels through the water column, it is absorbed or scattered by suspended and dissolved material. The remaining light reflects off the secchi disc and travels back through the water column where more is absorbed. The light that remains is what we see as the disc[21]. As the disc is lowered in the water, it gets harder to see as more of the light is absorbed. The depth at which the disc disappears from sight, is the depth at which all the light is being absorbed as it passes down and back up through the water column. This is recorded as the secchi disc depth (Tyler 1968). The frequency of using a secchi disk to sample turbidity should account for tidal regime and hydroperiod and include post-storm measurements whenever possible as these will affect water depth and clarity. More precise, electronic methods for measuring turbidity are also commercially available.

Figure 4. Lake Springfield water volunteer demonstrates the use of a Secchi disk. Photo courtesy Illinois EPA. http://www.epa.state.il.us/gallery/lake-monitoring.

Temperature

Water temperature, in part, determines the growing season for SAV and thus determines when SAV habitats should be monitored. Temperature also controls the rate at which chemical reactions take place and can thus affect primary productivity and plant species composition (Kirk 1994). Most plants and animals have a specific temperature range within which they perform most efficiently. As temperature deviates from the optimum, performance decreases (Thornton and Lessem 1978; McFarland and Barko 1987). Although chemical reactions take place at a faster rate at warmer temperatures and should theoretically increase productivity, extreme heat, as can occur in shallow areas with black sediments, may lead to metabolic stress, and reduce productivity. Colder climates or areas with strong, cold groundwater discharge may also experience reduced productivity (Wilcox 1995). Species temperature preferences may also change seasonally or geographically (Madsen and Adams 1989). This highlights the need for plant propagules and animals introduced as part of a restoration project to come from as local a source as possible since local populations should be best adapted to local environmental conditions.

Changes in weather patterns from one year to the next can also affect species presence or abundance. Some freshwater species such as the invasive hydrilla require high temperature and light availability during the spring when the dominant growth pattern for the plant is prostrate along the sediment. If spring temperatures are too low or turbidity too high during this period, hydrilla does not grow enough to come

[20] To avoid glare off the water's surface.
[21] Sunglasses should NOT be worn while taking a secchi disc measurement.

to dominate the canopy later in the summer (Carter and Rybicki 1994). Relationships of this sort, however, have not been worked out for all SAV species.

Dense beds of SAV in areas with low water velocity have been shown to help set up strong vertical temperature gradients in inland lakes (Dale and Gillespie 1977; Wetzel 1983) and in shallow, coastal areas of the Great Lakes (Suzuki et al. 1995). The ability of SAV to influence temperature in tidal areas, however, is not as clear. Some researchers have shown that temperature differences do exist within dense beds of SAV particularly during the warmest part of the day (Carter et al. 1988). Carter et al. (1988) and Carter et al. (1991) found temperature gradients throughout the water column to be as much as 5˚C. Water temperatures at the surface tended to be higher within areas of SAV than in adjacent unvegetated areas. Bottom temperatures in vegetated areas, however, were much more variable compared to unvegetated areas. Jones (1990), however, found no vertical temperature differences in SAV beds in tidal areas. Although the relationship between tides, wind, available sunshine, and SAV is not completely understood (Carter et al. 1991), it seems likely that in areas with strong tidal exchange, the ability of SAV to limit mixing and set up vertical temperature gradients is much lower than in areas with weaker tides.

Sampling

A variety of manual and electronic methods are commercially available to measure temperature. If only temperature needs to be recorded as part of a study, small, inexpensive temperature loggers can be used inside waterproof cases.

Sediment

Grain size

The physical and chemical characteristics of sediments directly affect wetland vegetation and organisms inhabiting the area. SAV in turn affects local sediment characteristics by slowing current velocity and increasing the deposition of suspended sediments. In areas that are prone to flooding and/or large storms, sediment grain size and associated nutrient concentrations may change from time to time as sediments are moved into and out of an area. Conditions may temporarily arise that are conducive or detrimental to SAV growth and indeed SAV populations have been shown to fluctuate greatly over time in relation to these events (Orth and Moore 1984; Carter and Rybicki 1986; Bates and Smith 1994; Nichols 1994; Titus 1994). In SAV habitats where sediment accretion is rapid (such as coastal Louisiana) or where sediment accretion is a primary goal of restoration, sediment grain size or bulk density can be measured to determine whether or not the rooting medium for SAV is adequate for plant establishment. In areas that are not exposed to relatively rapid changes in sediment level, these sediment characteristics may not need to be monitored after the initial assessment of their condition for plant species selection purposes.

Koch (2001) compiled a list of common SAV species and their known preferences for percent silt and clay (i.e., fines) in sediment. She found that SAV grew in a wide range of % fines from 0.4% to 72%. Freshwater species tended to prefer a greater percentage of fines than did marine species. Koch along with Barko and Smart (1986) theorize that this has more to do with sediment geochemical processes such as oxygen concentration, chemical diffusion, or the build up of toxic sulfides in anaerobic marine sediments[22] than simply the physical characteristics of the sediment.

Nutrient concentration in sediment porewater

Submerged plants obtain most of their nutrients (i.e., nitrogen and phosphorus) from the sediments where concentrations of these nutrients are typically higher than in the water

[22] Sulfide accumulation is not a common characteristic of freshwater areas.

column (Carignan and Kalff 1980; Barko and Smart 1981b). Phosphorus, for example, binds to the surface of organic matter and mineral sediments in the presence of oxygen. In anaerobic environments, such as wetland sediments, phosphorus becomes soluble and available for uptake by plants (Mortimer 1941; Mortimer 1942). Nitrogen, in the form of ammonia, is also more readily available in anaerobic sediments than from the more oxygenated water column.

Sediment types (organic, sand, silt-clay, and rock) vary in level of nutrient availability, contributing to the establishment of different plant communities (Kiorboe 1980). Sediments dominated by silts and clays, for example, are typically nutrient rich. Sandy sediments or bedrock areas are typically nutrient poor. Sediments with high concentrations of organic matter may be rich or poor depending on the local hydrodynamics and mineral sediment content. Areas prone to large storms or flooding events that change sediment grain size and associated nutrient concentration may also exhibit variability in the presence and abundance of SAV (Terrell and Canfield 1996). Areas with sandy sediments may have nutrient concentrations that are too low for SAV to become successfully established. In these areas, it is not recommended that additional nutrients be added to the water column (since SAV typically does not get a majority of its nutrients from the water column) nor should nutrients be added to the sediment since sandy sediments do not have the ability to hold nutrients for plant use and nutrients could simply be leached away.

Organic matter

Organic matter accumulates in SAV areas through deposition of fine sediments as a result of lowered water velocities and through the production and burial of rhizomes and roots (Koch 2001). A vast majority of healthy SAV beds are limited to areas with a percent soil organic matter below 5% dry weight (Koch 2001). The mechanism behind the limitation has not been completely explained but the relationship is clear. She recommends that SAV not be planted in areas with organic matter content higher than 5% until additional studies have been completed to better explain the mechanism behind this relationship and methods are developed to overcome it. Barko and Smart (1986) also found that SAV grew poorly in low-density, high organic soils and also in high-density, sandy sediments. The poor growth in sandy sediments has been generally attributed to the nutrient-poor nature of sandy sediments (Kiorboe 1980). Poor growth in sediments with high organic content (when nutrient levels should be high) and low bulk density was explained as being caused by the low rate of diffusion in these types of sediments (Barko and Smart 1986). Thus, the nutrients were present and attached to soil particles but the plants could not get to them efficiently due to the high porosity of low-density soils.

The type and decomposition of organic matter in the sediment also contributes to the nutrient cycling process. In a study of decomposition of sediment organic matter in beds of the seagrasses blume (*Rhizophora apiculata*) and sea fruit *(Enhalus acoroides)*, Holmer and Bachmann (2002) found that the stems and leaves of seagrasses contributed relatively more nitrogen than carbon to the water column than did the rhizomes of the same species. Thus, the type of detritus available (e.g., leaves or rhizomes) influences sediment nutrient concentrations and nutrient cycling dynamics and may need to be sampled as well if a comprehensive understanding of nutrient cycling and the role of organic matter is desired.

Measuring and Monitoring Methods

Sediment grain size can be measured directly by drying and sifting samples through a series of different sized sieves (Poppe et al. 2003). It can also be measured indirectly through measuring bulk density. Bulk density is the dry weight of the sediment per unit of volume (Steyer et al. 1995). It is generally low (e.g., 0.2 to 0.3 g/cm^3)

for sediments with high organic matter content and high (e.g., 1.0 to 2.0 g/cm^3) for sediments with high mineral content (Mitsch and Gosselink 2000). Detailed methods for sampling sediment characteristics such as grain size, nutrient concentration, and organic content can be found in Folk (1974), Gosselink and Hatton (1984), Liu and Evett (1990), and Steyer et al. (1995) as well as other resources listed in the second appendix of this chapter.

Topography/Bathymetry

Acreage of habitat

Monitoring the area of SAV created as part of a restoration project over time can be used as an indicator of whether the habitat has deteriorated or improved. The spatial and temporal distribution of seagrass beds (primarily eelgrass) in Barnegat Bay, New Jersey, for example, has been studied by combining existing historical mapped survey information (Lathrop et al. 2001). Maps from the 1960s, 1970s, 1980s, and 1990s were digitized and assembled in a geographic information system (GIS). Comparisons were then made between earlier maps and a survey conducted in the 1990s that showed a decrease of about 2,000 to 3,000 ha in seagrass beds over time. Aerial photography, remote sensing, side scan solar, and acoustic sounder systems are also convenient methods for mapping and monitoring changes in the acreage of SAV over time (Ackleson and Klemas 1987; Ferguson and Korfmacher 1997; Malthus and George 1997; Weinstein et al. 2001; Mumby and Edwards 2002; Sabol et al. 2002; Dierssen et al. 2003). Ground truthing to verify SAV presence and species composition is a very valuable supplement to any mapping done by aerial photography or other remote sensing method. For a description of the use of ground surveys by the Virginia Institute of Marine Science (VIMS) in its 2002 survey of Chesapeake SAV, see: http://www.vims.edu/bio/sav/sav02/report/ground_surveys_page.html.

Geomorphology

Geomorphology is the study of the physiographic features of the earth's surface. By understanding the shape of a particular feature on the landscape and how it was formed, insights into the functions an area can perform can be better understood. Geomorphic features are delineated based on the shape and geologic history of an area, the degree of protection from wave energy, and the amount of hydrologic exchange with their receiving water body. A given geomorphic feature may contain a variety of vegetation communities (i.e., habitats) within it. For example, the geomorphic feature of a drowned river mouth (see Figure 5) may contain a mix of riverine forest, marsh, SAV, and open water habitats. All of these habitat types are subject to similar physical forces such as bidirectional flow and water level fluctuations tied to receiving body of water because of their location within the drowned river mouth. In addition, the physical forces that act upon a SAV community within a drowned river mouth are different than those that affect a SAV community along an open coast. Thus, some of the functions the drowned river mouth community can perform may be different than those of an SAV community along an open coastline.

The basic geomorphic types of coastal wetlands are outlined in Figure 5. They are: open, drowned river mouths, and protected. Although the particular type of geomorphic setting a SAV habitat is in will not change over time, each type has characteristic influences on other structural and functional characteristics that will be monitored. In addition, short-term differences in the connection between the wetland and the receiving body of water such as the formation of temporary barrier beaches can also affect many wetland structural and functional characteristics. Therefore, when developing a restoration monitoring plan, the geomorphic type of the coastal wetland as a whole needs to be taken into consideration[23].

Open Coastal Wetlands

Open coastal wetlands are subject to more wave energy and hydrologic exchange than drowned river mouths or protected wetlands. Open wetlands have direct chemical and hydrologic connects to the water body they are associated with. They may also have upland water sources such as small streams. They typically do not have as much sediment organic matter accumulated as drowned river mouths or protected wetlands (Keough et al. 1999). Plants and animals that live in open wetlands must be tolerant of higher rates of erosion caused by waves and ice and daily water level fluctuations from tides or seiches compared to other geomorphic types of wetlands (Keough et al. 1999).

Drowned River Mouths

Drowned river mouths were formed during the last ice age when water levels of the Great Lakes and oceans were much lower than they are today. As the lakes and oceans rose to present levels, deep river valleys filled with sediment creating linear wetland complexes chemically and hydrologically dominated by both the rivers moving through them and their receiving body of water. Many of the estuaries in the United States such as the Chesapeake and Delaware Bays on the east coast, Coos and Siletz Bays in Oregon, and those in the Great Lakes such as Muskegon Lake in Michigan are drowned river

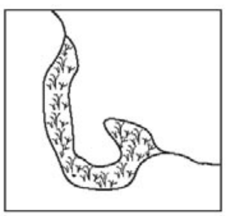
Type	Physical	Hydrologic	Biological	Chemical
Open 	Variable inorganic substrate (clay to gravel). Thin to non-existent organic substrate. Moderate to high wave climate. Low rate of sediment supply. Gentle offshore and underlying-surface slopes. May or may not have offshore bars of sand to gravel.	Direct surface-water connection to the receiving body of water. Ground-water flow-system directly influenced by elevation of receiving body of water.	Plant morphometry adapted to hydraulic stress. Vegetation aligned with shoreline bars and dunes. Vegetation sensitive to wave climate and protective dunes, ridges, bars, and points. Plant species preferring inorganic substrates. Stray estuarine fauna. Biota tolerant of ice action.	Strongly influenced by constituents of the receiving body of water. Low turbidity. Vegetation may isolate nearshore water from mixing with the receiving body of water.
Drowned River 	Variable inorganic substrate (clay to gravel). Variable thickness of organic substrate. Low to moderate wave climate. Low to moderate rate of sediment supply from coast and river.	Direct surface-water connection to river and the receiving body of water. Ground-water flow-system influenced by elevation of the receiving body of water and the river. Many local flow systems. Seiches transmitted upstream.	Plants and animals of riverine, lagoonal, and coastal habitats. Mud-flat annuals, and plants preferring organic sediments. Warm-water fish. Biota tolerant of flooding and high turbidity.	Upstream-downstream gradient in water constituents caused by seiches mixing of river water with water from the receiving body of water and reversal of currents. Variable turbidity.
Protected 	Uniform inorganic substrate (sand to gravel). Thick organic substrate. High rate of sediment supply to shoreline.	May or may not have a surface-water connection to receiving body of water. Ground-water flow-system may or may not be influenced by the elevation of the receiving body of water. Many local flow systems.	Peatland vegetation is often present in northern areas. Ridges and swales show successional patterns. Warm-water fish in lagoons. Plants preferring organic substrates.	Organic matter may dominate water chemistry if limited riverine inflow. High water temperatures in summer. Ground-water seepage may cause temeprature gradients. Low turbidity. Ground water may dominate chemistry where inputs are high.

Figure 5. Three main types of coastal wetland geomorphology, open, drowned river mouth, and protected. The specific type of geomorphology has direct effects on the physical hydrological, biological, and chemical characteristics of the whole wetland and associated SAV habitats. Modified from Keough et al. 1999.

[23] Some aspects of geomorphology *within* habitats such as the pattern of tidal creeks, however, can change as habitats mature (Weinstein, M. P., J. M. Teal, J. H. Balletto and K. A. Strait. 2001. Restoration principles emerging from one of the world's largest tidal marsh restoration projects. *Wetlands Ecology and Management* 9:387-407). These within-habitat patterns and structures can be monitored using aerial photography but are not the main topic covered here.

mouths. During periods of low flow, barrier beaches may form over the river mouth. This increases the retention time of water within the wetland, increasing the potential for sediment deposition and nutrients uptake but preventing the migration of fish. During severe storm events or high water levels, these protective structures can be eroded away and flow through the wetland increased, thus reducing retention time and flushing accumulated sediments, nutrients, and organic matter into the receiving body of water.

Protected Coastal Wetlands

Protected coastal wetlands are located behind some sort of barrier (often an island) that protects them from the full force of waves coming off the main water body. It may also isolate them from water level fluctuations if the barrier is complete. The extent of the barrier has direct effects on the accumulation of organic matter, water chemistry, and other physical and biological characteristics as well by altering the flow and retention time of water through the wetland. As with barriers on drowned river mouths, barriers for protected wetlands can be temporary, completely isolating, or open to allow some hydrologic exchange with the receiving body of water.

Elevation and Slope

Slight topographic differences in the wetland substrate[24] create habitat for different plant species and plant communities to grow. All other things being equal, SAV beds with uniform substrate elevations will have a much more uniform vegetative community with lower species diversity than will beds with a topographically complex substrate. Sedimentation rates, water level changes, and subsidence can change the depth of water to the substrate and thus change the vegetation community (Hatton et al. 1983; Wilcox and Whillans 1989; Wilcox and Meeker 1995; Minc 1997). In any restoration project involving planting or seeding, careful measurement of depth to substrate, substrate elevations, and topographic diversity will need to be done in order for the proper plant species to be selected. In projects using dredge material or dike removal, for example, practitioners may need to monitor substrate elevations and topographic diversity for a period after project implementation and before planting to determine if the planned-for elevations have been achieved. Once sediments have settled into place and final elevations of the substrate are known, final selections of plant species can be made and placed in the field.

The slope of the sediment surface can influence the primary production of SAV (Duarte and Kalff 1986). This effect is related to the rate and quality of sediment deposition and the slumping of sediments that can stress plant roots. Gently sloped areas (e.g., slope < 5.0%[25]) have more stable sediments and greater deposition of fine, nutrient-rich sediments than areas with steeper slopes that tend to be areas of erosion and sediment transport (Hakanson 1977). As will be shown in the discussion of wave energy below, the slope of the substrate in relation to wave energy and light availability directly affects the spatial location of SAV communities within a particular area.

Sampling

The bathymetric features on an SAV bed can be sampled using a boat and a method to measure depth such as a weighted rope, pole, or radar. Depending on the amount of detail desired and the size of the habitat being mapped, this method may be adequate. For larger areas or where more detail is desired, remote sensing techniques can be used. High-resolution aerial imagery can be used to create detailed maps of bathymetry over large areas that would be hard to sample with traditional methods. Imagery can also be analyzed to distinguish different sediment types

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[24] Underwater topography is referred to as bathymetry.

[25] Hakanson's study was conducted in a lake. Since sediments in freshwater tidal and coastal areas of the Great Lakes may experience greater energy stress than inland lakes due differences in hydrodynamics, deposition and stability of sediments within SAV communities may require even smaller slopes in these environments.

(Lee et al. 2001; Dierssen et al. 2003; Louchard et al. 2003). Results need to be referenced to accurate tidal reference data so the depths can be referenced to mean low water levels. To do this the time of day needs to be recorded with each measurement, so they can be compared to measured water levels at the nearest reference station. NOAA provides a variety of water level data free to the public that may be of use; see http://co-ops.nos.noaa.gov/data_res.html.

HYDROLOGICAL

Current Velocity

SAV affects and is affected by the current velocity of the water column. Areas of high energy and strong current velocities such as those with large tidal exchanges or high freshwater flow areas tend to be dominated by SAV with linear, ribbon-like leaves. Areas with lower current velocities are dominated by species with bushier, more complex canopies (Stevenson 1988; Dudgeon and Johnson 1992; Sand-Jensen and Mebus 1996; Dodds and Biggs 2002). These differences in canopy type and structure further alter the flow and mixing of water through the bed. SAV beds with higher canopy complexity slow water to a greater extent than do beds with lower density and/or

Figure 6. This dense canopy of SAV growing in the Mississippi River Delta creates friction and slows water velocity. Photo courtesy of Teresa McTigue http://www.photolib.noaa.gov/coastline/line1211.htm

less complex canopy structure (Figure 6 - Dodds and Biggs 2002). Dense stands of SAV can slow water velocity by as much as 2 to 10 times that found in adjacent unvegetated areas and can even dampen tidal exchange (Ackerman 1983; Madsen and Warncke 1983; Carter et al. 1988; Gambi et al. 1990; Rybicki et al. 1997; Heiss et al. 2000).

Reductions in water velocity due to SAV can result in:

- Decreased sediment transport and increased sediment deposition (Fonseca et al. 1982; Bulthuis et al. 1984; Ward et al. 1984)
- Less vertical mixing of water in thermally stratified lakes and impoundments (Suzuki et al. 1995)
- Changes in nutrient uptake and biomass production (Fonseca et al. 1982; Dodds and Biggs 2002), and
- Increases in animal diversity by creating low-energy habitats in otherwise high-energy environments (Suren 1991)

SAV also benefits from its own effect of reducing water velocity. These benefits include:

- Reduction in self shading
- Lower shear forces at the sediment surface reducing sediment resuspension
- Increased sedimentation and deposition of organic and fine inorganic particles
- Longer residence time of water within the bed, facilitating greater nutrient uptake, and
- An increase in the settling of algal spores and other larvae resulting in higher biodiversity (Koch 2001)

Current velocity also affects primary productivity and biomass production (Butcher 1933). Each plant species is adapted to a particular range of velocities within which it functions best (see review in Carr et al. 1997). Water velocities within the plant bed as slow as 5 cm/s have been shown to increase productivity, while velocities of 50-100 cm/s or more can stress plants and limit productivity (Chambers et al. 1991; Koch 2001). The velocity of water also influences productivity by affecting the diffusion of nutrients and waste products through plant leaves. The flow of water across the leaf surface facilitates the exchange of dissolved substances by replenishing nutrient and carbonate concentrations and removes accumulated sediment and waste products from leaves (Odum 1956).

Sampling

A variety of manual and automated flow meters are commercially available for use in determining water velocity within and around vegetated areas. Equipment costs and sophistication range from low-tech, manual methods that measure flow at one point and time to electronic meters that can be left in place for weeks or months.

Water Sources

The amount and source of water to an area also has an effect on SAV. Changes in the amount of freshwater discharge to estuarine and marine areas or fluctuations of the water level of the Great Lakes can change the specific location of the habitat from year to year. Certain species may dominate vegetation communities one year and give way to others the next. Whole communities can appear and disappear in response to changes in upstream flow (Klarer and Millie 1992), land use (Carter et al. 1994), and associated changes in water quality. For example, a strong storm surge along an ocean coast can bring salt water upstream to areas that are typically freshwater. If the saltwater is not quickly flushed from the area, it can kill the established species and create conditions for more salt-tolerant species to grow.

Wave Energy

Wave energy can directly and indirectly impact SAV communities and limit their ability to grow at shallower depths. Waves as small as 0.1 meter in height can significantly damage plants (Stewart et al. 1997). Direct effects of wave energy include washout and burial of seedbanks, damage and uprooting of individual plants, and reduced survival of seedlings and developing winterbuds (Doyle 2001). These effects can be seen from storm-induced waves (Figure 7 - Terrell and Canfield 1996) as well as from waves caused by boats (Stewart et al. 1997). Moderate amounts of wave energy can actually be beneficial to SAV by reducing the epiphyte layer, thus enhancing photosynthesis and increasing rates of diffusion at the plant

Best Management Practices

The type of land cover in upstream areas producing runoff can also influence SAV. Exposed soil from agricultural land or construction projects can wash into water bodies during rain events. This can harm SAV in two ways, first by increasing turbidity and second by literally burying plants if sediment loads are high enough. The use of vegetated buffer strips in upstream areas can reduce the amount of sediment entering waterways from non-point source areas such as farm fields. Urban best management practices (BMPs) can be used to minimize the impact of point sources or urban stormwater systems on aquatic systems. Many local governments around the country have BMP guides that practitioners can obtain free-of-charge to learn more. Some examples include Prince George's County's Design manual for use of bioretention in stormwater management (Engineering Technologies Associates Inc. and Biohabitats Inc. 1993) and Cost estimating guidelines: best management practices and engineered controls from the Rouge Program Office in Wayne County, Michigan (Ferguson et al. 1997). Schueler et al. (1992) have also developed a series of commercially available guidelines for implementing BMPs into urban stormwater management programs. The US Environmental Protection Agency (EPA) also provides stormwater BMPs for the protection of wetlands. This document is available at: http://www.epa.gov/owow/wetlands/pdf/protecti.pdf. Additional resources are also available from the EPA that cover a variety of land use situations. These resources can be found by searching the EPA's website http://www.epa.gov.

Figure 7. Horned pondweed (*Zannichellia palustrus*) generally grows in shallow, calm areas but can be killed by high water temperatures where it floats to the surface and is washed up on shore by high waves. Photo courtesy of Mary Hollinger, NOAA Photo Library. http://www.photolb.noaa.gov/coastline/line0763.htm

surface (Wetzel 1992). Moderate levels of wind exposure and wave energy are also correlated with higher species diversity (Bailey 1988).

By monitoring wave energy on plants and at the sediment surface, restoration practitioners will be better able to understand and address the physical impacts to their restored area and better select plant species tolerant of such conditions during the planning process. Canopy forming plants such as milfoil suffer greater damage than ribbon-like plants such as wild celery. Even plants such as wild celery adapted to higher energy environments, however, can be negatively affected by waves. Waves 0.15 m in height can produce shear velocities around 1.4 meters per second on the surface of the plants and impact the ability of canopy-forming freshwater plants to reproduce (Doyle 2001). Wave energies of this magnitude can easily be produced by recreational watercraft in shallow water (Doyle 2001). SAV beds in higher energy environments or meadow-forming species growing deeper in the water column may be able to tolerate much larger waves without the same level of impact. SAV species that have a shorter, meadow forming growth form that overwinters, and that develop longer branched reproductive shoots in the summer, may remain in the short form all summer in high wave energy environments. In Chesapeake Bay this has been observed in horned pondweed, widgeongrass, and sago pondweed (Bergstrom pers. comm.).

Indirect effects of wave energy on SAV communities often involve the impact of waves on sediments. Wave energy can sort sediments, resuspending and removing finer silts and clays, leaving behind sands and coarser materials with lower nutrient availability (Spence 1982; Wilson and Keddy 1985). Wave energy can also maintain turbidity levels high enough to prevent SAV from re-establishing in areas it had previously dominated (Engel and Nichols 1994). Wave energy near the shoreline also

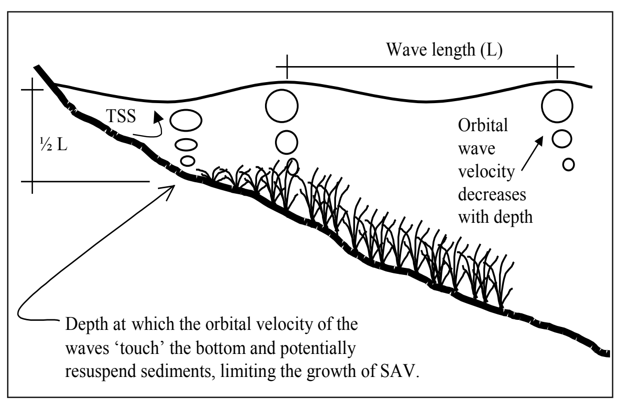

Figure 8. Cross section of a SAV bed showing the depth limitation imposed by waved energy reaching the sediment surface and increasing total suspended solids, eroding plants and decreasing light availability. TSS = Total Suspended Solids (i.e., sediments). Modified from Koch 2001.

limits SAV to deeper water, below the area of wave-induced sediment resuspension (Figure 8 - Chambers 1987). The relationship between wave energy and limiting the spread of SAV can be more easily seen in areas with steeper slopes (Chambers 1987). Areas with more gently sloping substrates have a more complicated interaction of wave energy and sediment resuspension, the details of which have not been well studied (Koch 2001).

Sampling

The Army Corps of Engineer's Shore Protection Manual (U.S. Army Coastal Engineering Research Center 1984) is an extensive document that explains many wave characteristics and mathematical formulae for predicting them. Using equations from that document, it is possible to calculate the depth at which waves reach the sediment surface (i.e., touch the bottom). Simplified equations that may be of use in some coastal areas are provided in Appendix IV of this chapter. Electronic devices to measure wave energy (such as pressure sensors) are also commercially available.

Tides/Hydroperiod

The magnitude, frequency, timing, and duration of water level fluctuations are all important characteristics in determining the location and species composition of SAV (Wilcox and Meeker 1995). Water level fluctuations may occur daily, seasonally, or on annual/decadal cycles. These patterns are driven by tidal patterns and/or changes in weather. Humans can also control water level fluctuations through the use of dikes and dams. In coastal marine areas, tides are the major force responsible for circulating water within SAV beds and between a bed and adjacent habitats (Carter et al. 1991). In both freshwater and marine habitats, seiches can also drastically change water depth and mix lake or bay water far into coastal wetland systems (Wilcox and Meeker 1995). They can also move material such as sediments, nutrients, and organic material back and forth between the wetland and open body of water (Keough et al. 1999). While extreme low water levels may stress plants and animals, longer-term cycles of high and low water levels are necessary to maintain healthy, diverse SAV habitats. For example, Wilcox and Meeker (1992) studied regulated lakes in Minnesota. They found that water level management schemes that did not mimic natural water level fluctuations of similar lakes resulted in a loss of SAV species, abundance, cover, and structural diversity. Changes in the structural characteristics of SAV habitats can impact invertebrate communities, waterfowl, and fish use.

Natural inter-annual variation in the surface elevation of the Great Lakes has a tremendous impact on SAV communities. Increases in water level can deprive deeper plants of light but also create conditions for SAV to grow further inland in areas that may have once been dominated by marsh vegetation. During prolonged droughts or lowering of Great Lakes water levels, freshwater habitats may move farther downstream or out into the lake basin. These system dynamics must be taken into consideration during the preparation of restoration goals and monitoring plans (Wilcox et al. 2002). Estuarine and marine habitats typically have more predictable water levels over time than do Great Lakes habitats, although sea levels are rising worldwide (Warrick 1993).

Tidal regime, wave energy, and light availability-at-depth determine which specific locations may be most conducive to a successful restoration effort. SAV are intolerant of desiccation and are therefore restricted to sub-tidal areas (Cowardin et al. 1979; Koch 2001). The upper limit of SAV growth is then determined by the effect of tides and wave action as previously described as well as the effects of ice, grazing, and other disturbance in shallow water. The lower extent of SAV is limited by light availability (Figure

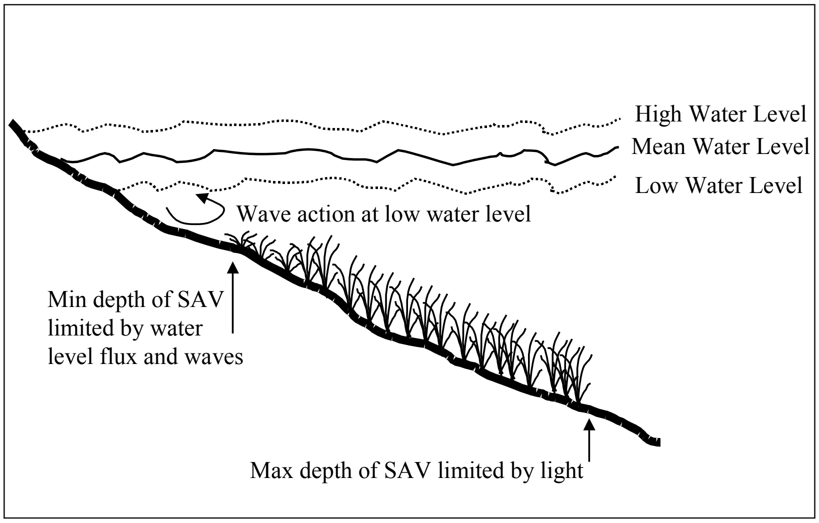

Figure 9. The minimum depth SAV can colonize is limited by low water levels and wave action. The maximum depth is limited by light availability. Modified from Koch 2001.

9 - Dennison et al. 1993; Koch 2001 and literature cited therein). The horizontal extent of SAV growth is then limited by the slope of the substrate.

Sampling

Tide tables for most of the United States and its protectorates are available from the National Oceanic and Atmospheric Administration (NOAA) at http://tidesonline.nos.noaa.gov/ and http://co-ops.nos.noaa.gov/data_res.html. The United States Geological Survey also operates a series of gaging stations on rivers throughout the country. Historical and real-time data on hydroperiod and characteristics of the watershed are available for many areas at http://water.usgs.gov/waterwatch/. If the restoration site is reasonably close to a listed site, monitoring of the tidal period as part of the restoration monitoring may not be necessary. Smaller coastal rivers, however, may not have gaging stations requiring that restoration practitioners implement other methods to collect this information. A variety of manual and electronic gages are commercially available. Gages that are read manually and checked during site visits can be attached to metal poles and driven into the substrate. Mechanical gages that record maximum and minimum water level since the last site visit can also be useful. Electronic gages can be set up and left in place to continually record water level fluctuation data over time as well. This method has the advantage of recording data that might otherwise be missed by manual sampling alone.

CHEMICAL

Salinity

Salinity plays a role in the zonation and distribution of SAV. By definition, only seagrass species can tolerate the salinity of full strength seawater. Different species of seagrasses, however, tolerate different salinity levels (Lirman and Cropper 2003). Factors that contribute to changes in salinity levels include industrial and agricultural inputs (typically increase salinity) and changes in weather patterns that increase or decrease inputs of freshwater. Increasing the amount of impervious surfaces in a watershed tends to lower salinity as a greater percentage of rainfall is delivered to rivers and streams instead of infiltrating into the groundwater. High salinity levels can result in lower seagrass productivity. Salinity levels also influence fauna zonation within seagrass habitats (Ingram and Dawson 2001). Salinity should therefore be monitored in tidal areas subject to changing salinity levels. Some tidal freshwater areas can also become brackish during drought years thus requiring salinity to be monitored. In strictly freshwater areas, monitoring salinity is not necessary.

Nutrient Concentration

While the main source of nutrients (nitrogen and phosphorus) to submerged macrophytes is sediment porewater (Carignan and Kalff 1980; Barko and Smart 1981b; Fourqurean et al. 1992), they can absorb small amounts of nutrients from the water column through their leaves. Despite their ability to remove nutrients from the sediment and water column, excessive amounts of nutrients can disrupt SAV habitats and result in habitat degradation. When nutrient concentrations in the water column are too high, SAV cannot absorb them before phytoplankton and epiphytic algae do. These microscopic plants can then grow fast enough and thick enough in the water column and on the surfaces of macrophytes that they outcompete SAV for light, killing the host plant.

Under certain circumstances, SAV can also increase the concentration of nitrogen and phosphorus in the water column. Rooted plants move nutrients from the sediment to the upper portions of the plant (Carignan and Kalff 1980). Plants then lose nutrients through four possible mechanisms: leaching, excretion, autolysis, and decomposition (Barko and Smart 1981b). Only a small amount (if any) nitrogen and phosphorus, however, is lost through excretion during active growth of plants. The vast majority of nutrients lost by SAV result from plants dying or having pieces broken off. As plant tissues begin to break down, nutrients are leached into the water column. As plants continue to decay, cell walls are broken down (autolysis) and their nutrient-rich contents are spilled into the water, the remaining plant materials are then colonized by fungi and microbes. These organisms complete the decomposition and nutrient cycling processes. As nutrients become available in the water column, they can be quickly absorbed by phytoplankton (Stevenson 1988). Thus, in temperate climates at least, a seasonal cycle of water column nutrient concentrations can be seen in areas with large beds of SAV. Nutrient concentrations in the water column can be high in spring, low during the growing season and high again in the fall and winter.

Sampling

Detailed methods for sampling salinity, nutrient concentrations, and other characteristics of the water column that may affect the growth of SAV are covered in the American Public Health Association's, *Standard Methods for the Examination of Water & Wastewater* (APHA 1999) and in a variety of methods manuals listed in Appendix II of this chapter. Bergstrom (2002) has also compared several methods for measuring salinity. Results of this study are available online at http://www.epa.gov/volunteer/winter02/volmon.pdf.

Many of the physical and chemical functions performed by SAV were covered with the associated structural characteristics above.

FUNCTIONAL CHARACTERISTICS OF SUBMERGED AQUATIC VEGEGATION

The following sections focus on the biological functions of freshwater and marine SAV. A list of common functional characteristics of SAV includes:

Biological

- Contributes to primary production
- Supports biomass production
- Provides breeding grounds
- Provides nursery areas
- Provides feeding grounds
- Provides refuge from predation
- Supports high biodiversity
- Supports a complex trophic structure
- Provides substrate for attachment

Physical

- Affects transport of suspended/dissolved material
- Alters turbidity
- Reduces erosion potential
- Reduces wave energy
- Modifies water temperature

Chemical

- Supports nutrient cycling
- Modifies chemical water quality
- Modifies dissolved oxygen

The SAV literature, and particularly the marine SAV literature, is quite extensive. Wherever possible, a marine and/or freshwater example is used below to illustrate each characteristic function and parameter(s) that may be useful in monitoring restoration projects. The examples provided, however, are only a few of the many available. In topics where literature is particularly abundant, sources are cited at the end of the section to guide readers to additional information. Readers are also encouraged to use the *Annotated Bibliography* and *Review of Technical Reference Manuals* in the appendices to find additional information, examples, and resources.

BIOLOGICAL

Contributes to Primary Productivity

SAV are primary producers, using the sun's energy to produce organic material that can then be used by other organisms. In the process, they utilize and recycle nutrients in the water column and sediments (McRoy and Helffreich 1977) and help to increase water clarity and quality. SAV also contribute to the overall productivity of the area in a variety of other ways. They often increase the amount of nutrients available to epiphytes, phytoplankton, and other meio- and benthic flora, increasing the productivity of these plants as well.

The energy produced by submerged macrophytes and their associated flora, can be used by animals directly or indirectly. A simplified version of the process is illustrated in Figure 10. The movement of dead plant and animal material (black arrows) along with that of SAV, epiphytes, and phytoplankton (green arrows) that are not directly eaten by grazers, is toward the detrital pool in the sediment. This forms the basis of the detrital food web. These materials are then eaten (red arrows) by decomposers such as fungi and bacteria. These microorganisms are then eaten by meiofauna in the sediment such as worms and nematodes. Meiofauna are then fed upon by omnivores such as shrimp and crayfish. Grazers and omnivores such as crayfish, sea urchins, and other benthic fauna, fish, turtles, manatees, and waterfowl can also eat live plant material. That said, relatively few species, compared to the total number found in SAV habitats, feed directly on living macrophytes. The small number of direct grazers may be linked to the greater

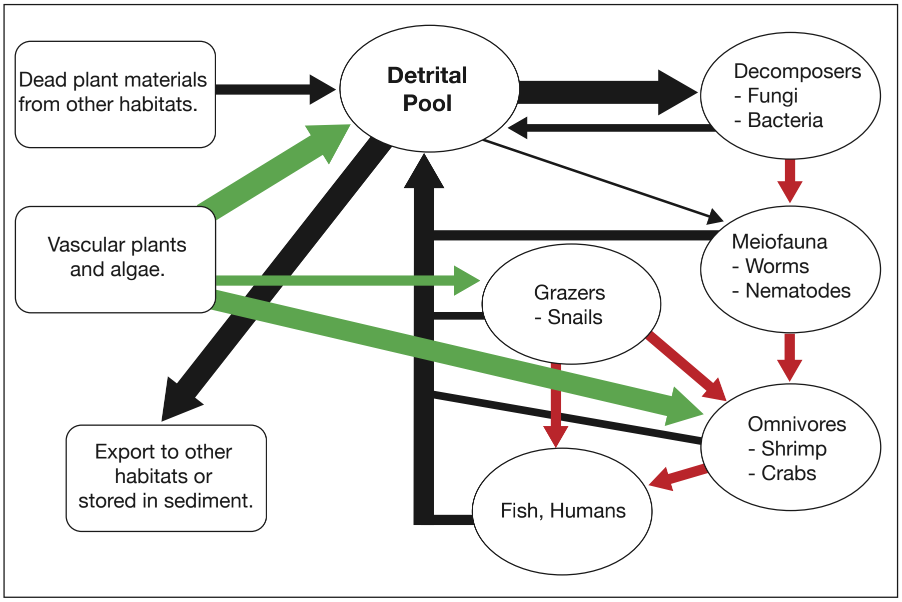

Figure 10. An example of a food web in SAV habitats. Green arrows represent the flow of live plant material, black arrows represent dead plant and animal material, red arrows represent predation. Although arrows are sized to represent relative amounts, exact amounts of energy moving from one component to the next will vary among individual areas. Figure by David H. Merkey, NOAA Great Lakes Environmental Research Laboratory.

availability of nitrogen compounds from other food sources such as the epiphytes that grow on SAV, the presence of tough cell walls in many SAV species, and toxic or inhibitory chemicals (Thayer et al. 1983). Only a small amount of the energy produced by submerged vegetation enters the food web as live material. Most of the energy produced by SAV is available to animals only through the detrital food web. Grazers and omnivores are, in turn eaten by waterfowl, fish, and humans. At all stages, there is a possibility that individual animals will not be eaten but instead die and add their bodies to the detrital pool to be recycled. Some detritus never enters the food web but is exported to other habitats or stored in the sediment. This example is very simplified, additional components and examples could be added as well as additional arrows drawn between different components.

Epiphytes and benthic algae

As stated previously, algal species and epiphytes play an important role in SAV ecosystems by contributing to primary production (Bologna and Heck 1999). If SAV growth is reduced, it will not only affect the algae and epiphyte community but also the epifaunal community that relies upon these food sources. Epiphytic algae contribute approximately 50% of the primary productivity of SAV habitats (Moncreiff and Sullivan 2001). Measuring and monitoring the growth and productivity of SAV, algae, and epiphytes can be an important component of many restoration monitoring projects concerned with increasing productivity levels.

Sampling

Carpenter and Lodge (1986) and Stevenson (1988) reviewed the literature for techniques used to measure productivity in SAV. Methods discussed included leaf marking, O_2 and CO_2 exchange, and aboveground dry weight. Another method to estimate belowground productivity is rhizome tagging as described by Short and Duarte (2001). Each of the methods, however, underestimates the total primary productivity of submerged vegetation (Carpenter and Lodge 1986; Stevenson 1988). A more accurate assessment of macrophyte biomass production could be derived using a variety of measurements and taking many small samples over time instead of a few large ones (Stevenson 1988). Standard methods for measuring the productivity rates, weight or light attenuation effects of epiphytes, however, have not been established. Researchers at the University of Maryland Center for Environmental Science Chesapeake Biology

Laboratory have been working on methods to assess these characteristics[26]. Additional methods for measuring primary productivity may be found in resources listed in the second appendix of this chapter.

Habitat Created by Plants (i.e., SAV)

SAV provides a variety of wildlife habitat and physical functions[27]. SAV habitats support a complex trophic structure and often have high biodiversity compared to unvegetated areas. SAV provides surfaces for:

- Algae and microbes to colonize
- Invertebrates to graze, hide from predators, and deposit eggs; and
- Fish to spawn, protect young, and feed

SAV (particularly freshwater species) create vertical structure that shades lower portions of the water column, setting up temperature and light availability gradients, thus, vertically diversifying habitats. SAV also provide important biochemical functions by transporting oxygen to the sediment and in return, transporting nutrients from the sediment into the water column (Wilcox 1995). Although specific relationships have only been worked out for a small number of species, some generalizations at the community level can be made for fish, birds, and invertebrates (Maynard and Wilcox 1997). Marine SAV, for example, provides foraging areas for fish, shrimp, dugongs, sea turtles, and a host of benthic organisms (Dunton 1998). Shrimp, fish, and crab larvae inhabit seagrass beds to avoid predation from larger animals (Day et al. 1989). Stem density and structural characteristics of the particular plant species present determine the species and abundance of animals that are able to use the habitat (Wilcox and Meeker 1992; Brazner 1997; Grenouillet and Pont 2001; Harrel et al. 2001; Spence-Cheruvelil et al. 2002; Valley and Bremigan 2002). As such, any natural or man-made change to SAV species composition can affect the abundance and distribution of animals and other plants found in the area (Sheridan et al. 1997; Wyda et al. 2002).

Breeding, nursery, and feeding grounds (including productivity and refuge)

Many species of fish, birds, and invertebrates use SAV habitats as feeding, breeding, and nursery areas. Many different types of invertebrates such as shrimp, crabs, snails, insects, and zooplankton use SAV to hide from predators, feed, and lay their eggs. Small fish species and juveniles of larger species use SAV to forage on invertebrates that tend to be more abundant in SAV areas than in open water. Smaller fish (and their invertebrate prey) also use SAV to hide from predators (Rozas and Odum 1987a). Herbivorous and piscivorous birds also feed in SAV habitats. Even mammals such as dugongs (*Dugong dugons*) and West Indian manatees (*Trichichus manatus*) and reptiles such as the green turtle (*Chelonia mydas*) use seagrass habitats as feeding grounds.

Invertebrates

SAV provides refuge for small and juvenile animals from predation. The distribution and abundance of micro- and macroinvertebrates, zooplankton, and zoobenthos are directly related to the presence, abundance, and complexity of habitat structure supplied by SAV. Macro- and microinvertebrates depend upon SAV to provide holdfasts, places to hunt and graze, and protect from predators. These invertebrates are often the basis of the food chain for larval fish and older stages of numerous species (Krieger 1992).

Marine Invertebrates

A variety of macroinvertebrates, many of them commercially important, use seagrass habitats

[26] http://cblcbos1.cbl.umces.edu/sone/

[27] For a detailed discussion of physical and habitat functions specific to seagrasses, readers are referred to Thayer, G. W., M. S. Fonseca and W. J. Kenworthy. 1985. Restoration of seagrass meadows for enhancement of nearshore productivity. pp. 259-278. Proceedings of the International Symposium on Utilization of Coastal Ecosystems: Planning, Pollution and Productivity. Rio Grande, Brazil.

at some point in their lifecycle (see Orth et al. 1983 for a more thorough review). A few examples include:

Marine shrimps (*Penaeus semisulcatus*)
Molluscs such as sea snails (*Aplysia californica*)
Bay scallops (*Argopecten irradians*)
Conch (*Strombus peruvianus*)
Pink shrimp (*Farfantepenaeus duorarum*)
Blue crabs (*Callinectes sapidus)*, and
Spiny lobsters (*Panulirus* spp.)

Increased Productivity - Seagrass habitats have been shown to significantly increase the productivity of invertebrate populations. Perkins-Visser et al. (1996), for example, studied the role of seagrass beds as nursery habitat for blue crabs in the lower York River, Virginia. First-stage crabs were placed into the vegetated and unvegetated, predator-free, enclosures. Juvenile blue crabs within eelgrass beds grew more rapidly than crabs in enclosures placed outside the eelgrass beds. Juvenile crab survival was also significantly greater in vegetated enclosures. A study of seagrass beds in lower Chesapeake Bay, Virginia encorporated a number of trophically important species including isopods, decapods, percarids, and molluscs. The studied seagrass beds (140-ha) also produced as much as 4.8 metric tons dry weight of invertebrates at any one time and 55.9 metric tons of invertebrates over the course of a year (Fredette et al. 1990).

Protection From Predation - The density of seagrasses helps hide some invertebrates from predators. A study on two species of clams (Mercenaria mercenaria and Chione cancellata) in Bogue Sound, North Carolina showed that after seagrass was experimentally removed, both clam species experienced high death rates. The clams were not dependent upon seagrasses for food but for protection from whelk (Busycon carica, B. contrarium, and B. canaliculatum), one of their main predators (Peterson 1982). Leber (1985) also studied the effect of seagrasses in protecting epifauna from larger predatory invertebrates. Some bivalve mollusks also use SAV as an attachment substrate. For example, zebra mussels attach to milfoil stems and are sometimes dispersed that way, wrapped around boat propellers. Small dark false mussels (Mytilopsis leucophaeata) in Chesapeake Bay have also been found attached to the more delicate slender pondweed (Potamogeton pusillis) stems (Bergstrom pers. comm.)

Seasonal Differences - The use of SAV by different types of organisms changes seasonally. This will affect the timing of monitoring activities for certain species. Sea urchins (Lytechinus variegates), for example do not significantly affect the turtle grass populations in the summer. Increased urchin densities in the winter, however, lead to significant reductions in seagrass cover (Macia 2000).

Additional literature practitioners interested in invertebrate communities may find useful include:

- van Montfrans et al. (1983) who reviewed the literature on epiphyte-grazer relationships in seagrass meadows, and
- Zieman and Zieman (1989) who provide a thorough review of invertebrate use of seagrass habitats

Freshwater Invertebrates

Feeding Grounds - Omnivorous crayfish can have serious direct and indirect impacts on SAV. Crayfish (*Orconectes rusticus*) feed on freshwater SAV. In doing so, they can alter species diversity, and reduce the density of individuals and overall biomass (Lodge et al. 1994 and review therein). They have even been known to completely eliminate SAV in some lakes (see review in Carpenter and Lodge 1986). Crayfish also feed on snails that feed on the periphyton that grows on SAV. Lodge et al. (1994) showed that by reducing snail populations, crayfish indirectly increase the amount of periphyton growing on submerged plants, decreasing the amount of light available to them. In areas of high crayfish abundance, it may be necessary to protect newly planted SAV with exclosures to keep crayfish out until plants become established. This would only be a temporary fix though if overall crayfish population and numbers of other herbivores remained high.

Snails help maintain healthy SAV beds by feeding on periphyton[28] (Reavell 1980; Daldorph and Thomas 1995). Periphyton compete with their host plants for light. If periphyton populations get too high, as is possible under nutrient rich conditions, SAV can become light starved and die. If snail populations are too low as a result of disease or predation from fish, SAV communities may decline. At higher populations, however, snails have also been shown to graze on SAV. Pip and Stewart (1976) showed that herbivory on SAV by snails (*Physa*) could also significantly reduce biomass and species diversity. Intense herbivory by invertebrates or waterfowl may affect the timing and amount of nutrient cycling by SAV and directly influence the amount of biomass that enters the detrital food chain. It may also impact the success of restoration projects if methods to control herbivore populations are not implemented.

Refuge From Predation - Freshwater plants with complex structure, such as *Elodea* and milfoil, harbor a greater diversity and higher population densities of zooplankton than do less structurally complex species such as wild celery (Spence-Cheruvelil et al. 2002). These differences are largely attributed to the greater protection from predation and larger surface area for attachment that structurally complex plants offer. The function of providing refuge for zooplankton has an important benefit for SAV communities. Submerged macrophytes compete with phytoplankton for light (Jones et al. 1983). By providing refuge areas for zooplankton that feed on phytoplankton (Fryer 1957; Zaret 1980; Twilley et al. 1985), SAV benefit by decreased turbidity and increased light availability.

The community structure (species presence and abundance) of freshwater fish can also have complex interactions with SAV canopy cover and with zooplankton diversity and abundance. Perrow et al. (1999), examined the function of SAV as refuge for zooplankton in lakes. They looked at SAV bed characteristics such as percent cover, diversity, and plant height in association with zooplankton abundance and behavior in the presence of zooplanktivorous and piscivorous fish communities. In general, zooplankton preferred to feed in open water areas. In the presence of open water-feeding fish such as roach (*Rutilus rutilus*), however, a percent cover value of 30-40% SAV seemed sufficient to maintain refuge for populations of zooplankton. Species such as perch (*Perca fluviatilis*), however, are more efficient at feeding in SAV stands requiring a greater density of plant material to maintain zooplankton populations. Similarly, if the density of any zooplanktivorous fish species exceeds a high enough level (1 per m^2 is suggested) then no amount of SAV cover can protect populations of large zooplankton from being wiped out. Perrow et al. (1999) also theorized that piscivorous fish species such as pike (*Esox lucius*) can apply enough pressure on populations of zooplanktivores to enhance the refuge effect of SAV on zooplankton communities.

Sampling

Since macroinvertebrate communities change seasonally (Thorp et al. 1997), sampling should be conducted during the same season from one year to the next to make comparisons. As with fish, invertebrate communities also respond to episodic events and natural variability imposed by water level changes. Care must be taken to ensure that any changes in invertebrate community measured during the course of a restoration monitoring effort take these factors into account.

[28] Algae that attaches to SAV.

Benthic invertebrates – Benthic invertebrates are responsive to some forms of degradation and could be useful in monitoring SAV restoration activities (Krieger 1984). Benthic communities can, however, respond to a variety of environmental factors not directly associated with the presence, absence, or health of SAV communities, making interpretation of monitoring efforts challenging. Cole and Weigmenn (1983) found that benthic communities differed little between vegetated and unvegetated sites. Brady (1992), on the other hand, found greater diversity and productivity of invertebrates in the sediments of vegetated areas than in the sediments at unvegetated sites. The use of invertebrates to monitor the success or failure of efforts to restore SAV may be more useful if directed at sampling the invertebrate community of the water column and those within/upon the vegetation than focusing on the sediment surface.

Stove-pipe core samplers can be used to collect benthic invertebrates and sediment samples (Cuffney et al. 1993). These instruments are referred to as quantitative corers that are use to collect samples primarily in shallow-water habitats with rooted vascular plants. Stove-pipe cores are used by manually pushing the sampler into the sediment and then removing the SAV and coarse materials. The sample is then mixed and dispensed through a floating sieve where benthic invertebrates are collected and identified. This method is best used in slower moving waters. Van Veen samplers and ponar grab samplers can also be used to sample benthic invertebrates (Cuffney et al. 1993). The Van Veen grab sampler contains jaw-like structures that penetrate into sediments. Long arms attached to the Van Veen sampler increase leverage for penetrating into sediments. Weights can also be added to the Van Veen jaws to increase penetration in sediments (Bowman et al. 2000).

Insects – Although there are many methods with which to sample insect communities in freshwater SAV (see *Appendix II*: Review of Technical Methods Manuals), two types are commonly used to reduce effort in sorting insects and other invertebrates from sediments and detritus. Funnel traps can be placed over the surface of the water to capture any insects that emerge from the water and ultraviolet blacklight traps. The latter technique has been used to capture adult caddisflies (Order: Tricoptera) to differentiate between healthy and impacted Great Lake's coastal wetlands (Armitage et al. 2001).

The US EPA has put together a publicly available manual for using invertebrates to assess environmental conditions in wetlands. Although this manual is geared toward the development of Indices of Biological Integrity, many of the sampling methods and issues are similar to sampling for monitoring purposes. This reference *Methods for Evaluating Wetland Condition: Developing an Invertebrate Index of Biological Integrity for Wetlands* is available at http://www.epa.gov/ost/standards and at http://www.epa.gov/owow/wetlands/bawwg (EPA 2002b). The U.S. Geological Survey also has a variety of manuals for monitoring invertebrates and other aspects of SAV habitats. These can be found at http://water.usgs.gov/nawqa/protocols/bioprotocols.html.

Fish

A host of fish species use SAV habitats as feeding, breeding, and nursery grounds, many of which are completely dependent upon SAV at some point in their lifecycle. Species of small bodied fish and juveniles of larger species use SAV to forage on invertebrates that tend to be more abundant in SAV areas than in open water (Rozas and Odum 1987a). Others, such as the freshwater species of northern pike and largemouth bass (*Micropterus salmoides*) are able to navigate and exploit openings in SAV habitats to hunt for prey (Bry 1996; Trebitz et al. 1997; Valley and Bremigan 2002).

The extreme diversity and total number of marine fishes that use SAV habitats throughout the United States and its protectorates makes a comprehensive listing of all species well beyond the scope of this document. Those listed, as well as those presented below, are just a few examples to give practitioners an idea of the types of fish that use SAV and how the habitat is used. Any restoration effort with a fisheries component will need to find more local or regional literature to assist them in designing and monitoring their particular restoration project. Materials in Appendix I, and contacts listed in Appendix II may assist in this process.

Marine Fishes

A variety of fish species use seagrass habitats at some point in their lifecycle including many commercially important species such as:

Red snapper (*Lutjanus campechanus*)
Spotted seatrout (*Cynoscion regalis*)
Barracuda (*Sphyraena argentea*)
Snook (*Centropomus* spp.), and
Tarpon (*Megalops atlanticus*)

Nursery Ground

Nagelkerken et al. (2002) discussed the importance of seagrass beds as nursery habitats for juvenile fish near coral reefs. They noted previous studies showing that juveniles of 17 Caribbean reef-fish species were significantly associated with bay areas containing seagrass beds whereas bays without seagrass had very few juveniles, if any. Nagelkerken et al. (2002) also compared the densities of the 17 fish species between Caribbean island reefs with and without seagrass beds. Reefs without seagrass showed a complete absence or very low densities of 11 of the 17 fish species. Researchers concluded that seagrass played an important role as nursery habitat for these fish species and fisheries in general. In addition, if seagrass habitats are degraded or lost, then reef-fish stocks will be significantly affected.

Productivity

Deegan et al. (1997) used trawls to test the development of a fish-based Estuarine Biotic Integrity (EBI) index for SAV habitats. Of 15 possible metrics, they chose eight for inclusion in the EBI: total number of species, dominance, fish abundance (number or biomass), number of nursery species, number of estuarine spawning species, number of resident species, proportion of benthic-associated fishes, and proportion abnormal or diseased. They found that fish communities at the low-quality sites had fewer species and lower density and biomass compared with medium-quality sites. They also found that the EBI results based on number of species performed as well as results calculated from biomass that is more time consuming to obtain and that the extra work to obtain biomass numbers was not warranted in this case.

Freshwater Fishes

Freshwater SAV habitats provide spawning, nursery, and feeding areas for many coastal species as well (Figure 11 - Jude and Pappas 1992). Of the roughly 200 fish species found in the Great Lakes, about 90% are directly dependent on coastal wetlands (including areas of SAV) during some aspect of their life cycle (Whillans 1987; Stephenson 1990).

Productivity

SAV support the highest biomass, density, and diversity of fish compared to other available aquatic habitats (Keast et al. 1978). Estimates of fish productivity can be twice as high in vegetated vs. unvegetated areas (Randall et al. 1996). The number of fish species also increases with increasing stream order and related increases in the distribution of SAV (Rozas and Odum 1987b). Diversity and abundance of different species has also been shown to be higher in undeveloped areas compared to developed areas of Green Bay (Brazner 1997). This, coupled with the fact that about 75% of the original coastal wetland area of the Great

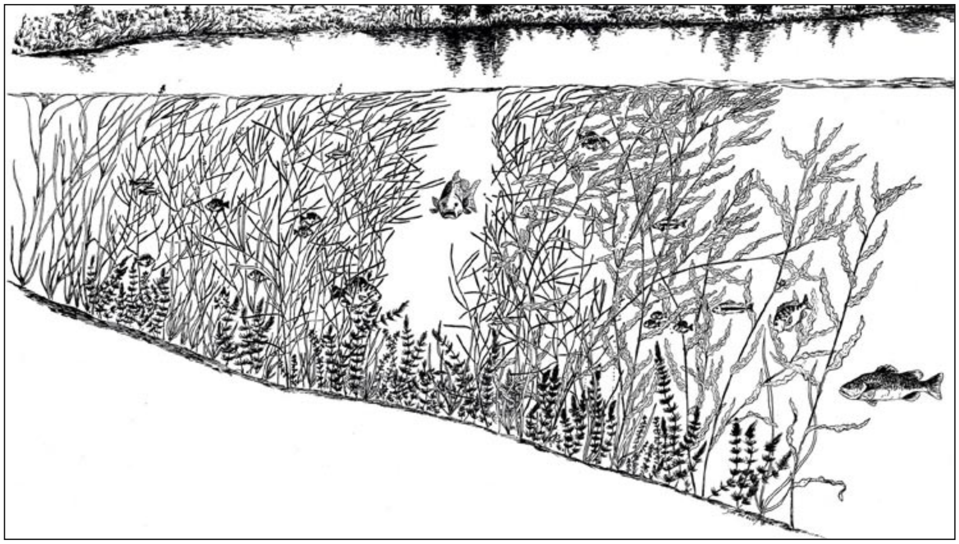

Figure 11. The diverse canopy created by freshwater SAV allows fish to use a variety of microhabitats. Smaller fish hide from predators within the vegetation, while large predacious fish cruise through gaps (lanes) in the vegetation or along the edge of the bed hunting for smaller fish. Figure modified from Engel 1985.

Lakes has been lost (Jude and Pappas 1992), highlights the importance of preserving the remaining areas for standing fish stocks and of restoring additional habitat if fish productivity is to increase.

Feeding

Grass carp (*Ctenopharyngodon idella*), an exotic introduced from Asia, is one of the few fish species in North America that feed directly on freshwater SAV (Mitzner 1978). Carp have been shown to dramatically reduce SAV and in the process increase turbidity thus contributing to further impacts to submerged plant species. The scarcity of SAV in some Great Lakes coastal wetlands has been attributed to increases in turbidity as a result of carp feeding activity (Klarer and Millie 1992). Effects of carp on water quality are worst when adult carp become trapped in a wetland. If carp are allowed free access to exit the wetland in the fall, damage to water quality and plants is minimal (Wilcox 1995).

It may, however, be desirable to exclude carp altogether (while allowing native fish access to the marsh for feeding and spawning) for newly planted/seeded material to establish. Gate-like structures have been demonstrated that keep adult carp out of coastal marshes and could be used for restoration projects (French et al. 1999). As constructed, the gate excludes adult carp but allows smaller fish to pass freely between open-lake and wetland waters.

Sampling Methods

A myriad of techniques and equipment are available for sampling fish populations in marine and freshwater environments. Many of the more common ones such as seining and electroshocking can, however, be problematic in SAV habitats and may underestimate fish biomass by as much as half. Fish also move from resting areas to foraging areas with the tides, time of day (Robertson 1980; Serafy et al. 1988), and between seasons (Stephenson 1990; Gelwick et al. 2001). This means that if sampling of fish is to be incorporated as part of restoration monitoring, very specific questions about the goal of the project and the timing of sampling need to be answered before fieldwork is conducted. The positives and negatives of using techniques such as trawling, seining, electroshocking, trapnets, hoopnets, gillnets, and visual assessment in areas of dense SAV are discussed below. In addition to these examples, the use of popnets, seines, and electroshocking techniques to sample fish in and around SAV habitats is discussed in Killgore et al. (1989) and Morgan et al. (1988).

There is no single perfect method for sampling the fish community in a given area. Different

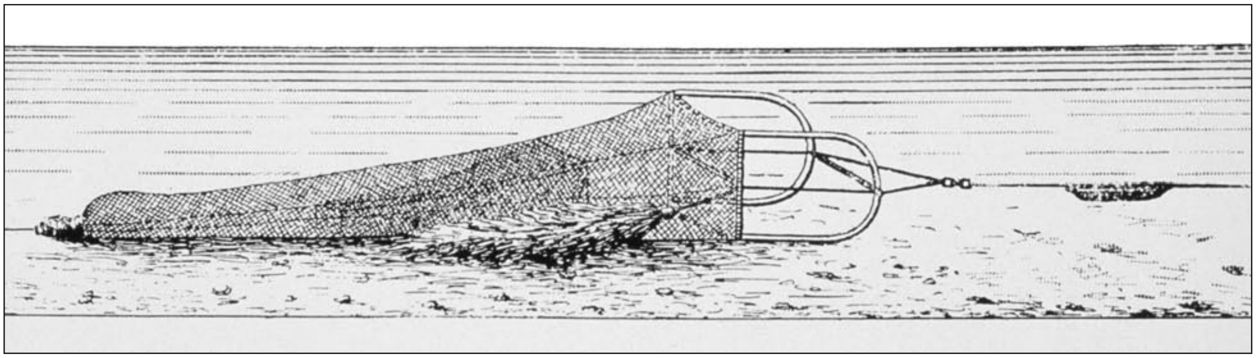

Figure 12. Trawls such as this are pulled behind a boat to collect samples. The example shown here is a Hirondelle sled or bottom trawl. Other styles are available for use throughout the water column. Photo courtesy of the Oceanographic Museum of Monaco and the NOAA Central Library. http://www.photolib.noaa.gov/ships/ship4113.htm

methods must be employed depending on the particular goal of the restoration effort and question to be answered. Typically several different methods used in combination will be the most effective approach. The methods described here as well as other passive and active techniques to sample fish communities can be found in Murphy and Willis' (1996) *Fisheries Techniques* published by the American Fisheries Society.

Trawls - Trawls are cone shaped nets that are towed through the water with the use of a boat (Figure 12). They can be used to sample either along the bottom (bottom trawls) or through the water column (midwater trawls). As the nets are pulled through the water, fish enter them, eventually tire and are held against the cod end of the net. Trawls are often tied shut on the cod end so that when the net is retrieved, the end can be untied and the fish more easily removed. Trawls are commonly used for scientific research because they are able to sample a known quantity of water (if you know the area of the trawl opening and the distance through the water it was pulled) and thus can be used to obtain information that can then be projected over a wider area. A large variety of trawls can be found, many with adaptations for specific species and habitats (Murphy and Willis 1996). As with other forms of nets, trawls work best in areas with open water above SAV communities. Trawls pulled through dense beds of SAV will quickly become clogged ruining the sample, destroying SAV habitat and possibly damaging the net and boat motor as well.

Electroshocking - Electroshocking does not work well in dense beds of SAV for several reasons. Smaller fish, that tend to be more abundant in SAV, are not as greatly affected by shocking as are larger fish (Zalewski and Cowx 1990). Dense vegetation also tends to hide fish that are fleeing or trap fish that are stunned, thus contributing to lower catch rates. This means that measures of fish abundance and levels of production are likely to be underestimated using this method (Randall et al. 1996). Electroshocking also does not work in deeper-water, seagrass habitats.

Gill nets - Gill nets can be used to sample fish in both fresh and marine waters. Gill nets consist of smaller panels that are connected together with bridles so that the net can be extended to any desired size (Figure 13 - Adkins and Bourgeois 1982). The nets contain a floatline, consisting of air filled structures that keep the net afloat and a sinker or leadline that contains weights that keep the bottom of the net below the water surface. Once the net is deployed, fish swim into the mesh where they become trapped as their

Figure 13. A gill net being retrieved for analysis. Photo courtesy of Chris Doley. http://www.photolib.noaa.gov/habrest/r0022603.htm.

head fits through the mesh but gills become trapped when they try to pull out (Adkins and Bourgeois 1982).

Although gillnets are destructive to fish, if particular size classes of fish are of interest, they can be an effective method for collecting samples (Pratt and Fox 2001). Nets of different mesh sizes can also be tied together to increase sampling efficiency, as gill nets tend to undersample smaller fish species. Gill nets, as other types of nets, can also become entangled in SAV making retrieval difficult.

Seines - Seines (also called beach seines) are nets attached to poles and are operated by two people walking through shallow water (Figure 14 - Meador et al. 1993). One person stands on or near the shore while the other (usually the taller and stronger of the two) wades out into the area to be sampled. Once the net is completely stretched open, the person out in the water sweeps the net back in toward the shore keeping it stretched open at all times. Once that person reaches the shore, the contents of the net can be lifted onto the shore and sorted. Beach seines tend to capture a large number of small, slow fish such as juveniles and forage fish (Hintz 1999). Larger, faster adult fish and those typically used for sport such as crappie (Pomoxis spp.), channel catfish (Ictalurus punctatus), and

Figure 14. A beach seine being taken near Galveston, Texas. Photo from the NOAA Photo Library. http://www.photolib.noaa.gov/fish/fish0814.htm

walleye (Stizostedion vitreum) are often able to escape the net and are thus underrepresented with this method. Additional problems with seines derive from hydrodynamics, particularly those of the Great Lakes. Seiches and inter-annual water level fluctuations of the lakes can erode sampling stations or make water too deep to sample safely. Thus, making year-to-year comparisons impossible. Seines may also get clogged with SAV and cannot be used where there is much woody debris, as the nets will get snagged.

Entrapment gear - Entrapment gear such as hoop nets, fyke nets (Figure 15), and trap nets capture fish in enclosed mesh traps. Like gill nets they come in various mesh sizes to capture different sizes and age classes of fish. Unlike gill nets, however, fish caught using these gear can be released with a minimum of harm (Meador et al. 1993; Murphy and Willis 1996).

Figure 15. A small fyke net such as this one can be used to sample for juvenile fish as well as macroinvertebrates invertebrates. Larger versions are also available for sampling larger, adult fish. Photo courtesy of Doug Wilcox, US Geological Survey.

Visual assessment - Visual assessment methods have also been developed for use by snorkelers and divers[29] to sample fish communities (Keast and Harker 1977; Jones and Thompson 1978; Bohnsack and Bannerot 1986; Pratt and Fox 2001). These methods include point counts and transect surveys among others (Murphy and Willis 1996; Hodgson et al. 2004). Point-count surveys are performed by scuba divers who observe and record fish within a particular area during a set interval of time. Transect surveys can be used to identify and estimate fish abundance and diversity. In transect surveys, divers move along a transect placed on the substrate and count and record fish within the sample area. This method has proven to be very effective and is being used in ecological and restoration monitoring by various environmental organizations such as NOAA Center for Coastal Monitoring and Assessment. Visual assessment methods can sample more species and life stages in moderate to dense stands of SAV compared to gillnetting but overall abundance can be underestimated. Cryptic and pelagic species also tend to be underrepresented by visual assessment. Despite these drawbacks, visual sampling methods are better than gillnetting for assessing certain characteristics of the fish community, namely species diversity and different life stages.

Physical characteristics of the water column such as turbidity and temperature can affect the success of these sampling methods. Reductions in visibility will obviously affect visual estimation methods but high turbidity has also been shown to alter fish behavior (Wright and O'Brien 1984; Hansson and Rudstam 1995) thus affecting other sampling methods as well. Temperature can also affect the accuracy of fish sampling. Fish tend to be less active at colder temperatures and are less likely to be caught in nets or noticed visually (Hillman et al. 1992).

Birds

Birds that use SAV habitats can be broken into two groups: herbivores that eat SAV and piscivores that hunt for small fish, amphibians, and other small animals in SAV habitats. The type of birds used in a monitoring program will depend upon the goals of the restoration effort as well as the availability of each type of food and adjacent habitats suitable for nesting.

Herbivores

A variety of waterfowl eat SAV. Swans (Figure 16), coots, and herbivorous diving ducks feed on tubers, seeds stems and leaves of freshwater SAV (Jupp and Spence 1977; Kiorboe 1980; Carter and Rybicki 1985; Blindow 1986; Prince et al. 1992; Mitchell and Wass 1996; Perry and Deller 1996; Knapton and Scott 1999). Waterfowl with longer necks such as swans can reach more SAV and thus do more damage. Also mute swans tend to pull up SAV by the roots which is much more destructive than feeding by other waterfowl that tend to only crop the portions of the plants they can reach. Resident waterfowl such as mute swans and non-migratory Canada geese are also more destructive to SAV since they are present

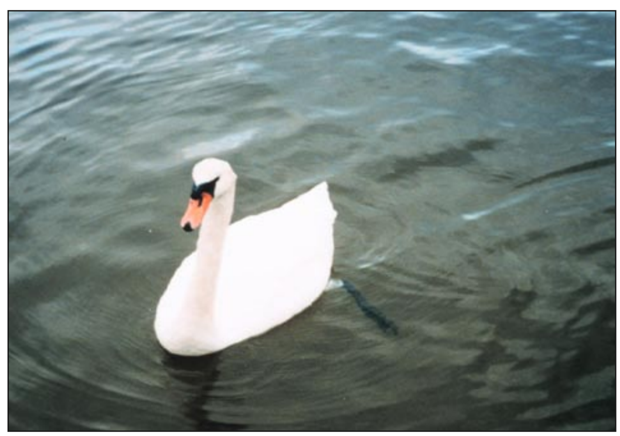

Figure 16. Mute swans commonly feed on SAV. Although beautiful, they are very aggressive and should never be approached, especially when their young are present. They are also an invasive species in the United States. Photo courtesy of Mary Hollinger, NOAA Central Library. http://www.photolib.noaa.gov/coastline/line0598.htm.

[29] If diving is not feasible, the use of underwater cameras may also be a useful technique for monitoring fish species presence and interactions in relation to SAV of different densities (Harrel, S. L., E. D. Dibble and K. J. Killgore. 2001. Foraging behavior of fishes in aquatic plantpp. APCRP Technical Notes Collection ERDC TN-APCRP-MI-06, U.S. Army Engineer Research and Development Center, Vicksburg, MS).

when SAV is actively growing and reproducing. In contrast, wintering waterfowl can only eat storage structures such tubers of as wild celery and sago pondweed (Bergstrom pers. comm.). Plants most commonly used as food include wild celery, muskgrass, pondweed, smartweed, and naiads (Knapton and Scott 1999). Waterfowl have been known to consume as much as 50% of the total annual biomass produced by SAV, however, most observed herbivory occurs at the end of the growing season when plants are dying (Kiorboe 1980). Although this herbivory and the small amount that occurs throughout the growing season may be enough to prevent the total domination of a system by aquatic macrophytes, and may alter species composition in future years as birds feed on reproductive structures, it is generally not thought to severely impact or control the growth of SAV in total (Kiorboe 1980; Mitchell and Wass 1996; Perrow et al. 1997; Knapton and Scott 1999; Noordhuis et al. 2002).

Piscivores

Piscivorous birds also use SAV habitats as foraging areas (Kersten et al. 1991; Prince et al. 1992). Juvenile egrets, for example, congregate in unvegetated shallow pools within aquatic macrophytes beds to feed on larval fish during early morning hours (Figure 17 - Kersten et al. 1991). Nocturnal respiration of macrophytes reduces dissolved oxygen to low enough levels to force fish into unvegetated shallows, and eventually to congregate and respire directly at the surface where they are vulnerable to predation. After sunrise, when photosynthesis returns dissolved oxygen to tolerable levels, remaining fish flee and the egrets disperse. High rates of primary production and abundant epiphytic algae provide food for a variety of crustaceans and mollusks that are also fed upon by other waterfowl and wading birds (Prince et al. 1992).

Measuring and Monitoring Methods

The EPA has developed a manual for using birds to assess environmental conditions in wetlands including SAV habitats. Although this manual is geared toward the development of Indices of Biological Integrity, many of the sampling methods and issues are similar when sampling for restoration monitoring purposes. This reference *Methods for Evaluating Wetland Condition: Biological Assessment Methods for Birds* is available at http://www.epa.gov/ost/standards and at http://www.epa.gov/owow/wetlands/bawwg (EPA 2002a).

PHYSICAL

Filters and Stabilizes Sediments

The physical water quality functions provided by SAV habitats include increased sediment stabilization and deposition (Hemminga and Duarte 2000). Seagrass beds, in particular, have thick underground mats made of roots, shoots, and stems that trap sediment particles. Water velocity and wave energy in coastal areas can be significantly diminished by the presence of SAV (Carter et al. 1988; Heath 1992; Carter et al. 1994; Madsen et al. 2001). This contributes to an increase in sedimentation rates and a

Figure 17. A greater egret (*Ardea alba*) fishing in a tidal pond. Photo courtesy of John White http://elib.cs.berkeley.edu/cgi/img_query?seq_num=121483&one=T.

decrease in turbidity, thus increasing the depth to which light can reach, further stimulating SAV growth (Gacia and Duarte 2001). Dense beds of SAV decrease the amount of shear stress that wave energy and current velocities can have on sediment surfaces. Winds as weak as ~12 km/hr are sufficient to resuspend sediments when SAV is absent (James and Barko 1994). When dense beds of SAV are present, wind velocity needs to be much higher in order to resuspend sediments (~20 km/hr). The frequency of resuspension events and the total amount of sediment discharged to downstream areas decreases as sediments are retained within the bed (Gacia and Duarte 2001). Even during high winds (e.g., > 30 km/hr), shear stress at the sediment surface can be near zero within beds of common watermilfoil (*Myriophyllum sibiricum*), muskgrass, and seagrasses when biomass levels were high (>200g/m^2 - Gacia and Duarte 2001; James et al. 2001). Interestingly, common water milfoil and muskgrass have very different architecture types. Common water milfoil forms dense canopies near the surface of the water while muskgrass forms meadows along the sediment surface. Both plants were effective at mitigating wave-induced shear stress and associated sediment resuspension. In areas where boating and other recreational activities are present, the planting of meadow-forming species such as muskgrass that reduces shear stress but also allows for a volume of open water above may accommodate both uses of the area more effectively than planting of canopy-forming species.

Practitioners needing additional detail on the importance of SAV for stabilizing sediments, increasing biological productivity, and reducing coastal erosion are directed to Fonseca et al. (1982).

Measuring and Monitoring Methods

Methods for measuring soil characteristics such as accretion, deposition, resuspension, sediment grain size, % organic matter, bulk density, and others can be found in the literature cited above, the previous section on Structural Characteristics: Physical, and in the second appendix of this chapter.

CHEMICAL

Modifies Water Quality

SAV enhances coastal water quality by reducing the amount of suspended material in the water column and by absorbing dissolved nutrients. The ability of SAV to reduce water velocity and increase sedimentation rates was also previously discussed. Short and Short (1984) evaluated previous studies and compared results to suspended sediment and dissolved nutrient removal experiments in culture tanks with and without SAV present. They monitored the addition and removal of nutrients in the tanks and determined that materials were removed from the water more readily in tanks with macrophytes present. Other researchers, however, found that macrophytes obtained more of their nutrients from the sediment rather than from the water column (Carignan and Kalff 1980; Barko and Smart 1981b; Fourqurean et al. 1992). Although macrophytes themselves obtain most of their nutrients from the sediment, they provide surfaces for epiphytes that do obtain the majority of their nutrients from the water column. Epiphytes can contribute almost half of the total primary productivity of SAV habitats (Moncreiff and Sullivan 2001). Thus, the mere presence of SAV as an attachment surface for epiphytes increases the overall primary productivity of the area and reduces the amount of available nutrients from the water column, thus helping to improve water quality.

Measuring and Monitoring Methods

Methods for measuring nutrient concentrations, turbidity, light availability, and other water quality characteristics in SAV habitats were previously covered in the Structural Characteristics section of this chapter

PARAMETERS FOR MONITORING STRUCTURAL/FUNCTIONAL CHARACTERISTICS

The matrices of structural and functional parameters for restoration monitoring presented below were developed through extensive review of the restoration and ecological monitoring-related literature. Additional input was received from recognized experts in the field of coastal SAV ecology. These lists are not exhaustive and are merely intended as a starting point to help practitioners develop monitoring plans for SAV restoration projects. Parameters with a closed circle (●) are those that, at a minimum, should be considered in monitoring restoration projects. Parameters with an open circle (❍) may also be monitored depending on specific restoration goals. Information on why these parameters are important for monitoring and how they relate to structural and functional characteristics as well as to one another is found throughout the previous text and in the literature cited herein. Literature directing readers toward additional information on the ecology of submerged aquatic vegetation, restoration case studies, and sampling strategies and techniques can be found in *Appendix I: An Annotated Bibliography of SAV* and *Appendix II: A Review of Technical Methods Manuals*, respectively.

Parameters to Monitor the Structural Characteristics of SAV

Parameters to Monitor	Structural Characteristics: Biological		Physical			Hydrological				Chemical	
	Habitat created by plants		Sediment grain size[30]	Topography / Bathymetry	Turbidity	Tides / Hydroperiod	Water Sources	Current velocity	Wave energy	Nutrient concentration	pH, salinity, toxics, redox, DO[31]
Geographical											
Acreage of habitat types	●										
Biological											
Plants											
Species, composition, and %cover of:											
Algae	❍										
Epiphytes	❍										
Herbaceous vascular	●										
Canopy extent and structure	❍										
Interspersion of habitat types	❍			❍							
Plant height	❍										
Seedling survival	❍										
Stem density	❍										
Hydrological											
Physical											
PAR[32]					●						
Secchi disc depth					●						
Shear force at sediment surface								❍	❍		
Temperature							❍				
Upstream land use							❍				
Water column current velocity								●			
Water level fluctuation over time						●	●				
Chemical											
Dissolved oxygen											❍
Groundwater indicator chemicals[33]							❍				
Nitrogen and phosphorus										❍	
Salinity (in tidal areas)						●	●				●
Toxics											❍
Soil/Sediment											
Physical											
Basin elevations				❍							
Geomorphology (slope, basin cross section)				●		●					
Organic content			●							●	
Percent sand, silt, and clay			❍								
Sedimentation rate and quality			❍	❍							
Chemical											
Pore water nitrogen and phosphorus										❍	
Redox potential											❍

30 Including organic matter content.
31 Dissolved oxygen.
32 Photosynthetically active radiation.
33 Calcium and magnesium.

Parameters to Monitor the Functional Characteristics of SAV

Parameters to Monitor	Functional Characteristics: Biological									Physical					Chemical		
	Contributes primary production	Supports biomass production	Provides breeding grounds	Provides nursery areas	Provides feeding grounds	Provides refuge from predation	Supports high biodiversity	Supports a complex trophic structure	Provides substrate for attachment	Affects transport of suspended/dissolved material	Alters turbidity	Reduces erosion potential	Reduces wave energy	Modifies water temperature	Supports nutrient cycling	Modifies chemical water quality	Modifies dissolved oxygen
Geographical																	
Acreage of habitat types	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●
Biological																	
Plants																	
Species, composition, and % cover of:																	
Algae	❍	❍	❍	❍	❍	❍	❍	❍	❍	❍	❍	❍	❍		❍	❍	❍
Epiphytes	❍	❍			❍		❍	❍		❍					❍		❍
Herbaceous vascular	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●
Invasives			❍	❍	❍	❍	❍	❍									
Canopy extent and structure		❍	❍	❍	❍	❍	❍		❍	❍	❍		❍	❍			
Interspersion of habitat types		❍	❍	❍	❍	❍	❍	❍		❍	❍	❍	❍	❍			
Plant health (herbivory damage, disease[34])					❍												
Plant height	❍	❍												❍			
Plant weight (above and/or below ground parts)	❍	❍			❍												
Rate of canopy closure	❍	❍												❍			
Seedling survival[34]												❍	❍				
Stem density				❍		❍		❍	❍	❍	❍	❍	❍	❍			

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Parameters to Monitor the Functional Characteristics of SAV (cont.)

Parameters to Monitor	Contributes primary production	Supports biomass production	Provides breeding grounds	Provides nursery areas	Provides feeding grounds	Provides refuge from predation	Supports high biodiversity	Supports a complex trophic structure	Provides substrate for attachment	Affects transport of suspended/dissolved material	Alters turbidity	Reduces erosion potential	Reduces wave energy	Modifies water temperature	Supports nutrient cycling	Modifies chemical water quality	Modifies dissolved oxygen
	Biological									**Physical**					**Chemical**		
Biological																	
Animals																	
Species, composition, and abundance of:																	
Birds		❍	❍	❍	❍	❍	❍	❍									
Fish		❍	❍	❍	❍	❍	❍	❍									
Invasives		❍		❍	❍	❍	❍										
Invertebrates		❍	❍	❍	❍	❍	❍	❍									
Hydrological																	
Physical																	
Fetch										❍	❍	❍	❍				❍
PAR	●	●								●	●						
Secchi disc depth	●	●								●	●						
Shear force at sediment surface										❍	❍	❍	❍				
Temperature			❍	❍										❍		❍	❍
Trash										❍							
Upstream land use										❍	❍					❍	
Water column current velocity										❍	❍	❍					
Water level fluctuation over time			●	●	●	●				●	●	●			●		●

Parameters to Monitor the Functional Characteristics of SAV (cont.)

Parameters to Monitor	Biological: Contributes primary production	Supports biomass production	Provides breeding grounds	Provides nursery areas	Provides feeding grounds	Provides refuge from predation	Supports high biodiversity	Supports a complex trophic structure	Provides substrate for attachment	Physical: Affects transport of suspended/dissolved material	Alters turbidity	Reduces erosion potential	Reduces wave energy	Modifies water temperature	Chemical: Supports nutrient cycling	Modifies chemical water quality	Modifies dissolved oxygen
Hydrological																	
Chemical																	
Dissolved oxygen			○	○			○	○							○	○	○
Groundwater indicator chemicals																○	
Nitrogen and phosphorus	○	○									○				○	○	
pH																○	
Salinity (in tidal areas)							○									○	○
Toxics			○	○	○											○	
Soil/Sediment																	
Physical																	
Basin elevations			○	○	○	○	○		○	○				○			
Geomorphology (slope, basin cross section)			●	●	●	●	●		●	●	●	●		●		●	●
Sediment grain size (OM[35]/sand/silt/clay/gravel/cobble)		○							○	○	○	○	○		○	○	○
Sedimentation rate and quality							○			○	○	○					
Chemical																	
Organic content in sediment		○			○		○	○		○	○				○	○	○

[35] Organic matter.

Acknowledgments

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APPENDIX I: SUBMERGED AQUATIC VEGETATION ANNOTATED BIBLIOGRAPHY

This annotated bibliography contains summaries of restoration case studies and basic ecological literature. It is designed to provide restoration practitioners with examples of previous restoration projects as well as overviews of papers from the ecological literature that offer more detail than that covered in the associated chapter. Entries are presented from both peer reviewed and grey literature. They were selected through extensive literature and Internet searches as well as input from reviewers. They are not, however, a complete listing of all of the available literature. Entries are arranged alphabetically by author. Wherever possible, web addresses or other contact information have been included in the reference to assist readers in easily obtaining the original resource. Summaries preceded by the terms '*Author Abstract*' or '*Publisher Introduction*' or similar descriptors were taken directly from their original source. Summaries without such descriptors were written by the authors of the associated chapter.

Batiuk, R. A., P. Bergstrom, W. M. Kemp, E. W. Koch, L. Murray, J. C. Stevenson, R. Bartleson, V. Carter, N. B. Rybicki, J. M. Landwehr, C. L. Gallegos, L. Karrh, M. Naylor, D. J. Wilcox, K. A. Moore, S. Ailstock and M. Teichberg. 2000. Chesapeake Bay submerged aquatic vegetation water quality and habitat-based requirements and restoration targets: A second technical synthesis. United States Environmental Protection Agency for the Chesapeake Bay Program. http://www.chesapeakebay.net/pubs/sav/index.html

Author Summary. The present report provides an integrated approach for defining and testing the suitability of Chesapeake Bay shallow water habitats in terms of the minimum light requirements for SAV survival. It incorporates statistical relationships from monitoring data, field and experimental studies and numerical model computations to produce algorithms that use water quality data for any site to calculate potential light availability at the leaf surface for SAV at any restoration depth. The original technical synthesis defined SAV habitat requirements in terms of five water quality parameters based on field correlations between SAV presence and water quality conditions. In the present approach, these parameters are used to calculate potential light availability at SAV leaves for *any* Chesapeake Bay site. These calculated percent light at the leaf surface values are then compared to minimum light requirements to assess the suitability of a particular site as SAV habitat. Values for the minimum light requirements were derived from algorithm calculations of light at SAV leaves using the 1992 SAV habitat requirements, extensive review of the scientific literature and evaluation of monitoring and field research findings. These calculations account for regionally varying tidal ranges, and they partition total light attenuation into water-column and epiphyte contributions; water-column attenuation is further partitioned into effects of chlorophyll *a*, total suspended solids and dissolved organic matter. This approach is used to predict the presence of suitable water quality conditions for SAV at all monitoring stations around the Bay. These predictions compared well with results of SAV distribution surveys in areas adjacent to water quality monitoring stations in the mesohaline and polyhaline regions, which contain 75 to 80 percent of all recent mapped SAV areas and potential SAV habitat in the Bay and its tidal tributaries.

The approach for assessing SAV habitat conditions described in this report represents a major advance over that presented in 1992. At the same time, areas requiring further research, assessment and understanding have been brought into sharper focus. The key relationships within the algorithm developed for calculating epiphytic contributions to light attenuation can be strengthened and updated with further field and experimental studies. Particular attention needs to be paid to the relationships between epiphyte biomass and nutrient concentrations and between total suspended solids and the total mass of epiphytic material, and to a better understanding of the relationships in lower salinity areas. Detailed field and laboratory studies are needed to develop quantitative, species-specific estimates of minimum light requirements both for the survival of existing SAV beds and for reestablishing SAV into unvegetated sites. Although this report also provides an initial consideration of physical, geological and chemical requirements for SAV habitat, more work is needed to develop integrated quantitative measures of SAV habitat suitability in terms of physical, geological and chemical factors.

Beck, M. W., K. L. Heck, Jr, K. W. Able, D. L. Childers, D. B. Eggleston, B. M. Gillanders, B. Halpern, C. G. Hays, K. Hoshino, T. J. Minello, R. J. Orth, P. F. Sheridan and M. P. Weinstein. 2001. The identification, conservation, and management of estuarine and marine nurseries for fish and invertebrates. *BioScience* 51:633-641.

Author Introduction. Nearshore estuarine and marine ecosystems—e.g., seagrass meadows, marshes, and mangrove forests—serve many important functions in coastal waters. Most notably, they have extremely high primary and secondary productivity and support a great abundance and diversity of fish and invertebrates. Because of their effects on the diversity and productivity of macrofauna, these estuarine and marine ecosystems are often referred to as nurseries in numerous papers, textbooks, and government-sponsored reports. Indeed, the role of these nearshore ecosystems as nurseries is an established ecological concept accepted by scientists, conservation groups, managers, and the public and cited as justification for the protection and conservation of these areas. Nonetheless, the nursery-role concept has rarely been stated clearly, even in papers that purport to test it. This ambiguity hinders the effectiveness of the nursery-role concept as a tool for conservation and management. We seek to redress that ambiguity by briefly tracing the history of the concept, developing a clear hypothesis with testable predictions, and discussing how this work can focus efforts in research, conservation, restoration, and management.

Biebl, R. and C. P. McRoy. 1971. Plasmatic resistance and rate of respiration and photosynthesis of *Zostera marina* at different salinities and temperatures. *Marine Biology* 8: 48-56.

A study was conducted on the *Zostera marina* functions and biological activities in the Izembek Lagoon, Alaska Peninsula. Although the study does not directly address restoration monitoring, the methods presented can be used to measure seagrass response to change in salinity and temperature. Changes in temperature and salinity levels may be due to anthropogenic inputs causing deterioration in seagrass community. The researchers distinguished different morphological forms of *Z. marina* in tide pools and subtidal areas both showed a high level of tolerance for differences in salinity and temperature. Photosynthesis reached maximum levels in normal seawater, decreased to almost zero in distilled water and in water with salinity levels twice that of seawater. Photosynthesis also increased in the tide pool form when temperatures were increased to 35° C. Photosynthesis reached maximum levels in the subtidal form as temperature increased to 30° C. At higher temperatures, photosynthesis in both forms declined. Respiration was minimal in distilled water at 0° C and increased when salinity and temperature also increased.

Bird, K. T., J. Jewett-Smith and S. Fonseca. 1994. Use of in vitro propagated *Ruppia maritima* for seagrass meadow restoration. *Journal of Coastal Research* 10: 732-737.

Author Abstract. The use of *in vitro* propagated *Ruppia maritima* for seagrass meadow restoration was monitored and evaluated in two experiments. Experiment 1 compared two different planting methods for *in vitro* propagated plants. In one method, cultured plants were attached to metal staples that were then inserted into the sediment. Almost all of these transplants disappeared within one month at the four different planting sites. For the other method, *in vitro* propagated plants were first transferred to peat pots and grown in a flowing seawater system for six weeks. These transplants showed 20 to 80% survival. *Ruppia maritima* was still growing in experimental plots after 11 months at three of the four sites. There was an increase in the number of short shoots m^2 and the percent cover. After 23 months, there was decreased cover of *R. maritima* and an increase in *Zostera marina*. In Experiment 2, *R. maritima* was propagated *in vitro* using a modified culture medium. Plants from these cultures were directly rooted *ex vitro* in peat pots during six weeks growth in a flowing seawater system. These planting units were transplanted to three sites. After 12 months, the experimental plots showed significant coverage of *R. maritima* at two sites. The other site was a more exposed location and had no *R. maritima* in the experimental plots from either Experiment 1 or 2, probably due to the severe winter storm of 1993. The increase in shoot numbers and areal coverage in the experimental plots suggests that *R. maritima* can be propagated in vitro and used successfully for habitat restoration.

Bologna, P. A. X. and K. L. Heck. 1999. Macrofaunal associations with seagrass epiphytes. Relative importance of trophic and structural characteristics. *Journal of Experimental Marine Biology and Ecology* 242:21-39.

Attached epiphytes often make important contributions to total primary production in seagrass meadows. Additionally, they may increase the spatial complexity of seagrass habitats. Experiments conducted using artificial seagrass units (ASU) manipulated both epiphytic structure and epiphytic food resources. Previous work suggested that the increase in faunal density associated with epiphytes was related to increases in structure, but our results indicate that the primary impact of epiphytes lies in their trophic role. Data showed that epifaunal density was significantly greater in 22 conditioned ASUs fouled with a live community of epiphytes (12 285 individuals m^{-2}) compared 22 to ASUs with artificially created epiphytic structure (5099 inds. m^{-2}) and to control ASUs (5955 22 inds. m^{-2}). This response to epiphytic trophic resources was significant for most herbivore omnivore taxa, but not necessarily for filter feeding or predatory epifauna. However, densities of two predatory taxa (fish and mud crabs) were significantly greater where epiphytic biomass was higher, which may reflect their response to increased prey abundance. Additionally, ASUs conditioned with live epiphytes had greater taxa richness than other ASUs. Epiphytic structure appeared to play only a limited role in determining the density of most mobile epifauna, but epiphytic structure appeared to be important in augmenting the settlement of bivalves. By using ASUs we were able to control aspects of blade length and shoot density, but the pre-experiment conditioning of treatments fouled with live epiphytes may have played a role in determining absolute differences in macrofaunal density among ASU treatments. Overall, our work suggests that the trophic role of epiphytes can have a dramatic impact on associated epifaunal communities, although future investigations are needed to assess this relationship more fully.

Burgess, C. 1995. Seagrass micropropagation and restoration in North Carolina and Florida, a case study of *Ruppia* (Widgeon grasss). Wetland Plants From Test Tubes, pp. 12-13. North Carolina State Univ., Raleigh, USA. Sea Grant publication UNC-SG-95-08.

Researchers studied the growth of *Ruppia* by evaluating plant health and established root systems within restored areas in North Carolina and Florida. Techniques used in this study should be considered in restoration monitoring. During the growing season, plants were collected from the field and sections were cut into single branch segments with two to five nodes. They were then soaked in fungicide, their surface sterilized with bleach and then submerged in selected antibiotics. A vacuum treatment was used to allow oxidants and antibiotics to filter through the plant's internal spaces. Researchers then added cytokinin to the growth media to stimulate branching and node creation. Each culture was lit with cool white fluorescent lamps in a temperate-controlled room. The plants were then transported from culture tubes or flasks to aerated aquaria to stimulate root formation. The planting units were attached to the mats using plastic-coated hairpins and allowed to root into the mats. Researchers then installed the mats at the site. Cultured *Ruppia* was attached to staples by first transferring the seagrasses into peat pots and then placed in a mariculture system with running seawater. After three to four weeks of growth, the potted *Ruppia* was transported to four different sites. Post-installation monitoring showed that plants were removed by heavy winter storms at one site. At the more protected sites, percent cover of *Ruppia* decreased while *Zostera marina* increased. Additional information on results and methods for monitoring restoration are presented.

Carpenter, S. R. and D. M. Lodge. 1986. Effects of submersed macrophytes on ecosystem processes. *Aquatic Botany* 26:341-370.

Author Abstract. Both natural and managed ecosystems experience large fluctuations in submersed macrophytes biomass. These fluctuations have important consequences for ecosystem processes because of the effects of macrophytes on the physical/chemical environment and littoral biota.

The first part of this paper reviews the effects of submersed macrophytes on the physical environment (light extinction, temperature, hydrodynamics, substrate), chemical environment (oxygen, inorganic and organic carbon, nutrients) and the biota (epiphytes grazers, detritivores, fishes). This extensive literature suggests that variations in macrophytes biomass could have major effects on aquatic ecosystems.

The second part of this paper considers the ecosystem consequence of several common changes in submersed macrophytes: replacement of vascular macrophytes by bryophytes during lake acidification; short-term biomass changes caused by invasion of adventive species, cultural eutrophication or macrophytes management; and changes in littoral grazers. These scenarios illustrate the importance of macrophytes in ecosystems, but raise many questions which cannot be answered at present. Controlled, whole-lake macrophytes experiments are needed to resolve these open questions.

Clark, J. R. and J. M. Macauley. 1990. Comparison of the seagrass *Thalassia testidinum* and its **epiphytes** in the field and in laboratory test systems, pp. 59-68. In Wang, W., J. W.

Gorsuch and W. R. Lower (eds.), Plants for Toxicity Assessment, Ecological Research Service, Environmental Protection Agency. *American Society for Testing and Materials, Philadelphia.*

Author Abstract. *Thalassia testudinum* and associated epiphytes from field plots were compared with plants from laboratory microcosms to determine if laboratory observations reflected responses characteristic of plants in natural systems: Changes in leaf chlorophyll and protein content and rhizome carbohydrate in *Thalassia* and standing crop and chlorophyll content of epiphyte communities were compared for 3 experiments conducted over 6-week intervals at different times of the growing season and for one 12-week laboratory-field comparison. *Thalassia* plants in the laboratory followed similar trends of field plants during the 6-week experiments but the laboratory plants differed significantly from field plants at 12 weeks. Chlorophyll content of epiphyte communities colonizing *Thalassia* leaves was significantly different in the laboratory compared to field samples.

Dennison, W. C., R. J. Orth, K. A. Moore, J. C. Stevenson, V. Carter, S. Kollar, P. W. Bergstrom and R. A. Batiuk. 1993. Assessing water quality with submerged aquatic vegetation. *BioScience* 43:86-94.

This article summarizes the structural characteristics (light availability, nutrient concentration, and other associated measures) required by healthy SAV habitats as they relate to water quality for the Chesapeake Bay. The authors provide a concise summary of the water quality parameters necessary to support SAV and are thus able to determine what levels of water quality and clarity are necessary to support SAV. The amount and health of SAV can then be used as a surrogate measure of water quality. This approach of matching the habitat needs of SAV to water quality characteristics could be exported to other estuaries around the country suffering similar levels of habitat loss and water quality degradation.

Durako, M. J., M. Hall, J. Hall, L. Hefty, J. Bacon and S. Kim. 1996. The status and trends of seagrass communities in Florida Bay. In Seagrass Ecology 1996 Abstracts, Florida Bay Science Conference Abstracts. Partnership with Florida Marine Research Institute (FDEP), St. Petersburg, FL., and Dade County Department of Environmental Resources Management, Miami, FL. http://www.aoml.noaa.gov/flbay/seag96.html.

Researchers assessed variation in macrophyte species distribution and abundance, community structure and population dynamics in relation to the multiple stressors along a northeastern Florida Bay. Four hundred stations in 14 basins were sampled seasonally for seagrass and macroalgal distribution and abundance. Methods are described that can be used by restoration practitioners in monitoring submerged aquatic vegetation restorations.

Analyses performed on seagrass cover/abundance showed significant *Thalassia* loss in western (Rabbit Key Basin, RKB) and southern (Twin Key Basin, TWN) Florida Bay. *Thalassia* cover/abundance values were stable or increased from spring 1995 to spring 1996 in all but one (TWN) of the ten basins sampled. In central-to-northeast basins *Thalassia* abundance was stable or increased. In spring 1995, about 39% of the area sampled had less than 5% of *Thalassia*. In central Florida Bay, *Thalassia* was less abundant (Rankin Lake, RNK and Whipray Basin, WHP) and had the most seagrass die-offs.

Seagrass composition and abundance at two sites in Little Madeira Bay remained unchanged. At Trout Cove, and Long Sound sites, *Thalassia* shoot density decreased from fall 1995 to spring 1996 and dropped below past ranges for each station. *Halodule* density at the Long Sound station increased significantly between Fall 1995 and Spring 1996. *Ruppia* shoot density decreased between Fall 1995 and Spring 1996 at the Highway Creek station. Researchers concluded that increased distribution, abundance, and significance of seagrass recovery may have been due to improved water quality conditions in Florida Bay.

Eleuterius, L. N. 1975. Submergent vegetation for bottom stabilization. *Estuarine Research* 2: 439-456.

Author Abstract. In this study *Thalassia testidinum*, *Cymodocea manatorum,* and *Diplantera wrightii* were transplanted from natural stands to infertile inundated spoiled areas and control areas adjacent to undisturbed seagrass beds. Anchoring devices were developed to hold the transplants in place. Methods used in this study are described in this publication. The results showed that *D. wrightii* had the highest survival, and its growth rate exceeded that of *T. testidinum; C. manatorum* did not survive at all. Based on its distribution, growth tolerance to sediment deposition, therefore *D. wrightii* is considered the best seagrass species for transplant studies. Transplants were unsuccessful on dredged material. Low temperatures and lengthened exposure to low salinity negatively affected seagrass beds and transplants. However, available plant nutrient levels of substrate samples did not vary significantly between vegetated and barren areas. This publication provides information on techniques and monitoring metrics that can be measured in evaluating success.

Eleuterius, L. N. and J. I. Gill. 1981. Long-term observations on seagrass beds and salt marsh established from transplants, pp. 72-86. In R. H. Stovall (ed.), Proceedings of the 8th Annual Conference on Wetlands Restoration and Creation. Hillsborough Community College, Tampa, Florida.

Author Abstract. This report discusses seagrass and saltmarsh transplant projects in Mississippi. The techniques used for this study are described in this article. The projects involved transplanting a wide variety of seagrass and salt marsh species. In seagrass projects, *Halodule beaudettei, Thalassia testudinum* and *Cymodocea manatorum* were transplanted. Approximately 30% of the transplants survived best, and spread rapidly. At these particular test sites the seagrass beds spread only westward, leaving their original planting sites empty as the eastern shoots died. This migration occurred within a few growing seasons and was due to the predominant westward current in the area.

Fisheries and Aquaculture Research. 2000. Oyster Point seagrass monitoring 1995 to 1998. Project leader R. Coles, Fisheries and Aquaculture Research Report*,* Queensland Government. Department of Primary Industries, 80 Ann St, Brisbane, Queensland Australia. http://www.dpi.qld.gov.au/far/9253.html

Researchers monitored seagrass abundance on both sides of Stony Creek Oyster Point and compared it to the baseline data collected in 1995. Baseline seagrass surveys at Oyster Point were conducted in November 1995 and August 1996, prior to dredging of the main boat access channel. Seagrass monitoring surveys were conducted immediately following dredging and the opening and widening of the marina entrance, and during the dredging of the marina and maintenance dredging of the main boat channel. A survey was conducted in December 1999 to test persistence of the silt layer and its impacts on seagrasses. Abundance (visual estimates) and aerial extent of seagrass habitat in December 1999 were similar to that in 1998. Data collected from field observations, show that biomass of all seagrass species may be similar to previous surveys. In addition, preliminary observations showed that long–term patterns of silt deposition following dredge and excavation activities at Oyster Point were not responsible for large changes in seagrass distribution and abundance.

Fonseca, M. S., W. J. Kenworthy and G. W. Thayer. 1985. Transplanting of the **seagrasses** *Zostera marina* and *Halodule wrightii* for sediment stabilization and habitat development on the east coast of the United States. 64 pp. Technical Report of United States Army Engineers Waterways Experiment Station WES-TR-EL-85-9.

Successful methods for transplanting seagrasses to achieve densities similar to natural, local seagrass populations are described in this report. Researchers used numerous measures and procedures to evaluate, analyze, and carrying out plant growth. The growth of transplants was determined by monitoring the growth rate of shoots, the population, the area covered per planting unit, and the number of planting units remaining. Plant material requirements were estimated by calculating the number of planting units needed for a transplant site. Harvest and storage of plant material included identifying preferred harvest sites, developing a suitable harvest technique, and providing storage for seagrass in transit. Planting units were prepared and carried out. Finally researchers monitored seagrass growth and abundance. Detailed information on these techniques used can be found in this publication.

Fonseca, M. S. 1990. Regional analysis of the creation and restoration of seagrass systems, pp. 179-185. In Kusler, J. A., and M. E. Kentula (eds.), Wetland Creation and Restoration: the Status of the Science. Island Press, Washington, D. C.

This book discusses goals that should be established for seagrass restoration and monitoring. Such goals include development of persistent cover, generation of equivalent acreage or increased acreage, replacement with the identical seagrass species, and restoration of faunal production. The author stated that during monitoring, records should be kept of the number of planting units that survive, the number of shoots, the population growth rate, and area coverage. Additional information for techniques is presented. Researchers suggested that hydrology, substrate, revegetation, reintroduction of fauna, buffers, protective structures, and long term management should be taken into consideration during planning to avoid any detrimental changes from occurring in the ecosystem.

Fonseca, M.S. 1992. Restoring seagrass systems in the United States, pp. 79-110. In Thayer, G. W. (ed.), Restoring The Nation's Marine Environment. Publication UM-SG-TS-92-06. Maryland Sea Grant College, College Park, Maryland

AuthorAbstract. Seagrass restoration has been performed as a defensive or remedial action in conjunction with natural resource damages. In order to protect seagrass habitat, the author suggests that better project goals be established from the outset. Goals may include developing persistent cover, generating equivalent acreage, increasing acreage, replacing the same seagrass species as was injured or removed, and restoring faunal production. See publication for additional information on methods to be use for monitoring and restoration of seagrasses. Site selection is considered a problem in ensuring seagrass restoration success. This paper discusses 8 research needs that are important for improving seagrass restoration science: 1) a definition of functional restoration, 2) a compilation of population growth and coverage rates, 3) the resource role of mixed species plantings, 4) the impact of substituting pioneer for climax species on faunal composition and abundance, 5) culture techniques for propagule development, 6) transplant-optimization techniques such as the use of fertilizer, 7) the importance of maintaining genetic diversity, and (8) resource agencies.

Fonseca, M. S. 1993. A guide to planting seagrasses in the Gulf of Mexico. 27 pp. Texas A&M University Sea Grant College Program. Report No. TAMU-SG-94-601.

This report presents methods used for planting and transplanting seagrass. Methods described include plug, staple, and peat methods. In the plug method, plugs of seagrass are harvested using a core tube. Core tubes remove plugs from the seagrass bed transported them in the tube to planting site. The tube is placed in the sediment while directing seagrass blades into the tube and then capped generating suction that pulls the small plug of seagrass with associated sediment. The bottom is then sealed to avoid losing the plug during transport. The staple method include digging up plants and sediment, shaking sediment from roots and rhizomes and placing the whole plant in flowing seawater tanks until placed in planting units. The plants are then attached to the staples in groups and secured using a paper, coated, metal twist-tie. Finally the staples are placed into the sediment. In the peat pot method, peat pots used were 3 inches on each side. A sod plugger was used to cut plugs from existing beds. The plugs are then placed immediately into peat pots and placed in a floating holding tray descended to the bottom and remains until transported to the planting site. For planting, the sediment is loosened and peat pots are placed in the bottom sediment. Additional information on techniques is also discussed in this manual.

Fonseca, M. S., W. J. Kenworthy, F. X. Courtney and M. O. Hall. 1994. Seagrass planting in the southeastern United States: methods for accelerating habitat development. *Restoration Ecology* 2: 198-212.

Author Abstract. Seagrass transplanting experiments were conducted in Back Sound, Carteret County, North Carolina, and Tampa Bay, Pinellas County, Florida. In Florida, we compared three planting methods (cores, stapled bare root, and peat-pot plugs) for shoot addition rate, coverage, and labor cost (harvest, fabrication, and deployment) using *Halodule wrightii*. Only planting methods and development rates were recorded for *Syringodium filiforme*. Fertilizer additions were made to peat-pot plantings of *H. wrightii* and *Zostera marina* in both North Carolina and Florida. Exclosure cages were tested to attempt to minimize bioturbation of *H. wrightii* and *Z. marina* in both North Carolina and Florida. Recovery from harvesting impacts to existing, natural beds of *S. filiforme* and *H. wrightii* were assessed in Florida. The peat-pot method was about 35% and 63% less expensive in work time than staples and core tubes, respectively. Response to fertilizer additions was masked by inconsistent release properties of the fertilizer, although some indication of positive response to phosphorus fertilizer in sediments with low carbonate content, and nitrogen in general, was detected. Complete loss of peat pots, largely ascribed to bioturbation, occurred in a large planting (Tampa Bay) but not in nearby smaller ones where exclosure cages were used. Cages did not affect planting unit survival in North Carolina but did improve number of shoots per planting unit in one of three experiments. No detrimental effects of cages were noted. Existing natural beds used to harvest transplanting stock in Tampa Bay recovered from excavations as large as 0.5 m in one year. Significant cost savings were found to be possible through methodological improvement, including planting techniques, bioturbation exclusion, and possibly fertilizer additions.

Fonseca, M. S., W. J. Kenworthy and F. X. Courtney. 1996. Development of planted seagrass beds in Tampa Bay, Florida, USA. 1. Plant components. *Marine Ecology Progress Series* 132: 127-139.

Author Abstract. In this study we evaluated the floral attributes of planted seagrass beds as they developed over time. The seagrasses *Halodule wrightii* and *Syringodium filiforme* were planted on 0.5 m centers at several sites within Tampa Bay, Florida, USA. Planting unit (PU) survival, change in aerial shoot density, plant morphometrics and associated macroalgae were monitored over a 3-yr period. These parameters were compared with nearby, natural beds as a reference. Comparisons were not limited to the same species, but included *Thalassia testudinum* in order to address management issues regarding the substitution of one habitat type for another. Despite use of experienced personnel, in some plantings, an average 47% loss of PU was sustained, apparently due to seasonal bioturbation. Depending on the spatial distribution of loss, persistent cover at equivalent densities was still attained within 1.8-yr (for plantings on 0.5 m centers) over portions of some planted sites. Seagrass recovery rate and recommended monitoring times have a positive, linear relationship to spacing of plantings. Although moderately variable, aerial shoot density clearly defined trends in bed development over time. Many plantings exhibited little spread in the first year after planting, and then expanded rapidly in the second year. Seagrass surface area, length or biomass, as well as macroalgal biomass, proved to be weak indicators of system development for most seagrass species. Although substantial PU losses were experienced, the subsequent survival, spread and persistence of seagrasses indicate that large areas of Tampa Bay, which historically had supported seagrass, are now suitable for restoration. For remaining seagrass habitat however, conservation provides a more certain basis for maintaining the resource than attempting to mitigate through planting.

Fonseca, M. S., W. J. Kenworthy and G. W. Thayer. 1982. A low cost transplanting procedure for sediment stabilization and habitat development using eelgrass (*Zostera marina*). *Wetlands* 2:138-151.

This paper describes procedures for conducting a low cost planting technique for seagrass. Procedures for harvesting and storing plants include identifying preferred harvest sites, developing a harvesting technique and storage guidelines. In order to prepare the planting units, the plants were first collected and the number of shoots per planting unit isolated. Researchers attached the anchor and fasteners with one plant per unit. The planting units were then placed into containers for transport to the planting site. The planting method for eelgrass involved inserting plants into the sediment so that the top of the L-shaped anchor was covered with sediment. Additional information on techniques used for planting eelgrass is described in this report. Requirements for seagrass transplants included establishing the number of units required for a planting and the number of shoots required for planting. Labor requirements must also be taken into consideration. For instance the number of men needed and the amount of hours required for harvesting and preparation of planting units and actual planting. The article provides details on how construction of an efficient time- and man-power schedule can be completed.

Fonseca, M. S., W. J. Kenworthy and G. W. Thayer. 1998. Guidelines for the conservation and restoration of seagrass in the United States and adjacent waters. 222 pp. NOAA Coastal Ocean Program Decision Analysis Series No.12. http://shrimp.ccfhrb.noaa.gov/library/digital.html

Author Abstract. Several criteria have been used for evaluating seagrass planting success. Many habitat functions seem to relate directly to measures of coverage and persistence for structural criteria. Seagrass monitoring should provide for mid-course correction and improve planning of future restoration projects. Structural criteria include planting survival, aerial coverage, and number of shoots. The methods used for planting and transplanting of seagrass included plug methods, staple method and peat pot method. Details of techniques used are described in this publication, and should be used as a guideline in planting and monitoring. Seagrasses should be monitored at least quarterly after the first year and every six months for at least the following four years. In terms of achieving success, a nearby reference site may be used for comparison. An alternative strategy should be used to compare the monitored site with currently published structural values to gauge restoration performance. Cost estimates per hectare of seagrass restoration are presented.

Fonseca, M. S., B. E. Julius and W. J. Kenworthy. 2000. Integrating biology and economics in seagrass restoration: how much is enough and why? *Ecological Engineering* 15:227-237.

Author Abstract. Although success criteria for seagrass restoration have been in place for some time, there has been little consistency regarding how much habitat should be restored for every unit area lost (the replacement ratio). Extant success criteria focus on persistence, area, and habitat quality (shoot density). These metrics, while conservative, remain largely accepted for the seagrass ecosystem. Computation of the replacement ratio using economic tools has recently been integrated with seagrass restoration and is based on the intrinsic recovery rate of the injured seagrass beds themselves as compared with the efficacy of the restoration itself. In this application, field surveys of injured seagrass beds in the Florida Keys National Marine Sanctuary (FKNMS) were conducted over several years and provide the basis for computing the intrinsic recovery rate and thus, the replacement ratio. This computation is performed using the Habitat Equivalency Analysis (HEA) and determines the lost on-site services pertaining to the ecological function of an area as the result of an injury and sets this against the difference between intrinsic recovery and recovery afforded by restoration. Joining empirical field data with economic theory has produced a reasonable and typically conservative means of determining the level of restoration and this has been fully supported in Federal Court rulings. Having clearly defined project goals allows application of the success criteria in a predictable, consistent, reasonable, and fair manner.

Green, E. P. and F. T. Short. 2003. World Atlas of Seagrasses. University of California Press, Berkeley, CA.

Publisher Description. Seagrasses, a group of about sixty species of underwater marine flowering plants, grow in the shallow marine and estuary environments of all the world's continents except Antarctica. The primary food of animals such as manatees, dugongs, green sea turtles, and critical habitat for thousands of other animal and plant species, seagrasses are also considered one of the most important shallow-marine ecosystems for humans since they play an important role in fishery production. Though they are highly valuable ecologically and economically, many seagrass habitats around the world have been completely destroyed or are now in rapid decline. *The World Atlas of Seagrasses* is the first authoritative and comprehensive global synthesis of the distribution and status of this critical marine habitat--which, along with mangroves and coral reefs, has been singled out for particular attention by the United Nations Convention on Biodiversity.

Illustrated throughout with color maps, photographs, tables, and more, and written by a large team of international collaborators, this unique volume covers seagrass ecology, scientific studies to date, current status, changing distributions, threatened areas, and conservation and management efforts for twenty-four regions of the world. As human populations expand and continue to live disproportionately in coastal areas, bringing new threats to seagrass habitat, a comprehensive overview of coastal resources and critical habitats is more important than ever. *The World Atlas of Seagrasses* will stimulate new research, conservation, and management efforts, and will help better focus priorities at the international level for these vitally important coastal ecosystems.

Gulf of Maine Council Habitat Restoration Subcommittee. 2004. Gulf of Maine habitat restoration strategy: Restoring coastal habitat in the Gulf of Maine region, 25 pp., Gulf of Maine Council on the Marine Environment. www.gulfofmaine.org

The Gulf of Maine Restoration Strategy states that habitat restoration is necessary to support aquatic resources in the Gulf of Maine to meet both biological and socioeconomic needs. While restoration projects have already occurred in each of the States or Provinces that share the Gulf of Maine, no formal statement of shared goals or a unified strategy to meet them has been presented. This document lays the groundwork for this by:

- Stating the purpose and scope of regional habitat restoration in the Gulf of Maine
- Identifying habitat types, impacts, and restoration needs, and
- Developing recommendations for enhancing habitat restoration

This report identifies resources of regional significance and promotes habitat restoration that is needed to support the viability of these resources. The strategy presented focuses on four categories of habitats:

(1) Riverine

(2) Intertidal

(3) Subtidal, including nearshore and offshore waters, and

(4) Beaches, sand dunes, and islands

Recommendations provided for the continued success with habitat restoration efforts in the Gulf of Maine include:

- Restore the four coastal marine habitat types identified in this document using a regional strategy to prioritize projects
- Improve our ability to identify habitat restoration sites, focus regional efforts, understand regional trends, and develop effective long-range planning
- Increase development and management capacity in all jurisdictions in the region to make restoration more efficient and effective
- Enhance outreach efforts to federal, state, local governments and the private sector to create a common understanding of the social, economic, and environmental benefits of habitat restoration
- Complete and maintain a database of restoration projects in the region to evaluate progress and ensure accordance with the US National Estuary Restoration Inventory (NERI)
- Refine existing salt marsh monitoring protocols and develop monitoring protocols for other habitats identified in this document

James, W. F., J. W. Barko and M. G. Butler. 2001. Shear stress and sediment resuspension in canopy- and meadow-forming submersed macrophyte communities. 16 pp. U.S. Army Engineer Research and Development Center, Vicksburg, MS. APCRP Technical Notes Collection ERDC TN-APCRP-EA-03. http://www.wes.army.mil/el/aqua/pdf/apcea-03.pdf

This technical note reviewed the impacts that differing plant architecture (canopy vs. meadow) and biomass production have on submerged macrophytes ability to decrease wave-induced shear stress at the sediment surface. Authors found that both growth forms significantly decreased shear stress at high biomass levels (<200 g/m^2). For restoration practitioners interested in monitoring shear stress during restoration activities, a detailed explanation of methods is included.

Kashian, D. R. and T. M. Burton. 2000. A comparison of macroinvertebrates of two Great Lakes coastal wetlands: Testing potential metrics for an Index of Ecological Integrity. *Journal of Great Lakes Research* 26:460-481.

Author Abstract. The macroinvertebrates of two northern Lake Huron wetlands were compared to assess water quality and test potential metrics for an Index of Ecological Integrity (IEI) for Great Lakes coastal wetlands. Macroinvertebrates were collected using sediment coring and dip-net sampling monthly from June through September 1996. One wetland was impacted by domestic wastewater from a lagoon, urban storm-water runoff, and local marina traffic. A nearby wetland with a similar size drainage basin, no wastewater or urban storm-water input or marina traffic served as a reference. Greatest differences in chemistry between sites occurred during lagoon discharge in September. Compared to the reference, the impacted wetland had higher Cl, NH_4-N, NO_3-N, soluble reactive P, conductivity and lower dissolved oxygen levels. There were fewer insects, especially Ephemeroptera and Trichoptera in the impacted wetland than in the reference wetland. A greater proportion of macroinvertebrates in the impacted wetland were Amphipoda, Isopoda, and Naididae. Observed differences in macroinvertebrate communities were used to test 38 metrics, used in indices of biological integrity for streams, to determine their potential as metrics for an index of ecological integrity for Great Lake wetlands. Invertebrate attributes sensitive to water quality changes were identified as candidate metrics if they exhibited low within-site variability and detected differences between wetlands for each sampling period. Candidate metrics included relative abundance of Ephemeroptera, Isopoda, Trichoptera, predators, collector-filterers, and herbivore/detritivore ratio.

Kenworthy, W. J. 1994. Conservation and restoration of the seagrasses of the Gulf of Mexico through a better understanding of their minimum light requirements and factors controlling water transparency, pp. 17-26. In Indicator Development: Seagrass Monitoring and Research in the Gulf of Mexico, Gulf Breeze, Fla., U.S. Environmental Protection Agency, Office of Research and Development, Environmental Research Laboratory.

This paper discusses measurements that should be taken in order to understand and predict seagrass distribution. Water quality and light metrics were used to determine the success and distribution of seagrasses. Detailed information on methods used is presented. Data collected on depth distribution showed that *Halodule wrightii* and *Syringodium filiforme* grew deeper than *Thalassia testidinum.* Mechanisms controlling *T. testidinum* light requirements may include phototoxicity instead of carbon balance. *Halodule wrightii,* however, produced more oxygen at low light levels. Results show that *H. wrightii* can maintain continuous growth at low light levels for longer periods than *T. testidinum.* This shows that seagrass growth in certain light levels and water depths will vary among species. The author states that this prognostic ability is particularly useful for designing management programs for monitoring, protection, and restoration of seagrasses. Other evaluations made and additional information on other parameters investigated for this study are described.

Killgore, K. J., R. P. Morgan II and N. Rybicki. 1989. Distribution and abundance of fishes associated with submersed aquatic plants in the Potomac River. *North American Journal of Fisheries Management* 9:101-111.

Author Abstract. The distribution and abundance of fishes in submersed aquatic plants of three relative densities (no plants, intermediate plant density, high plant density) were estimated in the tidal Potomac River near Alexandria, Virginia. Fish were sampled with a boat-mounted electroshocker at night in May (when plants were emerging), August (peak plant densities), and November (plant senescence) of 1986. Mean densities of all plants ranged from 9 to 33 g/m^2 (dry-weight basis) in May, and 400 to greater than 1,000 g/m^2 in August and November. *Hydrilla verticillata* was usually the dominant aquatic plant. In May, overall mean fish abundance was highest in areas of high plant density (36 fish/5 min shocking), whereas in August and November fish abundance was highest in areas of intermediate plant densities (100 and 62 fish/5 min electroshocking, respectively). Areas without plants contained a relatively high number of filter-feeding fishes, including Atlantic menhaden *Brevoortia tyrannus* and blueback herring *Alosa aestivalis*. The fish assemblage in the vegetated sites comprised mainly brown bullhead *Ictalurus nebulosus*, banded killifish *Fundulus diaphanus*, pumpkinseed *Lepomis gibbosus*, largemouth bass *Micropterus salmoides*, and yellow perch *Perca flavescens*. The bay anchovy *Anchoa mitchilli*, white perch *Morone americana*, and inland silverside *Menidia beryllina* were distributed throughout all three sites during the study. Fish also were sampled with pop nets in aquatic plants and with seines between shore and the plant beds. More than five times more fish (9.8/m^2) were collected with pop nets in areas with intermediate plant density, where there were several codominant plant species, than in areas with dense hydrilla (1.8 fish/m^2). Shore-zone fish densities estimated with seine hauls were higher in areas adjacent to dense hydrilla beds (9 fish/m^2) than in areas with no plants (1.5/m^2) or near intermediate plant densities (3.3/m^2), but the number of fish species was lowest near hydrilla.

Krieger, K. A. 1992. The ecology of invertebrates in Great Lakes coastal wetlands: current knowledge and research needs. *Journal of Great Lakes Research* 18: 634-650.

Author Abstract. This review summarizes the comparatively sparse information on the community structure, population dynamics, secondary productivity, and trophic relationships of invertebrates in coastal wetlands of the Laurentian Great Lakes. Community structure is discussed in terms of separate but interrelated communities comprising the zooplankton, zoobenthos, epiphytic invertebrates, and neuston. The composition and dynamics of these communities are controlled by a complex set of interacting and continuously changing biotic and abiotic factors. Much additional research is required before a fundamental understanding of invertebrate ecology in Great Lakes coastal wetlands can be achieved. Particular research needs include elucidation of geographic differences in community structure and dynamics within and among wetlands of the same and contrasting types; the influence of micro- and macro-habitat differences and environmental stresses on invertebrate communities; the contribution of invertebrates to energy and materials flow in wetland food webs; the interactions of wetland invertebrates with the adjoining lake biota; the role of invertebrates in nutrient and pollutant transformations and cycling within the wetlands; the impact of changing land used in wetland watersheds and of wetland alteration on the invertebrate communities, and the consequential impacts of these changes on the ecology of the lakes; and the impact on wetland invertebrate communities of predation pressure and competition from exotic species.

Levine, S. N., D. T. Rudnick, J. R. Kelly, R. D. Morton, L. A. Buttel and K. A. Carr. 1990. Pollutant dynamics as influenced by seagrass beds: experiments with tributyltin in *Thalassia* microcosms. *Marine Environmental Research* 30:297-322.

Author Abstract. Seagrass beds are highly productive ecosystems whose leaves and sediments provide considerable surface area for interactions with seawater; thus, they may be foci for the sorption, accumulation, and degradation of pollutants. The fate of the potent biocide tributyltin (TBT) in water that passes through seagrasses and over sediments was studied in marine microcosms containing sediment cores from a subtropical seagrass bed (including *Thalassia testudinum* and associated fauna) and seawater. The TBT was rapidly removed from the water column (half times of 10-20 h), primarily through adsorption onto sediments and seagrass leaves. Accumulation of TBT in sediments and grasses was temporary, however; at harvest, the seagrass microcosms contained just 20-30% of the super(14)C that had been adsorbed or assimilated during dose periods, and half of this label was in degradation products.

Lewis, R. R., III. 1987. The restoration and creation of seagrass meadows in the southeastern United States. pp. 153-174. Proceedings of the Symposium on Subtropical-Tropical Seagrasses of the Southeastern United States.

Author Abstract. The restoration and creation of seagrass meadows is of increasing concern in the southeastern United States, due to large-scale declines in seagrass meadow coverage. Researchers and environmentalists estimate that approximately one-third of the 600,000 ha of seagrass meadows that were present in coastal Florida in the 1940's no longer exist. Associated declines in fisheries harvests have been documented. In Mississippi, 1,970 ha of seagrasses remain, representing a loss of almost two-thirds. Both restoration and creation of meadows have been successful in individual projects at sites up to 6 ha in size, but failures are common. A more analytical approach to successful plantings is encouraged; prior knowledge of water quality and stresses on existing seagrass meadows is essential. Simple transplanting with plugs from existing healthy meadows (particularly *Thalassia testudium* plugs) in not encouraged for large-scale projects. The use of non-destructive sources of material for culture of planting units is documented and recommended. Salvage of seagrasses from areas to be impacted can ensure successful, non-destructive meadow restoration and creation, and is encouraged.

Lores, E. M., E. Pasko, J. M. Patrick, L. Q. Robert, J. Campbell and J. Macauley. 2000. Mapping and monitoring of submerged aquatic vegetation in Escambia-Pensacola Bay System. *Florida Gulf of Mexico Sciences* 18:1-14.

Author Abstract. Recently, the distribution and changes in submerged aquatic vegetation (SAV) in the Escambia-Pensacola Bay System in northeastern Florida were monitored by two techniques. One technique used divers to measure changes in the deepwater margin of beds and provided horizontal growth measurements to the nearest centimeter, the other used a differential global positioning system (DGPS) on a small boat to map the perimeter of SAV beds in shallow water. Current distribution of SAV in Escambia Bay shows that most of the SAV losses that occurred during the 1950s to 1970s have been recovered. In Santa Rosa Sound and Pensacola Bay, SAV showed significant increased growth with horizontal growth rates of some beds averaging more than 50 cm over the past year. In Big Lagoon, however, SAV has declined an average of 10 cm in horizontal coverage along the deepwater edge. Water quality and photosynthetically active radiation light measurements from the Escambia-Pensacola Bay System suggest that increased light availability was associated with the increased seagrass coverage in Santa Rosa Sound and Pensacola Bay, and elevated nutrient concentrations were associated with the seagrass declines in Big Lagoon.

Lundholm, J. T. and S. W. Len. 1999. Regeneration of submerged macrophyte populations in a disturbed Lake Ontario coastal marsh. *Journal of Great Lakes Research* 25:395-400.

Author Abstract. Previous studies in disturbed Great Lakes coastal marshes have determined that seed banks for submerged macrophytes tend to be depauperate if not absent. This was thought to be a major factor that would prevent the regeneration of macrophyte populations under improved conditions, so the transfer of seed or adult plants from healthy wetlands within the same region has been recommended as a restoration strategy. Cootes Paradise is a large, disturbed coastal marsh with a poor seed bank for submerged plants. In this report a large increase in submerged macrophyte population densities following the reduction of carp (*Cyprinus carpio*) densities from approximately 700 kg/ha in 1996 to 50 kg/ha in 1997 is documented. Much of this regeneration occurred in areas devoid of aquatic vegetation in 1996. It was determined that these plants developed from vegetative structures buried in the sediment. It is recommended that detailed surveys of both seed and vegetative propagule banks be undertaken before assessing the likelihood of the recovery of submerged macrophyte communities in disturbed coastal marshes.

McRoy, P. and C. Helffreich. 1977. Culture methods and techniques, pp. 77-81. In McRoy, P., and C. Helffreich (eds.), Seagrass Ecosystems: A Scientific Perspective. Marcel Dekker. Inc., New York, NY.

This paper presents methods used for evaluating seagrasses tolerance to change in light levels under laboratory conditions. Cultures were sustained in outdoor and indoor conditions for a year. Data showed that *Thalassia* survived only seven months and *Halodule* for three and a half months. *Thalassia* present in outdoor tanks survived twelve months but only a few *Halodule* survived. The seawater used in the laboratory studies included synthetic seawater and natural bay water. Seagrass growth in synthetic seawater was less dependent on the source of the medium than salinity, temperature, and light. Additional information on techniques used is presented.

Cultured seagrasses were transplanted into two soils, river sand and sandy loam within the Gulf of Mexico. After five months, *Halophila, Thalassia*, and *Ruppia* had greater survival rates in the sandy loam. *Halodule* had a poor survival in both soil types but *Halophila* flourished in culture containers containing algae. Such data suggests that *Halophilia* can tolerate low light intensity and dense algal growth. A good technique for use in collecting eelgrass based on successful research conducted in the past is also presented.

Muehlstein, L. (draft). Seagrass monitoring protocol. The National Park Service Inventory and Monitoring. http://science.nature.nps.gov/im/monitor/refer.cfm?AutoNumber=3

Author Abstract. The Virgin Islands National Park has been using a SONAR-based underwater position-locating system (AquaMap by Desert Star Systems) for detailed mapping and monitoring of marine habitats. Using this system along with fixed transects has proved to be effective for monitoring seagrass beds. By using this system, complete randomization of sample points within a study site as well as accurate transfer of those points with sub-meter accuracy can be achieved. The advantage to using this method is that it prevents biases of fixed transects and increases the statistical precision for data analyses. Over-sampling a selected seagrass bed and applying the optimization analysis described in Bros and Colwell (1989) determines the optimum sample size. Seagrass species densities are calculated by counts within quadrats. Data is collected at fixed, long-term transects, on seagrass densities, percent cover of seagrasses, and macroalgal community structure. Additional information on methods used for mapping and monitoring seagrass can be obtained from the reference.

Orth, R. J., M. Luckenbach and K. A. Moore. 1994. Seed dispersal in a marine macrophyte: Implications for colonization and **restoration**. *Ecology* 75:1927-1939.

Author Abstract. The authors conducted seed dispersal experiments in the field and laboratory to better describe seed dispersal characteristics in one species, *Zostera marina* L. (eelgrass), the dominant seagrass species in the temperate zone of the United States, Japan, and Europe. Seeds were broadcast by hand into unvegetated 5 m diameter plots at three locations over 3-yr (1989-1991) in the York River, Virginia (Chesapeake Bay). These sites had been previously vegetated but were devoid of any vegetation prior to (since 1972) and during the course of the experiments. Resultant seedling distributions closely matched broadcast patterns, with 80% of all seedlings found within the 5 m diameter plots, despite the fact that geophysical processes would appear sufficient to transport seeds greater distances. Wind records for the 2-mo period between seed broadcasting and germination revealed time-averaged wind speeds in excess of 40 km/h on greater than or equal to 12-d in each of the 3-yr and gale-force winds (72 km/h) in 2 of 3 yr. A three-dimensional hydrographic computer simulation model of the York River provided instantaneous current velocity estimates from which maximum bottom shear velocities (u_*) in the study area were approximated (flood tide: 1.26 cm/s, ebb tide: 1.20 cm/s). These estimates exceeded the critical erosion threshold (u_{*crit}) = 0.7 cm/s) for *Z. marina* seeds determined from laboratory flume experiments. We postulate that small-scale topographic features on the bottom (burrows, pits, mounds, ripples) shield the seeds from the flow. Our results suggest that seeds settle rapidly, dispersing only up to a few meters under the influence of currents and become rapidly incorporated into the sediment. The limited dispersal capabilities of seeds underscore the need to address restoration goals and questions of seagrass ecology in the context of landscape-scale distributional patterns and metapopulation analyses.

Orth, R. J., M. C. Harwell and J. R. Fishman. 1999. A rapid and simple method for transplanting eelgrass using single, unanchored shoots. *Aquatic Botany* 64: 77-85.

Author Abstract. In a large-scale eelgrass (*Zostera marina* L.) restoration program that began in 1996 in Chesapeake Bay, a simple transplant technique was developed where single, unanchored shoots with rhizomes were planted by hand into the sediment at an angle to a depth of between 25 and 50 mm, allowing the more compact area of the sediment above the rhizome to assist in anchoring the plant. This method led to high success, as determined primarily by percent cover and shoot density at four transplant sites in two river systems, where 53,760 shoots were planted into 768 2 x 2 m^2 plots. The estimated total time to plant a single shoot using this method, including collection and sorting of shoots for planting, was approximately 21 s. Survivorship in the first month was high (73%) and compares favorably with methodologies from other published studies. Percent cover increased rapidly from 12.3% to 18.0% over the first eight months to 24.2-38.9% after twenty months. Vegetative growth from a single shoot was rapid, with shoot densities similar to those of nearby, natural beds attained in one year or less (e.g., transplanted areas at eight months: 772 ± 203 to 1234 ± 419 shoots m^{-2}; natural areas: 697 plus or minus 256 shoots m^{-2}). Despite the simplicity of this technique, it is fairly robust and complements the recent development of another simple technique (Davis and Short, 1997 Aquat. Bot. 59, 1-15) with applications for other seagrass species.

Perrow, M. R., J. H. Schutten, J. R. Howes, T. Holzer, F. J. Madgwick and A. J. D. Jowitt. 1997. Interactions between coot (*Fulica atra*) and submerged macrophytes: The role of birds in the restoration process. *Hydrobiologia* 342-343: 241-255.

Author Abstract. Grazing by herbivorous birds is often cited as an important factor in suppressing macrophyte development in shallow lakes undergoing restoration, thus delaying the attainment of the stable clear water state. Development and succession of macrophyte communities and size, diet and grazing pressure of coot (*Fulica atra*) populations upon macrophytes, were monitored over the seasonal cycle at ten shallow lakes of varying nutrient status, in the Norfolk Broads in eastern England. In spring, territorial breeding birds were at relatively low density and included only a small proportion of macrophytes in their diet, resulting in low grazing pressure on macrophytes. In summer, there was a significant relationship between macrophyte cover and bird density, illustrating the importance of macrophytes in the dispersion phase for birds following breeding. Macrophytes comprised the bulk of bird diet where they were available and the consumption of macrophytes was up to 76 fold higher than in spring. However, losses to grazing in both periods were negligible when compared to potential growth rates documented in the literature. Grazing experiments at two biomanipulated lakes confirmed that birds were not responsible for limiting macrophytes during the spring colonization phase or in the summer growth period. During the period of autumnal senescence and over the winter months where some macrophyte species remain available, e.g., as developed individuals or dormant buds, grazing by birds may conceivably have an impact on the development and structure of macrophyte populations in subsequent growing seasons. The relative importance of bird grazing compared to other factors limiting the development of macrophytes in shallow lakes is discussed in the light of other experimental studies.

Phillips, R. C. 1980. Planting methods, pp. 17-20. In Lutz, R. A. (ed.), Planting Guidelines for Seagrasses, Coastal Engineering. United States Army Corps of Engineers, Coastal Engineering Research Center. Technical Aid No. 80-2.

Planting methods for seagrass restoration are presented in this document. The methods described include seeding, planting of eelgrass sprigs, planting plugs, and planting sprigs. Seeding is used primarily for turtle grass because their seeds are larger and not easily away. The seeds are collected from mature fruits or as germinated seedlings that lay on the sediment surface. During the harvest season the fruit is clipped from the stalk and the spongy ovary wall is opened to expose the four to five seeds. Eelgrass sprigs are composed of three to four shoots. Shoal grass sprigs consist of fifteen to twenty shoots on the same rhizome. The sprigs are planted during low currents by excavating a small hole in the substrate, placing the sprigs in the hole, and covering them with sediment. Plugs are acquired by using a cylindrical coring device pushed into the grass bed. The grass plug is then transplanted in a hole, 6 to 8 inches deep. Plugs are recommended for shoal grass transplants. Planting and seagrass sprigs are anchored in areas where currents exceed 1.5 knots and wave currents are influenced by wind or storm. Construction rods and iron mesh painted with vinyl paint can be used as anchoring devices for seagrass plants. Using the rods and iron mesh prevent the plants from being swept away. Techniques are described in detail in this publication. The time in which planting occurs should also be considered because successful growth of seagrass will vary among species.

Phillips, R. C. and P. C. McRoy. 1990. Transplant methods: Seagrass research methods, pp. 51-53. In Phillips, R. C. and P. C. McRoy (eds.), Handbook of Seagrass Biology: An Ecosystem Perspective. Garland STPM Press, New York, NY.

Seagrass transplanting methods that have been successfully used are described in this document. The use of seagrass transplants is an attempt to restore seagrasses and provide structural and functionality to the habitat. Techniques including transplants and anchoring methods are described in detail and should be considering developing planting approaches for seagrass restoration projects. Seagrass transplanting methods include non-anchoring and anchoring methods. The non-anchoring methods include turfs where units of seagrass around $0.1m^2$ are dug up and removed from selected sites. The units are then transported to the transplant site and placed or plugged into the sediment. The plug is dug deep enough secure the root. A plastic cylinder is inserted into the sediment around the seed to protect the propagule from erosion. Anchoring methods used involve individual leafy shoots that are fixed using rubber bands to pipes or iron construction rods. Plants can also be fixed to concrete rings and thrown on the bottom. See reference for additional information on techniques used for transplanting.

Sand-Jensen, K. 1975. Biomass net production and growth dynamics in an eelgrass population in Vellerup Vig, Denmark. *Ophelia* 14:185-201.

Author Abstract. Researchers evaluated the biomass of an eelgrass population in Vellerup Vig, Denmark, and seasonal pattern, March to October 1974. Biomass of leaves and flowering turions was significantly greater than initial amount; biomass of rhizomes also increased significantly from March to August. The maximum total biomass was 433 grams dry weight per square meter. The leaf population was determined by a leaf marking technique that made it possible to estimate the rhizome population. Additional information on methods used is described in this publication. Results showed from April 9 – October 16,1974, the leaf production was 856 grams dry weight per square meter. The dominance of leaf production resulted from a higher turnover rate of leaves (1.8% per day) than of rhizomes (0.7% per day). On the average a new leaf was about 56 days. Total radiation seemed to control leaf production. The maximum leaf production rate of 7.9 grams dry weight per square meter per day in mid-June corresponds with maximum radiation. The total production was significantly greater than the net increase of total biomass and more than twice the maximum total biomass. The methods used could be employed in assessing some metrics for submerged aquatics.

Scott, W. A., J. K. Adamson, J. Rollison and T. W. Parr. 2000. Monitoring of aquatic macrophytes for detection of long-term change in river systems. *Environmental Monitoring and Assessment* 73:131-153.

Author Abstract. This paper presents details of the methodology developed by the United Kingdom's Environmental Change Network for the long-term monitoring of macrophytes in rivers and streams. The methodology is based on techniques first proposed by the Standing Committee of Analysts (1987) and later adapted by the National Rivers Authority (NRA) and Environment Agency, but differs in splitting the surveyed 100 m stretch of water into sections to provide an objective measure of the frequency of occurrence of individual species in place of the more subjective estimation of cover. A pilot study of the ECN methodology took place at five sites in 1997. The results of this study, including a few practical difficulties in the application of the methodology, are presented and discussed. For all but one of the sites strong associations were found between the number of species observed and the physical characteristics of the watercourse. The most important characteristics were degree of shading, substrate type, depth and clarity. The frequency of occurrence of individual species within sections of the watercourse was found to be strongly related to the log of the overall estimates of cover. Because the use of sections, rather than a single overall cover estimate, enables variation in the pattern of vegetation over surveyed stretches to be detected and related to watercourse characteristics, the precision with which change can be detected is increased, and the possibility of determining the causes of change is thereby enhanced. Moreover the use of sections allows within-site variation to be calculated and hence the accuracy of estimated changes to be quantified. In general implementation of the ECN methodology was not found to be particularly onerous or difficult. As a result of the pilot study some changes in the ECN methodology have been made, primarily to reduce the workload so that sites can be surveyed comfortably in a single day.

Simons, J. H. E. J., C. Bakker, M. H. I. Schropp, L. H. Jans, F. R. Kok and R. E. Grift. 2001. Man-made secondary channels along the River Rhine (the Netherlands; results of post-project monitoring. *Regulated Rivers: Research and Management* 17:473-491.

Author Abstract. Owing to river regulations in the past and intensive farming, the ecological value of the floodplains of the River Rhine in The Netherlands has decreased dramatically. One way to restore riverine biotopes is to create permanently flowing channels in the floodplain. Along the River Waal, the main branch of the Lower River Rhine, two such secondary channels have been created since 1994. A post-project monitoring program of 5 years was set up, which included hydrological, morphological and ecological parameters. This article focuses on the monitoring of aquatic macrophytes, aquatic macroinvertebrates, fish and wading birds. The results show that man-made, excavated secondary channels function as a biotope for riverine species including the more demanding rheophilic species. The demands for shipping and protection against flooding on the River Waal cause constraints on secondary channels. Despite these constraints there is still enough space for hydromorphological processes to create new habitats in secondary channel 1, near Opijnen. The space for hydromorphological processes is less in secondary channel 2, near Beneden-Leeuwen. The density and the number of (rheophilic) species are for a large part influenced by the water level and frequent inundation caused by the high hydrological connectivity. Man-made secondary channels seem to provide suitable habitat that is currently lacking for a broad range of rheophilic macroinvertebrate and fish species in the Lower River Rhine in The Netherlands. Owing to the lack of suitable habitats for rheophilic macroinvertebrate and fish species before the creation of the secondary channels, the importance of longitudinal and transversal migration could be illustrated by the drift of macroinvertebrates during floods and the seasonal migration of Age-0 and Age-1+ fish species.

Stevenson, J. C. 1988. Comparative ecology of submersed grass beds in freshwater, estuarine, and marine environments. *Limnology and Oceanography* 33: 867-893.

Stevenson's article compares the different types of SAV and the ecological roles they play in their respective environments. It can be a useful first step for those who are knowledgeable about the ecology of one type but not another. While there are 500-700 freshwater and estuarine species worldwide, only 50 species have been recorded in marine settings. This is due in part the physical and chemical stress involved with living in a marine environment. Despite this lack of diversity, marine SAV tends to have higher productivities than freshwater systems, in part due to greater mixing in marine settings. The secondary productivity of each system also differs. Fish, sea urchins, and other grazers make marine SAV a significant portion of their diet. Although ducks have been shown to graze heavily on SAV it is usually at the end of the growing season and few fish species feed on freshwater SAV. The majority of primary production in freshwater systems enters the detrital food web at the end of the growing season. Thus the trophic relationships between freshwater and marine SAV is quite different.

Terrell, J. B. and D. E. Canfield, Jr. 1996. Evaluation of the effects of nutrient removal and the "Storm of the Century" on submersed vegetation in Kings Bay - Crystal River, Florida. *Journal of Lake and Reservoir Management* 12:394-403.

Despite many of the ecological benefits, dense growth of SAV has often been viewed as a nuisance and signal of nutrient enrichment in coastal waters, a sign that something is wrong and needs to be fixed. Such was the case in Cedar Cove of King's Bay on the west coast of Florida. Dense SAV growth was perceived by the general public to be the result of high phosphorus and nitrogen concentrations stemming from a municipal wastewater facility situated on the cove. A grassroots effort was initiated to remove the wastewater effluent from the cove and 'improve water quality'. Hydrologic modeling showed that the main source of water to the cove, however, was naturally nutrient rich, rich enough that the wastewater facility had little to no effect on SAV growth. After the effluent was removed, at great expense, nutrient levels in the cove did decrease but the perceived problem of dense SAV growth was unaffected. Although this project does show that nutrient levels in the water can be successfully mitigated through alternative land use (and thus water quality was improved), the residents of the area did not see the result they had expected (i.e., less SAV growth). The need for all parties to have a clear understanding of the system dynamics and the expected outcomes of restoration projects is crucial to maintain local support for such efforts in the future.

Thayer, G. W., M. S. Fonseca and W. J. Kenworthy. 1982. Restoration and enhancement of seagrass meadows for maintenance of nearshore productivity. *Atlantica. Rio Grande* 5:118-119.

Author Abstract. Studies have been initiated on the use of transplanting as a means to ameliorate the loss of meadows, and to create seagrass habitat on previously unvegetated areas. Whole mature, vegetative shoots are dug from donor sites, washed free of sediments, attached in clumps to anchors and replanted. This technique yields viable meadows within a growing season at a cost comparable to salt marsh planting in man-hours, on an aerial basis. The seagrasses (*Zostera marina* and *Halodure wrightii*) used here exhibit an exponential growth and coverage rate until reaching densities comparable to natural meadows. Faunal recolonization is significantly increased in these areas over unvegetated areas. The number of fauna and taxa per core increased linearly with time and asymptotic when shoot density reached normal levels for that environment.

U.S. NOAA Coastal Services Center. 2001. Guide to the Seagrasses of the United States of America (Including U.S. Territories in the Caribbean), 20 pp., U.S. National Oceanic and Atmospheric Administration, Coastal Services Center, Charlston, SC. http://www.csc.noaa.gov/benthic/cdroms/sav_cd/pdf/overview.pdf

This short report is intended as a primer to introduce the basic concepts of seagrass biology, ecology, and habitat disturbance and loss to the uninitiated. This report is not intended as an exhaustive treatment or catalog of seagrasses, it does provide practitioners with a common vocabulary to explore SAV issues in greater detail.

In addition to this report, other seagrass-related resources are available on a CD-ROM provided by NOAA. The CD-ROM can be requested through contact information on the following webaddress: http://www.csc.noaa.gov/benthic/cdroms/sav_cd/

Weber, D. E., D. A. Flemer and C. M. Bundrick. 1992. Comparison of the effects of drilling fluid on macrobenthic invertebrates associated with seagrass, *Thalassia testidinum*, in the laboratory and field. *Estuarine Coastal Shelf Science* 35: 315-330.

Author Abstract. The structure of a macrobenthic invertebrate community associated with the seagrass, *Thalassia testudinum*, was evaluated under laboratory and field conditions. The research focused on: (1) the effects of pollution stress from a representative drilling fluid used in off-shore oil and gas operations, and (2) a comparison of responses of the seagrass-invertebrate community in the laboratory and field. A series of 15.3 cm diameter cores of the seagrass-invertebrate community was collected from field sites for establishment and sampling of microcosms and in the sampling of field plots over time. Weekly exposures to drilling fluid were conducted in the laboratory microcosms at a mean total suspended matter concentration of 110.7 $mg l^{-1}$ (± 17.7 SD), and in field plots by usage of acrylic exposure chambers at a mean concentration of 132.8 $mg l^{-1}$ (± 33.3 SD). Standing crop of *T. testudinum* was not affected by drilling fluid in the laboratory or field when measured after 6 and 12-week exposure periods. The numbers of macrobenthic invertebrates were suppressed by drilling fluid at both exposure periods in the laboratory, but inhibitory effects were absent in the field. Invertebrate densities in the field were similar among control and treated plots, and were much lower than densities occurring in the laboratory control. In most instances, species richness values were similar in the field and laboratory at the end of each 6 and 12-week period.

Wilcox, D. A. and T. H. Whillans. 1999. Techniques for restoration of disturbed coastal wetlands of the Great Lakes. *Wetlands* 19:835-857.

Author Abstract. A long history of human-induced degradation of Great Lakes wetlands has made restoration a necessity, but the practice of wetland restoration is relatively new, especially in large lake systems. Therefore, we compiled tested methods and developed additional potential methods based on scientific understanding of Great Lakes wetland ecosystems to provide an overview of approaches for restoration. We addressed this challenge by focusing on four general fields of science: hydrology, sedimentology, chemistry, and biology. Hydrologic remediation methods include restoring hydrologic connections between diked and hydrologically altered wetlands and the lakes, restoring water tables lowered by ditching, and restoring natural variation in lake levels of regulated lakes Superior and Ontario. Sedimentological remediation methods include management of sediment input from uplands, removal or proper management of dams on tributary rivers, and restoration of protective barrier beaches and sand spits. Chemical remediation methods include reducing or eliminating inputs of contaminants from point and non-point sources, natural sediment remediation by biodegradation and chemical degradation, and active sediment remediation by removal or by in situ treatment. Biological remediation methods include control of non-target organisms, enhancing populations of target organisms, and enhancing habitat for target organisms. Some of these methods were used in three major restoration projects (Metzger Marsh on Lake Erie and Cootes Paradise and Oshawa Second Marsh on Lake Ontario), which are described as case studies to show practical applications of wetland restoration in the Great Lakes. Successful restoration techniques that do not require continued manipulation must be founded in the basic tenets of ecology and should mimic natural processes. Success is demonstrated by the sustainability, productivity, nutrient-retention ability, invasibility, and biotic interactions within a restored wetland.

Wood, N. and P. Lavery. 2000. Monitoring seagrass ecosystem health - the role of perception in defining health and indicators. *Ecosystem Health* 6: 134-148.

Author Abstract. Thirty-four seagrass researchers/managers were asked to identify seagrass sites in Cockburn Sound, Western Australia, which they perceived to be healthy or unhealthy, and indicate the basis for these perceptions. The average respondent based their perception on three variables, ranging from ecosystem features to plant attributes. Four variables were considered very important in developing perceptions: canopy cover, shoot density, epiphyte biomass, and the proportion of calcareous epiphytes. Three sites perceived to be healthy and three perceived to be unhealthy were then compared to determine if features indicated as important in developing perceptions about health differed between the sites. None of the four variables considered important by respondents differed statistically between healthy and unhealthy sites in winter, but shoot length and above ground biomass were different. In summer, two of the important variables (canopy cover and shoot density) differed, along with shoot height, productivity, and leaf area index. Despite their perceived importance, epiphyte features were not different between perceived healthy and unhealthy sites. The study suggests that shoot density, canopy cover, shoot height, aboveground biomass, productivity, and leaf area index of *Posidonia angustifolia* ecosystems differ statistically between sites perceived to be healthy and unhealthy. However, the usefulness of these variables as indicators of seagrass health varies seasonally. Health was clearly a respondent-dependent concept. The basis of perceptions about health among a group of expert scientists did not correspond strongly to measurable differences between sites. The unwarranted importance placed on epiphytes may be due to previous studies that have reinforced their importance. These observations highlight the role of personal perspective and scientific preconditioning in forming concepts of health, and raise the question of the role that experts should be playing in formulating those concepts.

APPENDIX II: SUBMERGED AQUATIC VEGETATION REVIEW OF TECHNICAL METHODS MANUALS

This Review of Technical Methods Manuals includes a variety of sampling manuals, Quality Assurance/Quality Control (QA/QC) documents, standardized protocols, or other technical resources that may provide practitioners with the level of detail needed when developing a monitoring plan for a coastal restoration project. Examples from both peer reviewed and grey literature are presented. Entries were selected through extensive literature and Internet searches as well as input from reviewers. As with the Annotated Bibliographies, these entries are not, however, a complete list. Entries are arranged alphabetically. Wherever possible, web addresses or other contact information is included in the reference to assist readers in easily obtaining the original resource. Summaries preceded by the terms '*Author Abstract*' or '*Publisher Introduction*' or similar descriptors were taken directly from their original source. Summaries without such descriptors were written by the authors of the associated chapters.

Adamus, P. R., L. T. Stockwell, E. J. Clairain, Jr., M. E. Morrow, L. P. Rozas and R. D. Smith. 1991. Wetland evaluation technique. United States Army Corps of Engineers, Waterways Experiment Station. Technical Report WRP-DE-2.

The Wetland Evaluation Technique (WET) provides information on predictors of wetland functions. The target audience for this manual includes persons such as community groups, NGO's, and anyone who has no contact on a regular basis with technical experts. The manual is divided into two volumes. Information presented in volume one includes conceptual fundamentals for WET, wetland functions in relation to their processes and interactions with other functions, a review of technical literature on each function, the predictors used for determining the probability ratings for wetland functions, and the concept of wetland social significance as used in WET. Volume two of the manual outlines steps required to put into practice the WET method, discusses its application and limitations in detail, and provides documentation for a computer program designed to assist data analysis in WET. Detailed information on methods and procedures described here can be obtained from the manual.

Adamus, P. and K. Brandt. 2003. Impacts on quality of inland wetlands of the United States: A survey of indicators, techniques, and applications of community level biomonitoring data. U.S. Environmental Protection Agency. http://www.epa.gov/owow/wetlands/wqual/introweb.html

This on-line resource is based on the now out of print Report #EPA/600/3-90/073 prepared for the U.S. EPA Wetland Research Program. It is currently being updated. Although it is intended for inland wetlands, many of the resources cited and information provided is applicable to coastal freshwater wetlands. The report describes in detail many of the interactions and possible effects of eutrophication, organic loading, contaminant toxicity, acidification, salinization, sedimentation, turbidity/shade, vegetation removal, thermal alteration, dehydration, inundation, and fragmentation of habitat on wetland biological communities. The effect of these stressors on microbes, algae, vascular plants, invertebrates, fish, amphibians, reptiles, birds, mammals, and selected biological processes is presented wherever information is available. Extensive lists of cited literature can also be used to supplement presented information.

This resource was originally designed for use in developing biological criteria for use in wetland assessment, protection, and management as well as to help identify degraded sites for potential restoration. The information presented can also be used to develop parameters to monitor the progress of restoration efforts, before and after implementation. By linking many of the structural components that help make up wetland habitats with functional components (in this case biota) the information presented can be used to help restoration practitioners select the appropriate structural and functional parameters to monitor as they relate to project goals.

American Public Health Association. 1998. Standard Methods for Examination of Water and Wastewater. 20th ed. American Public Health Association, Washington, D.C.

Standard Methods for Examination of Water and Wastewater is an essential resource for any laboratory performing any analysis on water samples whether they be for chemical, physical, or biological components. Procedures for the sampling of zooplankton, phytoplankton, periphyton, macrophytes, benthic macro-invertebrates, and fish are also included as well as general identification keys to these organisms. Each procedure is explained in step-by-step detail with information on the strengths and weaknesses of various measurement methods. To a general practitioner, this resource would be useful to explain the chemical and biological components they are sampling, what the analysis entails, and the meaning of the final value obtained from each analysis. Various editions should be available at most any laboratory, or scientific or university library.

Batzer, D. P., A. S. Shurtleff and R. B. Rader. 2001. Sampling invertebrates in wetlands, pp. 339-354. In Rader, R. B., D. P. Batzer and S. A. Wissinger (eds.), Bioassessment and Management of North American Freshwater Wetlands. John Wiley and Sons, New York.

Author Abstract. Difficulties in sampling have long hindered research on wetland macroinvertebrates. With the increasing interest in using macroinvertebrate populations to monitor the environmental health of wetlands, sampling of these organisms has become an important research focus. For this chapter we summarized sorting and subsampling procedures and queried many of the prominent researchers who study freshwater wetland macroinvertebrates about their preferences in samplers. For each device we provide a synopsis of their comments, both pro and con, and provide direction on how to use each sampler. Based on the results of this survey as well as published studies that contrast sampler efficacies, we conclude that the sweep net should probably become the sampler of choice for most bioassessment efforts that use wetland macroinvertebrates. We also recommend that most programs sort in the laboratory using either a selective or random technique (depending on the level of taxonomic expertise) and a fixed count of 100 to 300 individuals.

Bergstrom, P. 2003. Chesapeake Bay submerged aquatic vegetation (SAV) ground survey directions. June 10. 10 pp. National Oceanic and Atmospheric Administration. http://noaa.chesapeakebay.net/sav/SAVHunt0602.doc.

Author Introduction. Ground surveys of SAV in the tidal waters of Chesapeake Bay have four main purposes:

(1) "Ground truthing" to verify that beds mapped in the SAV Aerial Survey conducted by Virginia Institute of Marine Science (VIMS) are in fact SAV

(2) To identify and map the SAV species in those mapped beds

(3) To supplement the SAV aerial survey by locating additional SAV beds that are too small to be seen from the air, or were not visible when the photo was taken that year; and

(4) More detailed ground surveys done for research or for permitting such activities as dredging and dock construction.

These directions are designed to be used for the first three purposes, which are addressed by the volunteer "SAV Hunt" coordinated by the Chesapeake Bay Foundation and the US Fish & Wildlife Service. They can be used as the starting point for a detailed survey of the fourth type, but do not give complete instructions for detailed surveys. They do not apply to SAV in non-tidal waters, where more species are present, and different survey methods are needed.

These directions recommend the planning needed, the best types of boats and tools to use, the best times and places to look for SAV, and how to record the data. There is no one "right" way to hunt for SAV, but following these directions will reduce the chance of recording "false negatives", which means concluding an area has no SAV when in fact some was present. "False positives" are always possible if other types of plants in the water are mis-identified as SAV. How to do SAV identification is outside of the scope of this document, and requires a field guide or key.

Cheruvelil, K. S., P. A. Soranno and R. D. Serbin. 2000. Macroinvertebrates associated with submerged macrophytes: Sample size and power to detect effects. *Hydrobiologia* 441:133–139.

Author Abstract. When planning and conducting ecological experiments, it is important to consider how many samples are necessary to detect differences among treatments with acceptably high statistical power. An analysis of statistical power is especially important when studying epiphytic macroinvertebrate colonization of submerged plants because they exhibit large plant-to-plant variability. Despite this variability, many studies have suggested that epiphytic macroinvertebrates preferentially colonize plants based on plant architecture type (broad versus dissected leaves). In this study, we calculated the power and number of samples necessary to detect differences in epiphytic macroinvertebrate abundance (numbers and biomass) among five species and two architecture types of macrophytes in a lake in MI, U.S.A. Using power analysis, we found that we had very high power to detect the differences present between macroinvertebrate abundance by architecture type and by macrophyte species (power = 1.000 and 0.994; effect sizes = 0.872 and 0.646, respectively. However, to detect very small differences between the two architecture types and the five plant species, we determined that many more samples were necessary to achieve similar statistical power (effect size = 0.1–0.3, number of samples = 60–527 and 36–310, respectively; power = 0.9). Our results suggest that macroinvertebrate abundance does in fact vary predictably with plant architecture. Dissected-leaf plants harbored higher abundances of macroinvertebrates than broad-leaf plants (ANOVA, density $p = 0.001$, biomass $p < 0.001$). This knowledge should allow us to better design future studies of epiphytic macroinvertebrates.

Cook Inlet Keeper. 1998. Volunteer training manual: Citizens environmental monitoring program. U.S. Environmental Protection Agency, Region 10, Homer, AK. http://www.inletkeeper.org/training.htm

This manual provides Cook Inlet Keeper volunteers with information needed to monitor water quality in the Cook Inlet watershed. It also provides guidelines for monitoring procedures that are currently included in the Keeper's

Citizens' Environmental Monitoring Program (CEMP). Outlined in this document are safety and access issues; a monitoring overview that discusses water quality test methods, test parameters and a proposed sampling schedule; monitoring procedures including a field procedure checklist, field observations, collecting the samples, testing procedures, sample custody and completing data sheets; equipment care and waste disposal; data management and reporting; and quality control. Additional information for methods and procedures used can be obtained from this manual.

Davies, J., J. Baxter, M. Bradley, D. Connor, J. Khan, E. Murray, W. Sanderson, C. Turnbull and M. Vincent. 2001. Marine monitoring handbook. UK Marine Science Project, and Scottish Association of Marine Science. Joint Nature Conservation Committee, English Nature, Scottish Natural Heritage, Environment and Heritage Services. http://www.jncc.gov.uk/marine/mmh/Contents.htm.

The UK Marine Science Project developed this handbook to provide guidelines for recording, monitoring, and reporting characteristics and conditions of marine habitats. This manual addresses the fundamentals and procedures for monitoring different parameters in marine habitats, management tools, and benefits and costs for developing a monitoring project. Topics include the establishment of marine monitoring programs highlighting what needs to be measured and methods to use; guidance for developing a monitoring program; selection of proper monitoring techniques to attain precision and accuracy; and procedural guidelines for monitoring specific marine habitats. Detailed information on the tools needed for monitoring marine habitats are also described.

Dromgoole, F. I. and J. M. A. Brown. 1976. Quantitative grab sampler for dense beds of aquatic macrophytes. *New Zealand Journal of Marine and Freshwater Research* 10:109-118.

Author Abstract. The construction and operation of a simple mechanical grab, suitable for sampling dense beds of aquatic macrophytes, is described. The technique has several advantages over the diver-quadrat method. Both methods have been used in vegetation surveys of the Rotorua lakes where plant densities attain the maximum recorded for freshwater lakes. The results indicate marked variations in weed density over short distances, and thus both methods require a large number of samples for an accurate determination of biomass.

Ferguson, R. L., L. L. Wood and D. B. Graham. 1993. Monitoring spatial change in seagrass habitat with aerial photography. *Photogrammetric Engineering and Remote Sensing* 59:1033-1038.

Author Abstract. Photographs, taken during aerial surveys in 1985 and 1988, of seagrass habitat were interpreted, transferred to geo-referenced base maps and used to estimate spatial changes in bottom coverage. This paper spends a good deal of time carefully reviewing the criteria of acceptable conditions (e.g., sun angle, sea surface conditions, water clarity, etc) during which accurate aerial photographs can be taken of submerged aquatic vegetation. A particularly useful discussion is included concerning the geo-referencing of seagrass beds to the shoreline, and the need for adequate geodetic information. In addition, a thorough discussion details the steps used in transferring and geo-referencing the photographs to base maps. A helpful analysis of the size, shape, and location of polygons (representing seagrass beds) between years determined that habitat

loss was localized to specific areas and not experienced throughout the system. Field verification was done to identify the seagrass coverages, determine the causes for habitat loss, and confirm the accuracy of this procedure.

Gertz, S. M. 1984. Biostatistical aspects of macrophyton sampling, pp. 28-35. ASTM Special Technical Publication 1984, ASTM, Philadelphia.

Author Abstract. Problems of sampling macrophytes are related to the types of communities under consideration and the goals of a particular study. The communities may range from completely submersed beds of large algae, mosses, pteridophytes, or angiosperms to rooted plants with floating leaves or floating plants with emergent leaves to wetland areas. The goals of a study may be community description or impact analysis. Because of this community goal diversity a quantitative investigation often requires a rigorous statistical design to determine the best sampling design. Of the various sampling designs available there are two general techniques; plot or quadrat methods and plotless methods. Plot or quadrat methods are area methods of sampling communities where the plot may be rectangular, square, or circular, and all individuals in the plot are sampled. Plotless methods usually involve a more random approach of sampling; for example, a compass line is laid out through the community and samples are taken according to some fixed rule. It is the purpose of this paper to review these various sampling methodologies and to evaluate their efficacy, in a statistical sense, in view of the goals of a specific study.

Gibson, G. R., M. L. Bowman, J. Gerritsen and B. D. Snyder. 2000. Estuarine and coastal marine waters: Bioassessment and biocriteria technical guidance. EPA 822-B-00-024. U.S. Environmental Protection Agency, Office of Water, Washington, D.C. http://www.epa.gov/waterscience/biocriteria/States/estuaries/estuaries.pdf

The document describes four levels of investigative intensity or sampling tiers. These tiers are suggested as one possible approach to organizing data gathering efforts and investigation needed to be able to establish biocriteria in a scientifically defensible manner. Other approaches using variations of these tiers may be appropriate depending on program objectives. Tier 0 is a preliminary review of existing literature and data available for the estuary or coastal water of concern. It provides candidate reference sites for the development of a reference condition; Tier I is a one-time site visit with preliminary data gathering to refine the information in Tier 0 and establish candidate biocriteria; Tier II repeats and builds on measurements initiated in Tier I and establishes the reference condition data which is combined with the historical record, possible models or other extrapolations, and a consensus of regional expert opinion to establish and employ the biocriteria for management decision making; Tier III is the diagnostic investigation requiring the most sampling events and most extensive parameters to help establish management efforts for those waters which do not meet the biocriteria.

Biocriteria can be used to help support and protect designated uses of water resources; expand and improve water quality standards; detect problems other water quality measurements may miss or underestimate; help water resource managers set priorities for management planning and, assess the relative success or failure of management projects. Biocriteria do not supersede or replace physical or chemical criteria for water resource decision making and management. In fact, biocriteria augment these established measures so USEPA and the States and Tribes are better informed about the quality of our nations extensive and coastal water resources. The bioassessment/biocriteria process is a particularly cost effective screening tool to evaluate over all water quality and determine water resource status and trends.

An abbreviated table of contents for this document includes:

Goldsborough, G. 2001. Sampling algae in wetlands, pp. 263-295. In Rader, R. B., D. P Batzer and S. A. Wissinger (eds.) Bioassessment and Management of North American Freshwater Wetlands. John Wiley and Sons, New York.

Author Abstract. Algae are often neglected in wetland monitoring programs, but their contributions as food resources for herbivores and regulators of the physical and chemical environment can be significant. In this chapter, I introduce terminology pertaining to planktonic and benthic algal assemblages in wetlands. Some common methods for algal sampling and analysis, and their respective advantages and disadvantages are described. Also discussed are issues affecting the expression and comparability of data from different sites and studies.

Granger, S., M. Traber, S. W. Nixon and R. Keyes. 2002. A practical guide for the use of seeds in eelgrass (*Zostera marina* L.) restoration. Part I. Collection, processing, and storage. 20 pp. Rhode Island Sea Grant, Narragansett, RI. http://nsgl.gso.uri.edu/riu/riuh02001.pdf

Partial Author Introduction. Transplanting mature plants has failed to keep pace with the loss of eelgrass habitat. Consequently, there has been growing interest in the use of *Zostera marina* L. seeds as an alternative method of eelgrass habitat restoration (20). Sexual reproduction through flowering, cross or self pollination, and seed production has been shown to be an effective means by which *Zostera* colonizes new areas, fills in gaps that may form within a meadow, and increases genetic diversity within existing beds (19; 22). While there are many good reasons to believe that the use of seeds is an ecologically and economically attractive alternative to mature shoot transplants, the approach is still experimental. This guide has been prepared in an effort to encourage additional field trials and to assist those who may wish to help develop this very promising method. This guide describes the field and aquarium techniques for harvesting, preparing, and storing large quantities of viable eelgrass seed. A subsequent booklet will describe the methods used for planting the seeds in the field and offer preliminary cost comparisons between whole plant and seed-based restorations. Seeds can also be used to raise seedlings in aquaria for later field planting. Before designing a field program, however, keep in mind that some states have laws protecting submerged aquatic vegetation and a permit may be required for harvesting flowering stalks. It is always prudent to contact the relevant state and federal environmental and coastal management agencies to get the most up-to-date information.

Halse, S. A., D. J. Cale, E. J. Jasinska and R. J. Shiel. 2002. Monitoring change in aquatic invertebrate biodiversity: Sample size, faunal elements and analytical methods. *Aquatic Ecology* 36:395-410.

Author Abstract. Replication is usually regarded as an integral part of biological sampling, yet the cost of extensive within-wetland replication prohibits its use in broad-scale monitoring of trends in aquatic invertebrate biodiversity. In this paper, we report results of testing an alternative protocol, whereby only two samples are collected from a wetland per monitoring event and then analyzed using ordination to detect any changes in invertebrate biodiversity over time. Simulated data suggested ordination of combined data from the two samples would detect 20% species turnover and be a cost-effective method of monitoring changes in biodiversity, whereas power analyses showed about ten samples were required to detect 20% change in species richness using ANOVA. Errors will be higher if years with extreme climatic events (e.g., drought), which often have dramatic short-term effects on invertebrate communities, are included in analyses. We also suggest that protocols for monitoring aquatic invertebrate biodiversity should include microinvertebrates. Almost half the species collected from the wetlands in this study were microinvertebrates and their biodiversity was poorly predicted by macroinvertebrate data.

Hatcher, D., J. Eaton, M. Gibson and R. Leah. 1999. Methodologies for surveying plant communities in artificial channels. *Hydrobiologia* 415:87-91.

Author Abstract. The gathering of quantitative information on aquatic macrophyte communities in artificial drainage and navigation channels presents a number of methodological and analytical problems. These include subjectivity of plant abundance estimation, the conflict between standardization and adaptation of methods to specific purposes, and the concepts of randomness and homogeneity in linear surveying. As a result, much of the currently available information is highly subjective and difficult to use in any comparative way, either temporally or spatially. More standardized procedures should be developed which minimizes these shortcomings and permit later re-use of data in comparative studies.

Holst, L., R. Rozsa, L. Benoit, S. Jacobson and C. Rilling. 2003. Long Island Sound habitat restoration initiative: Technical support for coastal habitat restoration. EPA Long Island Sound Office, Stamford, CT. http://www.longislandsoundstudy.net/habitat/

Partial Author Introduction. This document contains a series of reports produced through the Habitat Restoration Work Group of the Long Island Sound Study (LISS). It is designed to provide basic technical information about the subject habitat and its restoration for persons interested in planning and pursuing a restoration project. Topics covered include ecological descriptions of the plant and animal communities associated with the habitat, the natural history and effects of human influence on the habitat, and the state of the science in restoring the habitat. Included at the end of each section is a list of the literature cited. The reader is strongly urged to investigate these source materials further to achieve a fuller understanding of the ecology and issues related to the subject habitat. The reader is also encouraged to contact the state and federal agency representatives of the Habitat Restoration Work Group for technical advice.

The habitats covered to date include: tidal wetlands, freshwater wetlands, submerged aquatic vegetation, coastal grasslands, coastal barriers, beaches, and dunes.

Killgore, K. J., R. P. Morgan II and N. Rybicki. 1989. Distribution and abundance of fishes associated with submersed aquatic plants in the Potomac River. *North American Journal of Fisheries Management* 9:101-111.

Author Abstract. The distribution and abundance of fishes in submersed aquatic plants of three relative densities (no plants, intermediate plant density, high plant density) were estimated in the tidal Potomac River near Alexandria, Virginia. Fish were sampled with a boat-mounted electroshocker at night in May (when plants were emerging), August (peak plant densities), and November (plant senescence) of 1986. Mean densities of all plants ranged from 9 to 33 g/m^2 (dry-weight basis) in May, and 400 to greater than 1,000 g/m^2 in August and November. *Hydrilla verticillata* was usually the dominant aquatic plant. In May, overall mean fish abundance was highest in areas of high plant density (36 fish/5 min shocking), whereas in August and November fish abundance was highest in areas of intermediate plant densities (100 and 62 fish/5 min electroshocking, respectively). Areas without plants contained a relatively high number of filter-feeding fishes, including Atlantic menhaden (*Brevoortia tyrannus*) and blueback herring (*Alosa aestivalis*). The fish assemblage in the vegetated sites comprised mainly brown bullhead (*Ictalurus nebulosus*), banded killifish (*Fundulus diaphanous*), pumpkinseed *Lepomis gibbosus*), largemouth bass (*Micropterus salmoides*), and yellow perch (*Perca flavescens*). The bay anchovy (*Anchoa mitchilli*), white perch (*Morone Americana*), and inland silverside (*Menidia beryllina*) were distributed throughout all three sites during the study. Fish also were sampled with pop nets in aquatic plants and with seines between shore and the plant beds. More than five times more fish (9.8/m^2) were collected with pop nets in areas with intermediate plant density, where there were several codominant plant species, than in areas with dense hydrilla (1.8 fish/m^2). Shore-zone fish densities estimated with seine hauls were higher in areas adjacent to dense hydrilla beds (9 fish/m^2) than in areas with no plants (1.5/m^2) or near intermediate plant densities (3.3/m^2), but the number of fish species was lowest near hydrilla.

Kornijów, R. 1998. Quantitative sampler for collecting invertebrates associated with submersed and floating-leaved macrophytes. *Aquatic Ecology* 32:241-244.

Author Abstract. A new hand-operated sampler was developed consisting of a perspex cylinder (thickness 0.5 cm, length 32 cm, diameter 13 cm) cut in half lengthwise. The valves are joined together by means of a piano hinge for opening and closing of the sampler. In each of the sites there are openings covered with a net of 0.18×0.18 mm mesh. The external free edges of the halves are covered with weather stripping. The apparatus allows sampling of epiphytic fauna, or animals swimming around various macrophyte structures, including those trailing on the bottom, and those with floating leaves.

Lougheed, V. L. and P. Chow-Fraser. 2002. Development and use of a zooplankton index of wetland quality in the Laurentian Great Lakes basin. *Ecological Applications* 12:474-486.

Author Abstract. Recent interest in biological monitoring as an ecosystem assessment tool has stimulated the development of a number of biotic indices designed to aid in the evaluation of ecosystem integrity however, zooplankton have rarely been included in biomonitoring schemes. We developed a wetland zooplankton index (WZI) based on water quality and zooplankton associations with aquatic vegetation (emergent, submergent, and floating-leaf) that could be used to assess wetland quality, in particular in marshes of tile Laurentian Great Lakes basin.

Seventy coastal and inland marshes were sampled during 1995-2000. These ranged from pristine, macrophyte-dominated systems, to highly degraded systems containing only a fringe of emergent vegetation. The index was developed based on the results of a partial canonical correspondence analysis (PCCA), which indicated that plant-associated taxa such as chydorid and macrothricid cladocerans were common in high-quality wetlands while more open-water, pollution-tolerant taxa (e.g., *Brachionus, Moina*) dominated degraded wetlands. The WZI was found to be more useful than indices of diversity (H', species richness) and measures of community structure (mean cladoceran size, total abundance) for indicating wetland quality. Furthermore, an independent test of the WZI in a coastal wetland of tile Great Lakes, Cootes Paradise Marsh, correctly detected moderate improvements in water quality following carp exclusion. Since wetlands used in this study covered a wide environmental and geographic range, the index should be broadly applicable to wetlands in the Laurentian Great Lakes basin, while further research is required to confirm its suitability in other regions and other vegetated habitats.

Madsen, J. D. 2000. Advantages and disadvantages of aquatic plant management techniques. 31 pp. ERDC/EL MO-00-1, U.S. Army Engineer Research and Development Center, Vicksburg, MS.

In areas were exotic or nuisance plant and animal species have come to dominate an area, it may be desirable to remove these organisms and try to establish populations of native species. Madsen reviews a variety of techniques that have been using primarily in lakes but could be adapted to coastal projects as well. There are advantages and disadvantages to each of the techniques presented, the final decision for which method to use will depend on the characteristics of the site and the amount of time and effort individuals are willing to commit to the process. Biological, chemical, mechanical, and physical means to control SAV are each described. Biological controls include the use of grass carp (*Ctenopharyngodon idella*), use of insects, pathogens, and introduction of native plants to compete with invasives. The chapter on chemical techniques includes an introduction to the herbicides currently in use in the United States and methods to apply them. Mechanical techniques such as hand cutting/pulling, cutting, harvesting, diver operations, and rotovating are discussed. A variety of physical techniques including dredging, drawdown, benthic barriers, shading, and nutrient control are also described. Madsen discusses the implications of taking no action as a management strategy as well.

Marshall, T. R. and P. F. Lee. 1994. An inexpensive and lightweight sampler for the rapid collection of aquatic macrophytes. *Journal of Aquatic Plant Management* 32:77.

Author Abstract. The quantitative sampling of aquatic macrophytes demands that all plants be sampled along a series of line transects, or within a large number of randomly-chosen quadrats. Scuba divers are frequently employed for this purpose, and offer the advantage of precise removal (by hand) of all plants within a sampling frame, regardless of substrate type and water depth. Their effectiveness is reduced in turbid waters, though, and even under optimal conditions this is an exceedingly time-consuming process. As an alternative to divers, remote sampling devices, such as corers, scoops, and dredges, can be employed from small boats to speed the collection process. Problems have been documented with these samplers, however, including small sample areas, the wrongful inclusion and exclusion of plants at the edges, and their inability to operate satisfactorily on hard lake bottoms. Several customized macrophyte samplers have been developed to overcome these problems, but these are generally massive and complicated devices which require permanent platforms with booms, winches, or pumps. None of these methods or devices were suitable for a survey of aquatic plants in northwestern Ontario, due to the number of lakes involved and the fact that many are without road access. This prompted the development of a new sampling device, designed to meet the following criteria: 1) allow the retrieval of rooted macrophytes from a known area of substrate without the need of a diver's assistance; 2) be rapidly deployed by a single operator; 3) be lightweight and easily transported from site to site; 4) be inexpensive to manufacture; and 5) function at both shallow and deep water sites, in clear or turbid water. This paper describes the design and operation of this sampler, and includes some observations on its use in these lakes.

McCauley, V. J. E. 1975. Two new quantitative samplers for aquatic phytomacrofauna. *Hydrobiologia* 47:81-89.

Author Abstract. A description and drawings are given for 2 new samplers for quantitative studies on invertebrates associated with aquatic macrophytes. One was designed for sampling rushes and bullrushes, and the other for submerged and/or floating vegetation.

McCobb, T. D. and P. K. Weiskel. 2002. Long-term hydrologic monitoring protocol for coastal ecosystems, Protocol. 93 pp. USGS Patuxent Wildlife Research Center, Coastal Research Field Station, University of Rhode Island, Narragnasett, RI. http://science.nature.nps.gov/im/monitor/protocols/caco_hydrologic.pdf

Author Abstract. Long-term monitoring of hydrologic change using a standard data-collection protocol is essential for the effective management of terrestrial, aquatic, and estuarine ecosystems in the coastal park environment. This study develops a consistent protocol for monitoring changes in ground-water levels, pond levels, and stream discharge using methods and techniques established by the U.S. Geological Survey for use in the Long-term Coastal Monitoring Program at the Cape Cod National Seashore. The protocol establishes a hydrologic sampling network in the four ground-water-flow cells in the Seashore area, and provides justification for the measurement methods selected and for the spatial and temporal sampling frequency. Data collected during the first year of monitoring are included in this report; common hydrologic analyses such as hydrographs for groundwater and pond levels, and rating curves between stream stage and discharge for stream flow, are presented for selected sites. Long-term hydrologic monitoring at the Seashore will aid in interpretation of the findings of other monitoring programs. Developing and initiating long-term hydrologic monitoring programs will provide a better understanding of effects of natural and human-induced change at both the local and global scales on coastal water resources in park units.

Merritt, R. W. and K. W. Cummins (eds.). 1996. An Introduction to the Aquatic Insects of North America. Third edition ed. Kendall/Hunt Publishing Company, Dubuque, IA, USA.

While the bulk of Merritt and Cummins is on identification of aquatic insects of North America, they include several chapters useful in project planning as well. Various experts in the field of aquatic insect collection and identification have submitted chapters on the general morphology of aquatic insects, designing studies, collection techniques, aquatic insect respiration, habitat and life history, and the ecology and distribution of aquatic insects. The rest of the manual is devoted to identification keys for each family of aquatic insect found in North America with many detailed and useful pictures of identifying characteristics.

Since this book is continental in scope, it is suggested that practitioners first look for identification keys prepared for their local or regional waterways. This will reduce much confusion in the identification process by eliminating species that are not found locally. Any local aquatics expert or science librarian should be able to locate these materials. If local materials are not available, then Merritt and Cummins will be useful, however, be sure to check the distribution of species identified whenever possible.

Miller, T., C. Bertolotto, J. Martin and L. Storm. 1996. Monitoring wetlands: A manual for training volunteers. Reports available by contacting: Adopt-a-Beach, P.O. Box 21486, Seattle, WA 98111-3486. Contact information: Phone # (206) 624-6013 and Fax # (206) 682-0722.

This manual provides quantitative and qualitative methods for monitoring structural and functional characteristics in natural and created wetlands. Volunteers identify major vegetation communities, locate photo points, identify surrounding land uses, and establish locations of transects. Data collected serves as a baseline for future monitoring. The manual presents protocols for monitoring hydrology; wetland buffer condition; soil types; vegetation; topography (determining elevations); and wildlife.

Methods described in this manual include plant survival counts, vegetation assessment, and percent cover surveys. Plants surveys are designed for use in wetlands or wetland mitigation sites. Data collected can be used to evaluate planting success, mark areas for replanting, and identify species that should not be replanted in an area, given their low survival rates. Vegetation assessment surveys provide qualitative information on the wetland vegetation characteristics. Plots used are circular, with the radius depending on the predominant type of vegetation in the plot (10 meters for forested, 5 meters for scrub-shrub, and 1 meter for herbaceous). For each plot, volunteers record three to five of the most dominant species in each vegetation layer (tree, shrub, and herb). Data collected can be associated with other data (for example, hydrology or soil types) in order to understand wetland functions and how it should be managed and protected. Percent cover vegetation surveys uses similar plot sizes in vegetation assessment survey but the plots are placed every 50 feet along five transects over the wetland. In each plot, volunteers identify all species and estimate the area in which they covered.

Molano-Flores, B. 2002. Critical trends assessment program: Monitoring protocols. 39 pp. Illinois Natural History Survey, Office of the Chief Technical Report 2002-2, Champaign, IL. http://ctap.inhs.uiuc.edu/mp/pdf/mp.htm

The Critical Trends Assessment Program (CTAP) monitors the conditions of forests, grasslands, wetlands and streams throughout Illinois. CTAP also assesses current and future trends in ecological conditions for state, regional and site-specific basis. The CTAP document presents standardized monitoring protocols for the habitat types previously mentioned. Wetland habitat criteria as well as wetland sampling protocols are discussed in this document. Highlighted in this section are methods used to monitor ecological changes occurring in wetlands. These methods include establishing study plots, GPS data, general site characteristics, slope and aspects, ground cover and woody vegetation measurements, big plot and collection of voucher specimens.

Each method used and parameters measured provide data on the structural and functional characteristic of the habitat as well as the habitat's condition.

Morgan, R. P., K. J. Killgore and N. H. Douglas. 1988. Modified popnet design for collecting fishes in varying depths of submersed aquatic vegetation. *Journal of Freshwater Ecology*. 4:533-539.

Author Abstract. Recent popnet development for the analysis of fish distribution and abundance in submersed aquatic vegetation (SAV) has focused on its utilization of popnets in shallow estuarine environments. A number of modifications have been made to the popnet and in seining techniques in order to deploy these nets in areas with SAV great than 2 m deep. A description of the modified net design and the procedure used in setting the popnets is presented. The coefficient of variation for fish density (per 10 sq. m) ranged from a low of 9.4% (2 replicates) to a high of 80.0% (3 replicates) depending on the species of SAV and the time of year.

Murphy, B. R. and D. W. Willis (eds.). 1996. Fisheries Techniques, Second edition. American Fisheries Society, Bethesda, MD.

Murphy and Willis have edited the standard reference for fisheries sampling techniques. A variety of experts in the field have written chapters that cover all aspects of how to sample and measure fish. Topics include planning for sampling, data management and statistical techniques, safety, habitat measurements, care and handling of samples, passive and active capture techniques, collection and identification of eggs and larvae, sampling with toxics, invertebrates, tagging and marking, acoustic assessment, field examination and measurements, age and growth rate determination, diet, underwater observation, creel sampling, commercial surveys, and socioeconomic measurements.

Muscha, M. J., K. D. Zimmer, M. G. Butler and M. A. Hanson. 2001. A comparison of horizontally and vertically deployed aquatic invertebrate activity traps. *Wetlands*. 21:301-307.

Author Abstract. Activity traps are commonly used to develop abundance indices of aquatic invertebrates and may be deployed with either the funnel parallel to the water surface (horizontal position) or facing down (vertical position). We compared the relative performance of these two positions in terms of numbers of invertebrates captured, species richness of samples, detection rates of specific taxa, and community-level characterizations. Estimates of zooplankton abundance were also compared to quantitative estimates obtained using a water-column sampler. We used a matched pairs design where 10 pairs of traps (one horizontal, one vertical) were deployed in each of 4 prairie wetlands on 5 dates in 1999. Vertical traps had higher detection rates and captured greater numbers of adult and larval Coleoptera, Hemiptera, Chaoboridae, Hydracarina, Cladocera, and Copepoda and also produced samples with greater species richness. Horizontal traps captured greater numbers of Amphipoda and Ostracoda and had higher detection rates for these taxa. Estimates of zooplankton abundance with vertical traps also correlated better with quantitative estimates and indicated greater differences between wetlands than horizontal traps. Both traps showed similar relationships among wetlands and changes through time at the community level, but vertical traps were more sensitive to temporal change. Our results indicate that vertical traps outperform horizontal traps and are preferable for obtaining indices of invertebrates.

National Park Service Inventory and Monitoring. Guidance for designing an integrated monitoring program. http://science.nature.nps.gov/im/monitor/vsmTG.htm#Introduction

The goal of the National Park Service (NPS) program is to monitor the status and trend of the park's habitat structure and function as well as its condition. Monitoring tracks management and restoration efforts, detects early warning signs of threats to the habitat, and provides fundamentals needed to understand and identify changes occurring in the habitat. NPS provides information on developing a scientifically sound monitoring program. Information needed to develop a monitoring plan include establishing and stating clearly the project goals and objectives; monitoring objectives must be effective, realistic, specific, unambiguous, and measurable; providing a process for developing conceptual models of relevant ecosystems; steps on how to prioritize and select indicators to be monitored; sampling designs to consider; how protocols will be developed; and data management and analysis. Additional information on guidelines for developing monitoring protocols is described in this report. Links are also provided to download individual reports that offer more detail.

Norris, J. G., S. W. Echeverria, J. R. Skalski and R. C. Zimmerman. 2001. Eelgrass monitoring in Puget Sound: Methods and preliminary results of the submerged vegetation monitoring project. http://www.psat.wa.gov/Publications/01_proceedings/sessions/poster/h_norris.pdf

Author Abstract. Eelgrass *(Zostera marina)* is an important nearshore resource. In order to monitor changes in the abundance and distribution of this habitat type, the Nearshore Habitat component of the Puget Sound Ambient Monitoring Program initiated a Submerged Vegetation Monitoring Project. We are using a rotational random sampling plan with partial replacement. One fifth of the selected sample units are replaced each year, and once chosen, the unit is sampled for five consecutive years. We designated two types of sample units, 1,000 m sections of shoreline (potential 'fringe' eelgrass habitat) and eelgrass 'flats' (eelgrass beds wider than 1000 m). In summer 2000, we sampled 68 stations throughout Puget Sound including the Straits of Juan de Fuca. At each station we used underwater videography on a line transect to estimate eelgrass abundance, patchiness index, and average maximum and minimum depths. At 28 sites, we collected whole plant samples using a van Veen benthic grab to estimate shoot density, leaf area index, and shoot/root ratio. Data on the physical properties of the water column (temperature, salinity, dissolved oxygen, pH, turbidity, photosynthetically active radiation, and backscatter) at each site can be linked to other data on stressors. The results show sound-wide patterns in overall abundance, density, subtidal extent and variability in eelgrass morphology.

Olin, T. J., J. C. Fischenich, M. R. Palermo and D. F. Hayes. 2000. Wetlands engineering handbook: Monitoring. U. S. Army Engineer Research and Development Center, Vicksburg, MS. Technical Report ERDC/EL TR-WRP-RE-21.

The *Wetlands Engineering Handbook* presents methods for monitoring and evaluating restoration success. Authors emphasize that local expertise and databases for particular wetland types must be used together with the guide to ensure monitoring plans for a specific project are effectively developed. Chapter eight of this report provides a guide for developing evaluation criteria and monitoring projects for wetland restoration and creation. Also presented is guidance for monitoring and success evaluation on basic monitoring concepts, assessing wetland hydrology, evaluating soils and vegetation, and fauna usage. The authors also outline an approach to determining project goals and evaluation criteria, basic considerations related to monitoring, provide detailed information on how to assess wetland structure and function regarding hydrology, soils, vegetation, and fauna (e.g., macroinvertebrates, birds and fish). Additional information needed on assessment, monitoring, and evaluating success is described within this report.

Ossinger, M. 1999. Success standards for wetland mitigation projects - a guideline, 31 pp. Washington State Department of Transportation, Environmental Affairs Office. http://pnw.sws.org/forum/success.PDF

This report offers guidance and examples on how to write specific success criteria for mitigation and restoration projects. Though it was designed to address mitigation projects in the Pacific Northwest, its information and approach make it useful throughout the United States. It outlines the steps necessary for planning the monitoring and management of a mitigation/restoration project. Guidance in writing the following program elements is provided: how to set project goals, how to select specific project objectives (i.e. what functions or values will the mitigation/restoration provide), how to select performance objectives (i.e. what structural characteristics need to be in place to provide desired functions), selection of success standards (measurable benchmarks used to determine success of performance objectives), monitoring method (how will the success standard be measured), contingency measure (what to do if the success standards are not met). Several examples are provided of each of these steps. These examples, while not all-inclusive, facilitate the application of this method to diverse areas and project types.

Pacific Estuarine Research Laboratory. 1990. A manual for assessing restored and natural coastal wetlands with examples from Southern California. La Jolla, California. California Sea Grant Report -T-CSGCP-021. http://www.tijuanaestuary.com/nat_res.asp

This manual provides information for assessing the structure and functions of coastal wetlands. The main purpose of this document is to standardize methods of assessing restored, enhanced or constructed wetlands in order to maintain biodiversity emphasizing salt marshes and tidal creeks. The document provides strategies for wetland construction, restoration, and enhancement that include stating the rationale for functional assessment, objectives of assessment, criteria, and reference wetlands and reference data sets. Sampling methods and comparative data collected from natural wetlands include hydrologic functions, water quality, soil substrate quality, and nutrient dynamics, vegetation composition and growth, and fauna presence and abundance. Additional information on methods used for coastal wetlands are described.

Phillips, R. C. 1980. Planting methods, pp. 17-20. In Lutz, R. A. (ed.), Planting guidelines for seagrasses, coastal engineering. United States Army Corps of Engineers, Coastal Engineering Research Center. Technical Aid No. 80-2.

Planting methods for seagrass restoration are presented in this document. The methods described include seeding, planting of eelgrass sprigs, planting plugs, and planting sprigs. Seeding is used primarily for turtle grass because their seeds are larger and not easily swept away. The seeds are collected from mature fruits or as germinated seedlings that lay on the sediment surface. During the harvest season the fruit is clipped from the stalk and the spongy ovary wall is opened to expose the four to five seeds. Eelgrass sprigs are composed of three to four shoots. Shoal grass sprigs consist of fifteen to twenty shoots on the same rhizome. The sprigs are planted during low currents by excavating a small hole in the substrate, placing the sprigs in the hole, and covering them with sediment. Plugs are acquired by using a cylindrical coring device pushed into the grass bed. The grass plug is then transplanted in a hole, 6 to 8 inches deep. Plugs are recommended for shoal grass transplants. Planting and seagrass sprigs are anchored in areas where currents exceed 1.5 knots and wave currents are influenced by wind or storm. Construction rods and iron mesh painted with vinyl paint can be used as anchoring devices for seagrass plants. Using the rods and iron mesh prevent the plants from being swept away. Techniques are described in detail in this publication. The time in which planting occurs should also be considered because successful growth of seagrass will vary among species.

Poppe, L. J., A. H. Eliason, J. J. Fredericks, R. R. Rendigs, D. Blackwood and C. F. Polloni. 2003. Grain-size analysis of marine sediments: methodology and data processing. 58 pp. In USGS East-coast Sediment Analysis: Procedures, Databases, and Georeferenced Displays. US Geological Survey Open-File Report 00-358. http://pubs.usgs.gov/of/of00-358/text/chapter1.htm

Partial Author Introduction. The purpose of this chapter is to describe some of the laboratory methods, equipment, computer hardware, and data-acquisition and data-processing software employed in the sedimentation laboratory at the Woods Hole Field Center of the Coastal and Marine Geology Program of the U.S. Geological Survey. The recommendations and laboratory procedures given below are detailed, but are by no means complete. Serious users are strongly encouraged to consult the original references and product manuals.

Raposa, K. B. and C. T. Roman. 2001. Monitoring nekton in shallow estuarine habitats, Protocol, Long-term Coastal Ecosystem Monitoring Program. 39 pp. Cape Cod National Seashore, Wellfleet, MA. http://science.nature.nps.gov/im/monitor/protocols/caco_nekton.pdf

Author Abstract. Long term monitoring of estuarine nekton has many practical and ecological benefits but efforts are hampered by a lack of standardized sampling procedures. This study develops a protocol for monitoring nekton in shallow (<1m) estuarine habitats for use in the Long Term Coastal Monitoring Program at Cape Cod National Seashore. Sampling in seagrass and salt marsh habitats is emphasized due to the susceptibility of each habitat to anthropogenic stress and to the abundant and rich nekton assemblages that each habitat supports. Extensive sampling with quantitative enclosure traps that estimate nekton density is suggested. These gears have a high capture efficiency in most habitats and are small enough (typically 1 m^2) to permit sampling in specific microhabitats. Other aspects of nekton monitoring are discussed, including seasonal sampling considerations, sample allocation, station selection, sample size estimation, parameter selection, and associated environmental data sampling. Developing and initiating long term nekton monitoring programs will help track natural and human-induced changes in estuarine nekton over time and advance our understanding of the interactions between nekton and the dynamic estuarine environments.

Rey, J. R., R. A. Crossman, T. R. Kain, F. E. Vose and M. S. Peterson. 1987. Sampling zooplankton in shallow marsh and estuarine habitats: Gear description and field tests. *Estuaries* 10:61-67.

Author Abstract. Pump and net samplers for collecting zooplankton from very shallow marsh and estuarine habitats are described. Their use is illustrated with data obtained in salt marshes along the Indian River lagoon in east central Florida. In general, both pump and net samplers were found to be satisfactory for sampling zooplankton in these areas. Larger sample volumes were obtained with gear utilizing 202 *u* mesh sizes than with gear using 63 u mesh because the latter became clogged very quickly. Quantitative and qualitative similarity between samples collected with different gear was moderate to low. Comparison of the kinds and densities of taxa captured with the various gear indicate that a combination of techniques may be needed to ensure a proper description of the plankton communities of the area.

Ribic, C. A., T. R. Dixon and I. Vining. 1992. Marine debris survey manual. 92 pp. NOAA Technical Report NMFS 108, NOAA National Marine Fisheries Service, Seattle, WA.

Author Introduction. Over the last several years, concern has increased about the amount of man-made materials lost or discarded at sea and the potential impacts to the environment. The scope of the problem depends on the amounts and types of debris. Once problem in making a regional comparison is the lack of a standard methodology. The objective of this manual is to discuss designs and methodologies for assessment studies of marine debris.

This manual has been written for managers, researchers, and others who are just entering this area of study who seek guidance in designing marine debris surveys. Active researchers will be able to use this manual along with applicable references herein as a source for design improvement. To this end, the authors have synthesized their work and reviewed survey techniques that have been used in the past for assessing marine debris, such as sighting surveys, beach surveys, and trawl surveys, and have considered new methods (e.g., aerial photography). All techniques have been put into a general survey planning framework to assist in developing different marine debris surveys.

Richardson, C. J. and J. Vymazal. 2001. Sampling macrophytes in wetlands, pp. 297-336. In Rader, R. B, D. P Batzer and S. A. Wissinger (eds.) Bioassessment and Management of North American Freshwater Wetlands. John Wiley and Sons, New York.

Author Abstract. The use of macrophytes as biomonitors in wetland ecosystems are presented in terms of assessment of plant population and community responses to disturbance or anthropogenic inputs. The life forms of macrophytes are reviewed and the sampling procedures for estimating changes in population size as well as community structure are presented for herbaceous plants, shrubs, and trees. The methods and formulas for determining abundance and cover as well as frequency, density and dominance are given for plant biomass and productivity measurements. We also outline procedures for establishing macrophytes growth rates and nutrient status in wetland plants. Procedures for determining both above- and belowground biomass, nitrogen and phosphorous as well as ash-free dry matter are present along with representative data for typical wetland species. In this chapter, we provide a comprehensive plan for sampling and monitoring of plant populations and communities in wetlands.

Shafer, D. J. and D. J. Yozzo. 1998. National guidebook for application of hydrogeomorphic assessment of tidal fringe wetlands. 69 pp. U.S. Army Engineer, Waterways Experiment Station, Vicksburg, Mississippi. Technical Report WRP-DE-16. http://www.wes.army.mil/el/wetlands/pdfs/wrpde16.pdf

Authors describe the procedures used to assess wetland functions in relation to regulatory, planning, or management programs. Several phases of the Hydrogeomorphic (HGM) method are introduced. The Application Phase includes characterization, assessment analysis, and application components. Characterization describes the wetland ecosystem and the surrounding landscape, describes the planned project and potential impacts, and identifies wetland areas to be assessed. Assessment and analysis involves collecting field data that is needed to run the assessment models and calculating the functional indices for the wetland assessment areas under the existing conditions.

The Tidal Wetland HGM Approach Application Phase involves determining the wetland assessment area (WAA) and the indirect wetland assessment area (IWAA) and, determining wetland type. The boundaries of the area and the type of tidal wetland to be assessed are identified. The WAA is the wetland area impacted by a proposed project. The WAA defines specific boundaries where many of the model variables are ascertained and directly contributes to calculations for other variables (e.g. maximum aquatic and upland edge). Methods for determining WAA are discussed in detail in the procedural manual of the HGM Approach. The IWAA is any adjacent portions of hydrologic unit that may not be affected by the project directly but indirectly affected through hydrologic flow alterations. Wetland types are determined by comparing the hydroperiod, salinity regime, and vegetation community structure with those described in the wetland type profiles for each region. Plant communities react to change in the environment (e.g., salinity and hydrologic alterations) so are considered good indicators of a wetland type. Descriptions of the vegetation present, salinity levels, and hydrological conditions for each wetland type are presented in each regional wetland type profile. To determine the salinity regime of an area, one can refer to available references on salinity and or wetland distribution. Data collected on average salinity or the range of salinity helps to sort each site into one of the four categories of the Cowardin system.

Shafer, D. J., B. Herczeg, D. W. Moulton, A. Sipocz, K. Jaynes, L. P. Rozas, C. P. Onuf and W. Miller. 2002. Regional guidebook for applying the hydrogeomorphic approach to assessing wetland functions of northwest Gulf of Mexico tidal fringe wetlands. U.S. Army Engineer Research and Development Center, Vicksburg, Mississippi. Technical Report ERDC/EL TR-02-5.

This manual is designed to provide practitioners with guidelines for monitoring and assessing wetland functions. The manual outlines protocols used for collecting and analyzing data needed to assess wetland functions in the context of a 404 permit review or comparable assessment setting. When assessing tidal fringe wetlands in the northwestern Gulf of Mexico the researcher must define the assessment objectives by stating the purpose (for e.g., assessment determines how the project impacts wetland functions); characterize the project area by providing a description of the structural characteristics of the project area (for e.g., tidal flooding regime, soil type, vegetation and geomorphic setting); use screen for redflags; define the wetland assessment area; collect field data using a 30-m measuring tape, quadrats and color infrared aerial photography; analyze field data; and apply assessment results. This document provides additional detail information on criteria selection and methods used for assessing tidal fringe wetlands.

Short, F.T., L. J. McKenzie, R. G. Coles and J. L. Gaeckle. 2004. SeagrassNet Manual for Scientific Monitoring of Seagrass Habitat – Western Pacific Edition. 71 pp. University of New Hampshire, USA; QDPI, Northern Fisheries Centre, Australia. http://www.seagrassnet.org/SeaNetMan.PDF

This manual discusses the importance of monitoring seagrasses, the process and methods used for monitoring, and parameters commonly measured in seagrass habitats. The monitoring process discussed in the manual include why monitoring should be performed for seagrass habitats and how changes in seagrass affects fisheries in this habitat and how to measure changes in seagrass meadows (e.g., the use of mapping and selecting parameters that should be measured). The monitoring methods include gathering background information of the selection restoration monitoring site, designing a sketch map for field studies and material that should be used (e.g. GPS, aerial photographs, temporary markers, etc.), and informing the community of the monitoring activity conducted in the area, seagrass establishment and transect marking, seagrass station measures (light, temperature, salinity and tidal range), quadrat measures and laboratory procedures, and cross transects measures. The highlighted points mentioned here are discussed in detail in the manual.

Smart, R. M. and G. O. Dick. 1999. Propagation and establishment of aquatic plants: A handbook for ecosystem restoration projects. Technical Report A-99-4, U.S. Army Engineer Waterways Experiment Station, Vicksburg, MS. http://www.wes.army.mil/el/elpubs/pdf/tra99-4.pdf

Smart and Dick have prepared an excellent document to help guide practitioners through the many steps necessary to grow and transplant aquatic plants for restoration or mitigation purposes. The first step in the process is the establishment of pioneer colonies on site. These are small groups of a variety of plant species, grown in wire cages to protect them from herbivores. Pioneer colonies should be scattered throughout the area to be restored. Through monitoring, it can be determined which plant species perform best under existing site conditions. These species then can be grown for the restoration project[1]. The authors explain why it is advisable to grow one's own plants, what the physical and chemical requirements of different aquatic plants types are, and how to prepare and build off-site and in-place facilities. They include a chapter on how to implement the planting project containing information on proper site selection, planting depth, species selection, and timing of planting projects. The authors also include a variety of methods for protecting plantings from herbivores, a critical part of successful planting projects.

[1] Note: Growing one's own plants for restoration projects can be a cost effective means for supplying propagules for a restoration project. However, it requires that the hydrodynamics of the area in question are relatively predicable from one year to the next. Coastal wetlands of the Great Lakes for example are subject to water level fluctuations of the lakes that can drastically alter available habitat type. Unless water level fluctuations can be controlled or reliably predicted from year to year, the expense of growing your own plants may not be worthwhile.

Spencer, D. F. and L. C. Whitehand. 1993. Experimental design and analysis in field studies of aquatic vegetation. *Lake and Reservoir Management* 7:165-174.

Author Abstract. Field experiments may be useful for researchers and managers concerned with aquatic plants. Since experimental design and statistical analysis are closely related, this paper discusses statistical and practical considerations for conducting and evaluating field experiments with aquatic plants. Special emphasis is given to the analysis of variance, assumptions required for its use, and concepts related to it (e.g., statistical power, means comparison procedures, treatment structure, pseudoreplication, etc.). The paper concludes with a brief introduction to papers in the literature which illustrate the use of field experiments for studying aquatic plants.

Steyer, G. D., R. C. Raynie, D. L. Steller, D. Fuller and E. Swenson. 1995. Quality management plan for Coastal Wetlands Planning, Protection, and Restoration Act monitoring program. 82 pp. Open-File Report 95-01, Louisiana Department of Natural Resources, Coastal Restoration Division, Baton Rouge, LA. http://www.lacoast.gov/cwppra/reports/MonitoringPlan/index.htm

This document is a Quality Assurance Project Plan (QAPP) used for all restoration projects conducted under the Coastal Wetlands Planning, Protection, and Restoration Act (CWPPRA) and similar legislation for coastal Louisiana. Although it does not explain how to develop a QAPP for new wetland restoration monitoring projects, it can be used as a template by which monitoring plans can be developed. Detailed explanations of how to data is to be collected, acceptable error rates, and methods to ensure high quality data is collected, recorded, and analyzed are included. Quality assurance guidelines are provided for field data collection, remote sensing and aerial photo interpretation, computer systems to be used, data entry procedures, data review, laboratory procedures, and documentation and reporting. Any restoration practitioner attempting to develop a monitoring plan or preparing a QAPP for their project may find this document a valuable example to follow.

Steyer, G. D., C. E. Sasser, J. M. Visser, E. M. Swenson, J. A. Nyman and R. C. Raynie. 2003. A proposed coast-wide reference monitoring system for evaluating wetland restoration trajectories. *Journal of Environmental Monitoring and Assessment* 81:107-117.

Author Abstract. Wetland restoration efforts conducted in Louisiana under the Coastal Wetlands Planning, Protection and Restoration Act require monitoring the effectiveness of individual projects as well as monitoring the cumulative effects of all projects in restoring, creating, enhancing, and protecting the coastal landscape. The effectiveness of the traditional paired-reference monitoring approach in Louisiana has been limited because of difficulty in finding comparable reference sites. A multiple reference approach is proposed that uses aspects of hydrogeomorphic functional assessments and probabilistic sampling. This approach includes a suite of sites that encompass the range of ecological condition for each stratum, with projects placed on a continuum of conditions found for that stratum. Trajectories in reference sites through time are then compared with project trajectories through time. Plant community zonation complicated selection of indicators, strata, and sample size. The approach proposed could serve as a model for evaluating wetland ecosystems.

Trippel, E. A. 2001. Marine biodiversity monitoring: protocol for monitoring of fish communities. A report by the Marine Biodiversity Monitoring Committee (Atlantic Maritime Ecological Science Cooperative, Huntsman Marine Science Centre) to the Ecological Monitoring and Assessment Network of Environment Canada. http://www.eman-rese.ca/eman/ecotools/protocols/marine/fishes/intro.html#Rationale

This document presents a monitoring protocol for estimating species diversity of bottom dwelling or demersal fish species inhabiting the Canadian continental shelf regions. Monitoring protocols presented in this document can be used to monitor and evaluate fish communities in regions other than the Canadian continental shelf. Methods used to estimate the abundance of different demersal fish species include random stratified sampling and fixed station sampling. Using these standardized procedures helps to maintain precision. Some factors

taken into consideration when monitoring fish communities include depth, temperature, salinity, seasonal shifts and diurnal behavior patterns. Additional information found in this document includes size of area and sampling intensity, sampling gear, sampling procedures, and treatment of data.

U.S. EPA. 1992. Monitoring guidance for the National Estuary Program. United States Environmental Protection Agency, Office of Water, Office of Wetlands, Washington D.C. EPA Report 842-B-92-004.

This document provides guidance on the design, implementation, and evaluation of the required monitoring programs. It also identifies steps to be taken when developing and implementing estuarine monitoring programs and provides technical basis for discussions on the development of monitoring program objectives, the selection of monitoring program components, and the allocation of sampling effort. Some of the criteria listed for developing a monitoring program and described in this document include monitoring program objectives, performance criteria, establish testable hypotheses, selection of statistical methods, alternative sampling designs, use of existing monitoring programs, and evaluate monitoring program performance. Additional information on guidelines for developing a monitoring program is described.

U.S. EPA. 1993. Volunteer estuary monitoring: A methods manual. 383 pp. EPA 842-B-93-004, U.S. Environmental Protection Agency, Office of Water, Washington, D.C. http://www.epa.gov/owow/estuaries/monitor/.

This document presents information and methodologies specific to estuarine water quality. Information presented in the first eight chapters include understanding estuaries and what makes them unique, impacts to estuarine habitats and human's role in solving the problems; guidance on how to establish and maintain a volunteer monitoring program; guidance for working with volunteers and ensuring that they are well-positioned to collect water quality data safely and effectively; ensuring that the program consistently produces high quality data; and managing the data and making it readily available to data users. Also presented are water quality measures that determine the condition of the estuary including physical (e.g., substrate texture), chemical (e.g., dissolved oxygen), and biological parameters (e.g., plant and animal presence and abundance). The importance of each parameter and methods used to monitor the conditions are described in a gradual process. Proper quality assurance and quality control techniques must also be described in detail to ensure that the data are beneficial to state agencies and other data users.

U.S. EPA. 1996. The volunteer monitor's guide to quality assurance project plans. 59 pp. EPA 841-B-96-003, U. S. Environmental Protection Agency, Washington, D.C. http://www.epa.gov/volunteer/qapp/vol_qapp.pdf

Author Abstract. The Quality Assurance Project Plan, or QAPP, is a written document that outlines the procedures a monitoring project will use to ensure that the samples participants collect and analyze, the data they store and manage, and the reports they write are of high enough quality to meet project needs.

U.S. Environmental Protection Agency-funded monitoring programs must have an EPA-approved QAPP before sample collection begins. However, even programs that do not receive EPA money should consider developing a QAPP, especially if data might be used by state, federal, or local resource managers. A QAPP helps the data user and monitoring project leaders ensure that the collected data meet their needs and that the quality control steps needed

to verify this are built into the project from the beginning.

Volunteer monitoring programs have long recognized the importance of well-designed monitoring projects; written field, lab, and data management protocols; trained volunteers; and effective presentation of results. Relatively few programs, however, have tackled the task of preparing a comprehensive QAPP that documents these important
elements. This document is designed to help volunteer program coordinators develop such a QAPP.

U.S. EPA. 2002. Assessing and monitoring floatable debris. 49 pp. EPA-842-B-02-002, Oceans and Coastal Protection Division, U.S. Environmental Protection Agency, Washington, D.C. http://www.epa.gov/owow/oceans/debris/floatingdebris/pdf.html

This manual is designed to help states, tribes, and local units of government develop assessment and monitoring programs for floating debris (trash) in coastal waterways. The manual is broken into five parts with appendices. Part 1 introduces the impacts of floating debris on the aquatic environment and describes current legislation to address the issue. Part 2 discusses the types and origins of trash in coastal waters. Part 3 describes a variety of plans and programs that have been developed and implemented in various coastal areas to assess and monitor trash. Part 4 provides recommendations for developing assessment and monitoring programs that were originally presented in NOAA's *Marine Debris Survey Manual* and the EPA's *Volunteer Estuary Monitoring: A Methods Manual*. Part 5 provides methods to prevent and mitigate the problems associated with floating debris. The Appendices include information on international coastal cleanup efforts, a National Marine Debris Monitoring Program data card, storm drain stenciling cards, and surveys from the *Marine Debris Survey Manual*.

U.S. EPA. 2002. Guidance for quality assurance project plans. 130 pp. EPA QA/G-5, U. S. Environmental Protection Agency, Washington, D.C. http://www.epa.gov/swerust1/cat/epaqag5.pdf

Author Abstract. This document is designed to guide those involved with Quality Assurance Project Plan (QAPP) development for environmental monitoring and data analysis. It describes various issues to be addressed when preparing a QAPP, with an emphasis on systematic planning. The report is divided into three chapters. An introduction describes the target audience and the importance of systematic sampling. A second chapter describes all of the pieces of a QAPP, focusing on environmental data collection and analysis. The third chapter describes methods for developing QAPPs for projects that use previously collected data.

The importance of having high quality, reliable data cannot be over estimated. Use of this document or the EPA's *Volunteer Monitor's Guide to Quality Assurance Project Plans*, will help restoration practitioners develop monitoring plans that will provide the high quality, reliable data necessary to monitor and manage restoration projects. The step-by-step approach of this document takes restoration practitioners through the entire planning, data collection, data analysis, and reporting process from start to finish. Ensuring that all aspects of the monitoring project are well thought out ahead of time and that contingency plans are in place.

U.S. EPA. 2002. Methods for evaluating wetland condition: Introduction to wetland biological assessment. 42 pp. Office of Water, U.S. Environmental Protection

Agency, Washington, D.C. EPA-822-R-02-014. http://www.epa.gov/ost/standards or http://www.epa.gov/waterscience/criteria/wetlands/

Author Abstract. In 1999, the U.S. Environmental Protection Agency (EPA) began work on this series of reports entitled *Methods for Evaluating Wetland Condition*. The purpose of these reports is to help States and Tribes develop methods to evaluate (1) the overall ecological condition of wetlands using biological assessments and (2) nutrient enrichment of wetlands, which is one of the primary stressors damaging wetlands in many parts of the country. This information is intended to serve as a starting point for States and Tribes to eventually establish biological and nutrient water quality criteria specifically refined for wetland waterbodies. This purpose was to be accomplished by providing a series of "state of the science" modules concerning wetland bioassessment as well as the nutrient enrichment of wetlands. The individual module format was used instead of one large publication to facilitate the addition of other reports as wetland science progresses and wetlands are further incorporated into water quality programs. Also, this modular approach allows EPA to revise reports without having to reprint them all. A list of the inaugural set of 20 modules can be found at the end of this section.

This series of reports is the product of a collaborative effort between EPA's Health and Ecological Criteria Division of the Office of Science and Technology (OST) and the Wetlands Division of the Office of Wetlands, Oceans and Watersheds (OWOW). The reports were initiated with the support and oversight of Thomas J. Danielson (OWOW), Amanda K. Parker and Susan K. Jackson (OST), and seen to completion by Douglas G. Hoskins (OWOW) and Ifeyinwa F. Davis (OST). EPA relied heavily on the input, recommendations, and energy of three panels of experts, which unfortunately have too many members to list individually: Biological Assessment of Wetlands Workgroup, New England Biological Assessment of Wetlands Workgroup, Wetlands Nutrient Criteria Workgroup.

More information about biological and nutrient criteria is available at the following EPA website: http://www.epa.gov/waterscience/criteria/wetlands/

More information about wetland biological assessments is available at the following EPA websites: http://www.epa.gov/owow/wetlands/bawwg and http://www.epa.gov/waterscience/criteria/wetlands/

U.S. EPA. 2002. Methods for evaluating wetland condition: Study design for monitoring wetlands. 21 pp. EPA-822-R-02-015, Office of Water, U.S. Environmental Protection Agency, Washington, D.C. http://www.epa.gov/ost/standards or http://www.epa.gov/waterscience/criteria/wetlands/

Author Abstract. State and Tribal monitoring programs should be designed to assess wetland condition with statistical rigor while maximizing available management resources. The three study designs described in this module—stratified random sampling, targeted/tiered approach, and before/after, control/impact (BACI)—allow for collection of a significant amount of information for statistical analyses with relatively minimal effort. The sampling design selected for a monitoring program will depend on the management question being asked. Sampling efforts should be designed to collect information that will answer management questions in a way that will allow robust statistical analysis. In addition, site selection, characterization of reference sites or systems, and identification of appropriate index periods are all of particular concern when selecting an appropriate sampling design. Careful selection of sampling design will allow the best use of financial resources and will result in the collection of high quality data for evaluation of the wetland resources of a State or Tribe. Examples of different sampling designs currently in use for State and Tribal wetland monitoring are described in the Case Study (Bioassessment) module and on http://www.epa.gov/owow/wetlands/bawwg/case.html.

U.S. EPA. 2002. Methods for evaluating wetland condition: Developing an **invertebrate** index of biological integrity for wetlands. 45 pp. EPA-822-R-02-019, Office of Water, U.S. Environmental Protection Agency, Washington, D.C. http://www.epa.gov/ost/standards or http://www.epa.gov/waterscience/criteria/wetlands/

Author Abstract. The invertebrate module gives guidance for developing an aquatic invertebrate Index of Biological Integrity (IBI) for assessing the condition of wetlands. In the module, details on each phase of developing the IBI are given. First, in the planning stage, invertebrate attributes are selected, the wetland study sites are chosen, and decisions are made about which stratum of the wetland to sample and what is the optimal sampling period or periods. Then, field-sampling methods are chosen. The module describes field methods used in several States, and gives recommendations. Laboratory sampling procedures are reviewed and discussed, such as whether and how to subsample, and what taxonomic level to choose for identifications of the invertebrates. Specific categories of attributes, such as taxa richness, tolerance, feeding function, and individual health are discussed, with examples. Appendices to the invertebrate module give details about the advantages and disadvantages of using invertebrates, of the different attributes, of various field sampling methods, and of lab processing procedures as used by several State and Federal agencies. The module and appendices give a detailed example of one State's process for developing an invertebrate IBI, with a table of metrics with scoring ranges, and a table of scores of individual metrics for 27 wetlands. A glossary of terms is provided as well as sampling methods.

U.S. EPA. 2002. Methods for evaluating wetland condition: biological assessment methods for **birds**. 22 pp. EPA-822-R-02-023, Office of Water, U.S. Environmental Protection Agency, Washington, D.C. http://www.epa.gov/ost/standards or http://www.epa.gov/waterscience/criteria/wetlands/

Author Abstract. Birds potentially detect aspects of wetland landscape condition that are not detected by the other groups commonly used as indicators. Moreover, birds are of high interest to a broad sector of the public. When using birds as indicators, one must pay particular attention to issues of spatial scale. This requires an understanding of home range sizes of the bird species being surveyed. The development of wetland and riparian bird indices of biological integrity is still in its infancy, but holds considerable promise.

Methodologies for sampling birds in coastal habitats are also presented.

U.S. NOAA Coastal Services Center. 2001. Guidance for benthic habitat mapping: an aerial photographic approach by Mark Finkbeiner, Bill Stevenson. and Renee Seaman. 75 pp. U.S. National Oceanic and Atmospheric Administration. Coastal Services Center, Charlston, SC. http://www.csc.noaa.gov/benthic/cdroms/sav_cd/pdf/bhmguide.pdf

Author Introduction. The goal of this document is to provide technical guidance to data developers working to produce digital spatial data on benthic habitat. Using these methods, developers will be able to produce consistent benthic data suitable for regional comparison and application to various coastal management issues. All mapping efforts are designed to answer specific questions about the environment and meet objectives specific to a given project. The techniques used in generating a map determine its utility for meeting those objectives. The methods described in this document are designed to meet the following general objectives:

- Produce digital baseline data on the spatial extent and characteristics of benthic habitats
- Produce synoptic data over estuary-sized study areas
- Provide data that optimize the efficiency of further in-situ sampling
- Provide data at a resolution that can contribute to environmental permitting processes (such as Clean Water Act Section 404 fill determinations)
- Produce data that support change detection over extensive areas

The technical recommendations are designed to allow some flexibility in the choices of classification scheme, remote sensor data source, analysis procedures, and other key elements that vary regionally; however, all have been applied in various regions of the country and should be usable with minor modifications in the majority of geographic settings.

The primary audience of this document is the spatial data analyst tasked with developing baseline benthic habitat data. The methods that follow rely strongly on aerial photointerpretation and photogrammetry. Effective implementation of these technologies requires a specialized set of skills and experience. Project analysts ideally should have a background in remote sensing and photogrammetry. A familiarity with the physical and biological components of the study area is also very important and a working knowledge of geographic information system (GIS) technology is essential to producing the digital data and conducting further spatial analysis of the results. A secondary audience is the coastal resource manager. Managers can use the major components of this document as guidance for preparing technical statements for grants or contracts, and for project planning. One element that is usually of particular interest to managers is the expected cost of a mapping project. The actual cost of a project is determined by many project variables and objectives. Therefore, specific information on costs is not provided in this document. Cost information is best obtained on a project-by-project basis in consultation with commercial data and service providers and other professionals working in the field.

In addition to this report, other seagrass-related resources are available on a CD-ROM provided by NOAA. The CD-ROM can be requested through contact information on the following webaddress: http://www.csc.noaa.gov/benthic/cdroms/sav_cd/

U.S. NOAA Coastal Services Center. 2001. Guide to the seagrasses of the United States of America (including U.S. Territories in the Caribbean). 22 pp. U.S. National Oceanic and Atmospheric Administration, Coastal Services Center, Charlston, SC. http://www.csc.noaa.gov/benthic/cdroms/sav_cd/pdf/guide.pdf

This seagrass field guide will help practitioners identify species that live, or that have historically existed, in their coastal waters. This handy, full-color guide contains photographs and identification information on individual species, their habitat preferences, and distribution maps for seagrasses of the United States and its Caribbean territories.

In addition to this report, other seagrass-related resources are available on a CD-ROM provided by NOAA. The CD-ROM can be requested through contact information on the following webaddress: http://www.csc.noaa.gov/benthic/cdroms/sav_cd/

Wenner, E. L. and M. Geist. 2001. The national estuarine research reserves program to monitor and preserve estuarine waters. *Coastal Management* 29:1-17.

The National Estuarine Research Reserve (NERR) sites in 1992 coordinated a program that attempted to identify and track short-term variability and long-term changes in representative estuarine ecosystems and coastal watersheds. Water quality parameters monitored include pH, conductivity, temperature, dissolved oxygen, turbidity, and water level. Standardized protocols were used at each site so that sampling, processing, and data management techniques were consistent among sites. Statistical techniques were used to identify periodicity in water quality variables. Periodic regression analysis indicated that diel periodicity in dissolved oxygen is a larger source of variation than tidal periodicity at sites with less tidal amplitude. Authors of this document stress how understanding the functions of estuaries and how they change over time will help predict how these systems respond to change in climate and anthropogenic sources.

Zedler, J. B. 2001. Handbook for restoring tidal wetlands. CRC Press, Boca Raton.

This handbook provides a collection of case studies and guidelines to assist tidal restoration management. Zedler describes the conceptual planning for coastal wetlands restoration, strategies for management of hydrology and soils, the restoration of vegetation and assemblages of fishes and invertebrates, and the process of evaluating, monitoring, and sustaining restored wetlands. She also highlights parameters that should be monitored and techniques that can be used during restoration. Parameters addressed include hydrology and topography, water quality, soils, substrate qualities, nutrient dynamics, elevation, species abundance and diversity (vegetation, invertebrates and fishes). Technology used to monitor certain parameters includes Global Positioning Systems (GPS) and Geographic Information Systems (GIS). Additional information on parameters monitored and techniques used are also described.

APPENDIX III: LIST OF SUBMERGED AQUATIC VEGETATION EXPERTS

The experts listed below have provided their contact information so practitioners may contact them with questions pertaining to the restoration or restoration monitoring of this habitat. Contact information is up-to-date as of the printing of this volume. The list below includes only those experts who were 1) contacted by the authors and 2) agreed to submit their contact information. Some of those listed also reviewed the associated habitat chapter. In addition to these resources, practitioners are encouraged to seek out the advice of local experts as well faculty members and researchers at colleges and universities. Engineering, planning, and landscape architecture firms also have experts on staff or contract out the services of botanists, biologists, ecologists, and other experts whose skills are needed in restoration monitoring. These people are in the business of providing assistance in restoration and restoration monitoring and are often extremely knowledgeable in local habitats and how to implement projects on the ground. Finally local, state, and Federal environmental agencies also house many experts who monitor and manage coastal habitats. In addition to the National Oceanic and Atmospheric Administration (NOAA), the Environmental Protection Agency (EPA), the Army Corps of Engineers (ACE), Fish and Wildlife Service (FWS), and the United States Geologic Survey (USGS) are important Federal agencies to contact for assistance in designing restoration and monitoring projects as well as potential sources of funding and permits to conduct work in coastal waterways.

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CHAPTER 10: RESTORATION MONITORING OF COASTAL MARSHES

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INTRODUCTION

Coastal marshes are characterized as having erect, rooted, herbaceous plants that extend above the water surface (Figure 1). They are extremely productive systems that provide an abundance of food for wildlife that directly access the marsh and exporting large amounts of organic matter to estuaries and other coastal systems. Coastal marshes also provide a variety of feeding and breeding needs for invertebrates, fish, and other wildlife. The characteristics of the marsh vegetation determines the quality and quantity of habitat available to these animals (Adam 1990; Wilcox 1995). The high stem density typical of marsh vegetation provides excellent cover for invertebrates such as crustaceans, snails, worms, and insect larvae, allowing them to feed on algae and on one another while escaping predation from larger fish and wading birds (Havens et al. 1995; Harrel et al. 2001). If plant stems are too dense, however, even small animals may be restricted. Fish use marshes during high water periods to feed, spawn, and as nursery habitat (Keast et al. 1978; Boesch and Turner 1984; McIvor et al. 1989; Jude and Pappas 1992; Wilcox and Meeker 1992; Yozzo and Diaz 1999). Canada geese and some ducks feed on the tender shoots of emergent vegetation[4] (Prince et al. 1992). Wading birds and songbirds migrate along routes through highly productive coastal marshes, using the habitat as temporary feeding areas or as seasonal destinations (Weeber and Vallianatos 2000). The vertical structure provided by emergent plants provides perching areas for birds (Brawley et al. 1998) and allows snails and other animals to escape high water levels (Hamilton 1977). Although many species of mammals such as mink, otter, deer, and raccoons use coastal marshes for feeding and refuge, others such as nutria and muskrats are completely dependent upon them to provide the majority of their habitat needs (Evans 1970; Weller 1981; Wilcox and Meeker 1992).

Coastal marshes also support a host of human uses. They have tremendously high productivity

Figure 1. Emergent vegetation such as arrow arum (*Peltandra virginica*) is a characteristic feature of marshes. Photo by David H. Merkey, NOAA Great Lakes Environmental Research Laboratory.

[1] 2205 Commonwealth Boulevard, Ann Arbor, MI 48105.
[2] 1305 East West Highway, Silver Spring, MD 20910.
[3] 646 Cajundome Boulevard, Lafayette, LA 70506.
[4] Geese can also negatively impact marsh revegetation efforts by feeding on young plants requiring that freshly planted areas be fenced off or otherwise protected from geese.

providing food and cover for a variety of commercially important species such as shrimp, crabs, crayfish, and a variety of finfish (Keefe 1972; Beck et al. 2003). They protect coastlines from erosion by buffering the energy of waves and currents (Möller et al. 2002). Coastal marshes can also temporarily store floodwater and absorb the impact of storm surges thereby protecting shoreline development from erosion (Zedler et al. 1986). They protect downstream and estuarine water quality by accumulating sediments and absorbing or transforming nutrients (Valiela et al. 1978; Heath 1992; Krieger 2003). Marsh sediments can also retain toxic chemicals and heavy metals providing additional estuarine water quality protection (Krieger 2003).

Coastal marsh habitats are dynamic and complex environments. At any one time, they may be wet or dry, aerobic or anaerobic[5], fresh or salty (Wiegert and Pomeroy 1981). The information presented in this chapter has been compiled from extensive literature reviews and input from experts in the fields of salt, brackish, and freshwater (including Great Lake) coastal marsh restoration and ecology. Although there are significant differences across the United States and its protectorates in some structural and functional characteristics and in the species that occupy these marsh types (as will be discussed), many characteristics between these systems are similar enough that they may be discussed together. Each section of this chapter will open with a general discussion of a particular structural or functional characteristic of coastal marshes. Specific examples from salt, brackish, and/or freshwater marsh will then be presented to add more detail for each particular habitat type that may not be generally applied to the others. Each section will conclude with recommendations on different sampling techniques or resources that can be used in monitoring restoration projects.

TYPES OF COASTAL MARSHES

Coastal salt, brackish, and freshwater marshes form a continuum from the ocean coasts inland (Figure 2). In tidal areas, changes in rainfall, river flows, and storm events can change the vegetation communities from freshwater to brackish or brackish to salt marsh and vice versa over time. When designing a restoration project and monitoring program in these areas it will be important for practitioners to have an understanding of each marsh type, how each type relates to one another, and how large physical processes influence the various plant and animal communities. In coastal areas that are not subject to such changes in salinity, such

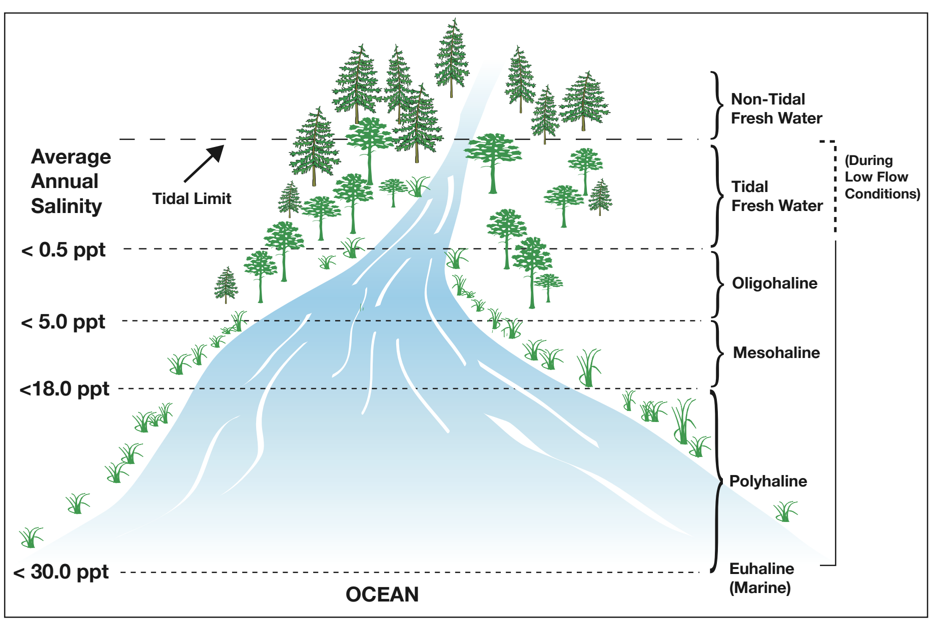


Figure 2. One method of classifying coastal marshes is by salinity. Salinity levels in parts per thousand (ppt) are shown on the left side of the graphic. The corresponding class of marsh is given on the right. The polyhaline and mesohaline marshes are referred to here as salt marshes. Oligohaline marshes are referred to as brackish. Maken from Odum et al. 1984.

[5] With or without oxygen respectively.

		Salinity Gradient		
		Fresh	**Brackish**	**Salt**
Hydrologic Regime	**Tidal**	• Ocean coasts • Gulf of Mexico	• Ocean coasts • Gulf of Mexico	• Ocean coasts • Gulf of Mexico
	Non-tidal	• Great Lake coastal marshes		

Table 1. Coastal marshes can be broken down into eight general classes based on salinity and hydrologic regime. Although, individual marshes may not fall neatly into these categories they are useful for introducing general marsh characteristics. Non-tidal, floating mat marsh communities may also be present along the northern coast of the Gulf of Mexico.

as Great Lakes coastal marshes, restoration practitioners can focus on a single marsh type.

For purposes of description, coastal marshes have been organized into several categories based on salinity and tidal regime (Table 1). Tidal salt, brackish, and freshwater marshes can be found on both ocean coasts of the United States and the northern shores of the Gulf of Mexico. The ocean and Gulf of Mexico have significant differences in tidal range and other characteristics that affect marsh ecology and will be further separated in some of the discussions below. Non-tidal, freshwater marshes occur along the shorelines of the Great Lakes. Non-tidal, floating mat marshes can also be found along the northern coast of the Gulf of Mexico. Much more is known about salt marshes than tidal freshwater marshes (Odum et al. 1984) or non-tidal coastal marshes, particularly those in the Great Lakes, which have only recently drawn the attention of researchers. Significant numbers of non-tidal freshwater, brackish, and salt marshes also occur in various inland portions of the United States. These, however, fall outside of the head-of-tide jurisdiction of the Estuaries Restoration Act of 2000[6] and are not discussed herein.

Salt Marshes

Salt marshes include all coastal marshes with salinities between 5.0 and 18.0 ppt[7] (Figure 2). The plant species in these ecosystems are mainly grasses, sedges, and other perennials tolerant of salty water and salty sediments. Salt marshes make up about 70% of all coastal marshes in the United States (Chabreck 1988). They occur along the intertidal shores of bays and estuaries on the ocean coasts and northern coast of the Gulf of Mexico (Chabreck 1988; Mitsch and Gosselink 2000). They are predominantly found, however, on the eastern and southern coasts of the United States, as the steep topography of the Pacific coastline is not favorable to extensive marsh development (Seliskar and Gallagher 1983; Chabreck 1988). Two subcategories of salt marshes often form on the Atlantic coast of the United States, high marshes and low marshes. High marshes form above the mean water level, low marshes occur below mean water level. Tidal ranges in the Gulf of Mexico are not large enough to create distinct high and low marshes (Odum 1988). The semidiurnal tidal ranges of the Pacific Northwest are also not conducive to high and low marsh development.

Brackish Marshes

Brackish marshes contain a mixture of salt and freshwater and are found farther inland than salt marshes in sounds, rivers, and tidal creeks. Brackish marshes can also be referred to as oliogohaline (salinities between 0.5 and 5.0 ppt - Figure 2). The plants and animals found in brackish marshes are a mix of both fresh

[6] The impetus for the publication of these documents.
[7] Parts per thousand.

and saltwater species able to tolerate periodic tidal flooding and associated changes in salinity levels (Cowardin et al. 1979). The vegetative communities within brackish marshes are determined by the relative contribution of fresh- and saltwater. Vegetative community shifts can occur in brackish systems as the result of either higher than normal, or lower than normal annual rainfall. In some cases, if brackish marshes receive additional freshwater input, it can promote the growth of invasive species such as the common reed (*Phragmites australis*, hereafter *Phragmites)* that may outcompete local plant species and dominate the vegetation community, changing some of the characteristic structure and function of brackish marshes (Able and Hagan 2000).

Freshwater Marshes

Freshwater marshes are found along the margins of the Great Lakes or within river systems that discharge to an ocean or the Gulf of Mexico but have water and soil salinities below 0.5 ppt (Odum et al. 1984). Extensive tracts of tidal freshwater marshes often develop in areas with a major source of freshwater, a high tidal amplitude (i.e., > 0.5 m), and a basin morphology that constricts and magnifies tides in upstream portions of the estuary (Odum et al. 1984). In the United States, these conditions occur most often along the coasts of the Atlantic Ocean and Gulf of Mexico. The bulk of the material presented here concerning freshwater tidal marshes is taken from studies conducted on those coasts. Freshwater tidal marshes do occur on the Pacific coast, especially in the region of San Francisco Bay and in the Columbia River, but they are relatively rare in comparison and are not as thoroughly studied as those on the eastern and southern coasts. Non-tidal coastal freshwater marshes are found along the fringes of the Laurentian Great Lakes[8]. These are not exposed to regular lunar tides but are subject to random water level fluctuations caused by seiches[9] as well as seasonal and annual changes in lake level.

HUMAN IMPACTS TO MARSHES

Coastal marshes of all types are subject to a wide variety of natural disturbances and impacts including:

- Fire
- Herbivory
- Deposition of organic debris
- Salt water intrusion
- High (and variable) soil salinity in tidal areas
- Low nutrient availability in internal marsh areas
- Anaerobic soils
- Hurricanes, and
- Burial with excess sediments (Bertness and Ellison 1987; Titus 1988; Adam 1990; Flynn et al. 1995; Guntenspergen et al. 1995; Nyman and Chabreck 1995; Allison 1996; Taylor et al. 1997; Valiela et al. 1998)

Fluctuating water levels can also stress plants by inducing:

- Temperature shock
- Changes in photoperiod
- Mechanical stress from waves and currents, and
- Deposition of sediments on the surface of leaves (Adam 1990)

In general, coastal marshes have adapted over time to these stressors and, barring sudden

[8] Non-tidal freshwater marshes may be found in other areas of the US as well. These systems, however, fall outside of the jurisdiction of the Estuary Restoration Act of 2000 and, as such, are not specifically addressed here. Many of the structural and functional characteristics of these systems may, however, still apply for restoration monitoring purposes.

[9] Wind-driven tides. They often have the effect of piling water up on the down wind side of the lake. Once winds stop blowing water sloshes back and forth throughout the basin creating water level fluctuations on either end.

vertical land moves caused be earthquakes or tsunamis, are generally able to rebound after a year or more depending on the type and level of impact.

Human-induced impacts are, however, often more difficult for marshes to recover from and can lead to complete loss of entire marshes. Common human impacts to coastal marshes in the United States include:

- Urban development
- Road construction
- Industrial and agriculture run-off
- Conversion to upland
- Logging
- Damming
- Diking, and
- Ditching (Seliskar and Gallagher 1983; Gosselink 1984; Odum et al. 1984; Page et al. 1995; Maynard and Wilcox 1997; Portnoy and Giblin 1997; Portnoy 1999; Hester and Mendelssohn 2000; Williamson and Morrisey 2000)

Early changes in land cover from forested to agriculture caused large sediment and nutrient inputs to coastal marshes. Later conversion to urban land uses further increased nutrient inputs through wastewater discharge (Chapman 1973). Pollution resulting from urban runoff from bridges, roads, industrial areas, farms, lawns and, golf courses (pesticides and fertilizers) has also been a major impact to coastal marshes (Hester and Mendelssohn 2000; Stewart et al. 2000; Lougheed et al. 2001).

Regional Examples

In many southern states, tidal freshwater areas have been diked for use in agriculture. Many of these dikes remain intact and are still used for rice production or management of the marsh for waterfowl (Odum et al. 1984). Along the gulf coast of Louisiana marsh losses have been attributed to:

- Saltwater intrusion from sea level rise and canal construction
- Decreases in nutrient input and sediment deposition due to construction of dams and flood control levees
- Dredging of gas and oil exploration canals and associated spoil bank creation, and
- Erosion by waves along exposed shorelines (Turner 1997; Day et al. 2000; Day et al. 2001; Gosselink 2001; Turner 2001)

Tidal freshwater marshes on the east coast were also originally altered by the conversion of adjacent forested areas to agriculture (Odum et al. 1984). That changed the amount of runoff and sediments entering the marshes. In the Great Lakes basin, most coastal marsh losses have been due to diking and drainage for agriculture (Jude and Pappas 1992; Edsall and Charlton 1997).

The Impact of Diking

Tidal marshes that have been diked and drained pose special problems for restoration[10]. Soils in diked and drained marshes are constantly aerated, increasing the decomposition of soil organic matter. Compaction and subsidence of the sediment surface and changes in sediment chemistry such as decreases in pH can also occur and impact plant growth (Portnoy 1999). As a result, tidal marshes that have been diked for several decades may have elevations much lower than the original elevation at mean sea level. In these cases, dikes cannot simply be breached to re-introduce tidal flushing of the system to re-create the marsh. The area would become open water instead. Efforts must first be undertaken to increase the substrate elevations closer to mean sea level for appropriate marsh communities to develop (Pezeshki et al. 1992; Wilsey et al. 1992; Wagner 2000).

[10]See Restoration Ecology volume 10 issue 3, an entire volume dedicated to dike-breaching restoration projects.

An additional problem with restoring marshes that have been diked for long periods of time is that, due to increased oxygen supply, soil chemistries can be drastically altered. Large concentrations of nutrients such as ammonium, phosphate, and iron may suddenly become mobilized from the soil upon reflooding and removed from the marsh with tidal flushing. These effects, however, will likely be short term and may enhance the growth of marsh plants (mobilization without flushing) but may also lead to nutrient enrichment in downstream areas (Portnoy and Giblin 1997).

Many of the impacts mentioned above have completely altered the structural and functional characteristics of marshes. For example, when marshes are channeled, diked, leveed, or dredged, fish become isolated from historic spawning and nursery habitats. Material export as well as nutrient and sediment dynamics are also disrupted (Wilcox 1995; Lathrop et al. 2000). Streams that once fed marshes with sediments and nutrients are often diverted around diked marshes and their material load is then deposited directly into downstream water bodies, reducing water quality. Dams for mills, irrigation, and flood control have also cut off normal tidal exchange altering sedimentation rates, nutrient inputs, and water exchange (Gosselink 1984). These changes, in turn, affect other aspects of water chemistry such as salinity and oxygen concentration and can reduce the diversity of vegetation communities (Odum et al. 1984; Reed and Rozas 1995). Changes in the dominant vegetation community of the marsh can lead to changes in the animal communities that use them as well (Adam 1990; Wilcox and Meeker 1995).

Sea Level Rise

Rising sea levels, in conjunction with shoreline stabilization and diking of tidal marshes, have serious implication for the future of coastal marshes, and salt marshes in particular. Armoring the coastline with riprap or sea walls to protect urban or residential development impacts coastal marshes by directing the erosive energy of waves downward, eroding away plants, less mobile animals, sediments, and seed banks, thus reducing the possibility of vegetation to regenerate naturally (Tsai et al. 1998; Davis and Streever 1999). As sea levels rise in response to global climate change and more coastal development is threatened, the extent of this problem will likely increase. In addition, as sea levels rise areas that are salt marshes today may become replaced by seagrass habitats or open water (DeLaune et al. 1983a). Brackish and freshwater marshes will be replaced with more salt-tolerant marsh species as salt marshes move inland (Boesch et al. 1994; Baldwin and Mendelssohn 1998). If dikes, abundant in many coastal areas, are not breeched to allow for tidal exchange and the movement of salt marshes inland, salt marshes may disappear from some coasts completely. This would have disastrous consequences on estuarine-dependent species and waterfowl populations, as well as on many other economically important species that use them (Park et al. 1993).

Invasive Species

One of the largest and most difficult to address impacts humans have had on coastal marshes is the introduction of invasive species. Through a variety of intentional and unintentional means, humans have introduced new plant and animal species wherever they have traveled. Plant and animal species new to an area may cause problems in the community by outcompeting native species. Several terms for these organisms have been used ('non-native', 'exotic', 'invasive') and are often used interchangeably. Some literature will, however, draw distinctions between these categories. 'Non-native' species are plants or animals that were not historically found in a particular area. They may be from a different state, coast, or country. 'Exotic' refers to those species historically not found in the

United States. These most often arrive in ballast water from ships or through other unintended mechanisms such as escaping from cultivation, aquaculture, fishing bait, or aquariums (Wilcox 1989; Mills et al. 1993). Some, such as carp (*Cyprinus carpo*), have been intentionally introduced (Mills et al. 1993). Only a small percent of species that enter an area ever cause any major problems in their new environment (Lodge 1993a; Lodge 1993b; Williamson 1996). 'Invasive species', on the other hand, may be non-native, exotic, or even native plants that for some reason suddenly spread uncontrollably through an area to the detriment of other species.

Some common examples of invasive species that cause problems in coastal marshes include plants such as:

- Smooth cordgrass (*Spartina alterniflora*) (native on the east coast, invasive on the west)
- *Phragmites*
- Japanese dodder (*Cuscuta japonica*)
- Pepperweed (*Lepidium latifolium*)
- Purple loosestrife (*Lythrum salicaria*)
- Hybrid cattail (*T.* x *glauca*)
- Chinese tallow (*Sapium sebiferum*), and
- Reed canary grass (*Phalaris arundinacea*)

Animals can also be invasive. Some notable examples include:

- Zebra mussels (*Dreissena polymorpha*)
- Nutria (*Myocastor coypus*)
- Common marsh periwinkle (*Littorina irrorata),* and
- Asian swamp eels (*Monopterus albus*)

The effects of *Phragmites* and purple loosestrife are briefly described below to illustrate the impact invasives can have on restoration monitoring programs.

Phragmites

Phragmites is a common invader of brackish and freshwater coastal marshes (Figure 3 - Windham and Lathrop 1999; Able and Hagan 2000). It is a tall, perennial grass that grows at or above mean water level in freshwater and brackish marshes (Ailstock et al. 2001). It spreads into new areas by wind- and water-borne seeds and vegetative fragments carried on construction equipment. Once established, it grows extensive networks of runners along the sediment surface and spreads quickly. Although *Phragmites* is native to North America (see review in Chambers et al. 1999), it has recently begun to form extensive, monospecific stands in wetlands throughout the United States, limiting plant species richness (Chambers et al. 1999), impacting wildlife habitat (Weinstein and Balletto 1999; Weinstein et al. 2000; Teal and Weinstein 2002; Currin et al. 2003), and altering nutrient cycling dynamics (Meyerson et al. 1999).

Figure 3. Large stands of *Phragmites* in tidal areas can indicate conditions of reduced tidal exchange. Photo by Louis Kane, Barnstable County, MA. Photo from the NOAA Photo Library. http://www.photolib.noaa.gov/habrest/r0011812.htm.

The conversion of dominant marsh vegetation from one vegetation type to another can change how fish and other animals use the marsh. Due to its large size and high stem density compared to other types of marsh vegetation, *Phragmites* can restrict the movements of fish and crustaceans into feeding areas (Roman 1978), thus limiting secondary productivity. In a study comparing the interaction of fish and crustacean use of smooth cordgrass and *Phragmites* dominated brackish marshes in southern New Jersey, researchers found that the abundance of mummichogs

(*Fundulus heteroclitus*) and spotfin killifish (*Fundulus luciae*) was significantly greater at smooth cordgrass sites than in *Phragmites* marshes. Blue crabs (*Callinectes sapidus*) and grass shrimp (*Palaemonetes* spp.) were also more abundant in smooth cordgrass dominated areas, whereas the non-native Harris mud crab (*Rhithropanopeus harrisii)* was most abundant within *Phragmites* dominated areas. *Phragmites* also negatively affected larval and small juvenile fish but showed little or no affect on larger fish and crustacean populations (Able and Hagan 2000), possibly because these larger animals are restricted from marsh surfaces by other factors such as hydroperiod.

Differences in the type and amount of macroinvertebrates have also been observed between smooth cordgrass and *Phragmites* dominated brackish marshes in the Mullica River (0-17 ppt salinity) in southern New Jersey (Angradi et al. 2001). Total macroinvertebrate density and mean taxa richness were significantly greater in the smooth cordgrass marsh compared to the *Phragmites* marsh. The relative abundance of the three most abundant taxa was also lower in the *Phragmites* marsh. Dense stands of *Phragmites* have been shown to lower bird species richness by excluding wading birds and facilitating the replacement of marsh specialists with generalist bird species (Benoit and Askins 1999). Dense *Phragmites* stands can also greatly diminish resting, feeding, and breeding areas for migratory waterfowl (O'Shea, cited in Chambers et al. 1999). Compared to saltmeadow cordgrass (*Spartina patens*) and salt grass (*Distichlis spicata*) communities, *Phragmites* has significantly greater live aboveground biomass than the other two species (Windham and Lathrop 1999). Soil salinities, water level, and microtopography are also all significantly lower in the *Phragmites* stands (Windham and Lathrop 1999). These results imply that water quality and nutrient cycling functions between these marshes may be different as well.

Some argue, however, that *Phragmites* is not all bad. Despite the list of affects on animals given above, other research has found no significant difference in the utilization of *Phragmites* versus smooth cordgrass marshes in terms of abundance or biomass, nor between the total number of species using the two marsh types (Meyer et al. 2001). One study of marsh nekton in Delaware Bay also suggests that *Phragmites* may actually be an important component of the estuarine food web (Wainright et al. 2000). Dense stands of *Phragmites* also do not seem to have a significant impact on the density, diversity, and productivity of insects in freshwater marshes (Ailstock et al. 2001). Due to its large size, *Phragmites* stores large amounts of nitrogen in its stems and leaves. Slow decomposition of these structures contributes to the accumulation of organic matter in marsh soils (Ailstock et al. 2001) and potentially high sedimentation rates (Harrison and Bloom 1977). In comparison to cattails, a plant *Phragmites* often replaces in freshwater and brackish marshes, *Phragmites* stores more nitrogen and accumulates greater amount of detritus in marsh soils. Detrital communities are somewhat negatively affected by this change but not necessarily enough to warrant control of *Phragmites* (Findlay et al. 2002). These characteristics, coupled with a strong root structure that holds wetland sediments in place (Ailstock et al. 2001), have caused *Phragmites* to be viewed favorably in some locations such as portions of coastal Louisiana where, as the result of physical or biological stressors, few other plants will grow (Stevenson et al. 2000).

Purple loosestrife

Purple loosestrife is a tall emergent plant with showy purple flowers. It was brought to the United States in the mid to late 1800s (Stuckey 1980), quickly spread across the continent, and is now found in all of the lower 48 states (Blossey et al. 2001). Purple loosestrife provides little to no food or cover value for most wildlife (Rawinski

Figure 4. Purple loosestrife dominates this marsh. Photo courtesy of Bernd Blossey, Cornell University. http://www.invasive.org/

1982) and can form dense, monospecific stands (Figure 4), displacing native vegetation to which animals are adapted (Wilcox 1995). Purple loosestrife produces an abundance of seeds that stay viable in the seed bank for several years (Rawinski 1982). Several methods of controlling it have been tried including hand pulling, flooding, and herbicide treatments, all with little success (Wilcox 1995). Recent experiments with biologic control, however, have shown promise at significantly weakening established plants without damaging other more desirable species[11] (Stamm-Katovich et al. 2001; Hoey 2002).

Careful selection of restoration project goals concerning the removal of invasives is particularly important. If, for example, the goal of a particular project is the simple reduction of purple loosestrife, a variety of methods to do so might temporarily work (Morrison 2002). If the goal of the restoration is to improve species richness, however, then simple removal of purple loosestrife alone may not be sufficient as removal alone may create a niche in the marsh plant community for another pest species, such as reed canary grass to invade (Morrison 2002).

These examples of purple loosestrife and *Phragmites* illustrate the point that both the positive and negative qualities of invasive species need to be taken into consideration when setting restoration and monitoring projects goals. In some areas where nothing else will grow due to severely altered hydrology, subsidence, or some other disturbance, invasive species such as *Phragmites* may be the best bet to get vegetation established and restore at least some marsh functions until the disturbance can be brought under control, if at all (Stevenson et al. 2000). In other areas where the establishment of a greater diversity of native plant species is possible and desirable, then efforts to control the spread of invasives should be undertaken.

[11] http://www.npwrc.usgs.gov/resource/1999/loosstrf/loosstrf.htm.

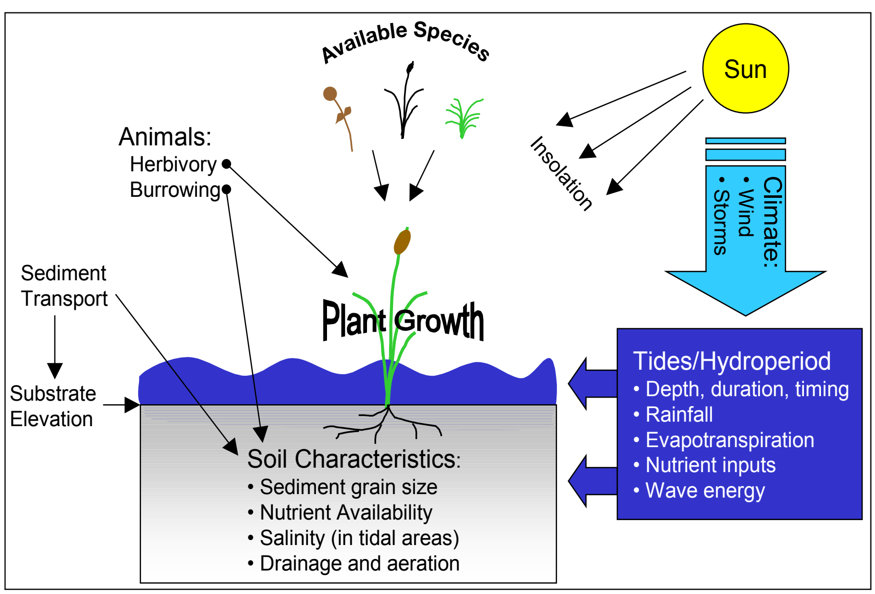
STRUCTURAL CHARACTERISTICS OF COASTAL MARSHES

Coastal marshes of the United States occur across a wide range of climatic conditions and in a variety of physical settings. All of them, however, share several important structural and functional characteristics that make them 'marshes.' Characteristics such as water velocity and source, tidal regime or hydroperiod, wave energy, sediment grain size, soil nutrient content, and substrate elevation and topography largely determine which particular plant species are able to grow in any given area (Figure 5). These factors, and others described in this chapter, represent the fundamental structural characteristics that allow a marsh plant community to develop. In addition to determining which plant species will grow, many of the functions that marshes perform are dependent upon these structural characteristics as well.

Structural characteristics are often manipulated during restoration projects to bring about changes in function. Therefore, structural characteristics should be considered when developing a restoration monitoring program, particularly in the short-term. For example, a goal of a restoration project may be to reintroduce tidal flooding to a diked coastal marsh in order to facilitate nutrient transformation, thus helping protect estuarine water quality. The ability of a marsh to perform this function depends, in large part, upon the elevation of the substrate relative to mean water level. Water level fluctuations that periodically inundate and expose the soil surface are also needed for higher nutrient transformation rates to occur. Quite often, however, the soils of diked marshes have subsided and/or been compacted so that substrate elevations are much lower than when the marsh was originally diked. Thus, the substrate elevation must be raised, or water levels increased slowly over time. Otherwise the relationship between water level and sediment elevation will not be appropriate for the marsh to perform the desired function. Marsh elevation and water level fluctuations will need to be monitored prior to, during, and immediately after project implementation to determine whether or not the marsh will be capable of performing the desired functions or if additional adjustments in sediment elevation will be needed.

The structural characteristics of coastal marshes determine which plant species are able to grow

Figure 5. Some of the structural and functional characteristics that influence plant growth. These characteristics and others are explained throughout the chapter as they relate to restoration monitoring. Graphic by David Merkey, NOAA Great Lakes Environmental Research Lab.



and influence a variety of functions performed by coastal marshes as well. Coastal march structural characteristics are broken into four categories, any or all of them may be monitored as part of a restoration project. These characteristics are:

Biological
- Habitat created by plants

Physical
- Acreage of marsh
- Sediment
  - Grain size
  - Organic content
  - Sedimentation
- Bathymetry/topography
  - Elevation and microtopography
  - Slope geomorphology

Hydrological
- Climate
- Tides/hydroperiod
- Water sources
- Current velocity
- Wave energy

Chemical
- Nutrient concentration
- Salinity, toxics, redox, DO

Each of these and its relevance to coastal marsh ecology and restoration monitoring is explained below.

BIOLOGICAL

Habitat created by plants[12]

The emergent, herbaceous vegetation that characterizes coastal marshes provides the bulk of the physical habitat used by fish, birds, invertebrates, and mammals (Adam 1990; Wilcox 1995). Characteristics of the plant community include:

- Stem density
- Plant height
- Species composition
- Percent cover, and
- Amount of edge to open water

All affect how, and which, animals use marsh habitats (Gosselink 1984; Zimmerman and Minello 1984; Browder et al. 1989; Wilcox and Meeker 1992; Wilcox 1995; Teal and Howes 2001). For example, the abundance of epibenthic[13] invertebrates is significantly higher in vegetated marshes with 80% or more plant cover than areas with less cover (Scatolini and Zedler 1996). Although, the mere presence of vegetation is often enough to increase the number and diversity of animal species that inhabit a particular area (Wilcox 1995 and literature cited therein). Which plant species are present, their growth form, decay rate, stem density, height, and interspersion with open water and other habitats also determine the type, quality, and amount of habitat marshes provide.

Marsh vegetation can be divided into two categories, persistent and non-persistent, based on the speed with which it is decomposed and nutrients cycled back into the system (Cowardin et al. 1979). Persistent marsh plants are those that are visible above the sediment surface throughout the year (Figure 6). Non-persistent marsh plants are those that decompose quickly when the plants die, leave no evidence aboveground outside of the growing season (Odum and Heywood 1978). They may also not be apparent during large parts of the year or even portions of the growing season. Wild rice, for example, can grow up to 3 m tall and dominate marsh vegetation communities in midsummer where no vegetation was even apparent in late spring (Odum 1988).

On the Atlantic and Pacific coasts of the United States, high marshes are often dominated by

[12]This section describes some of the characteristics of coastal marsh plant communities and methods that can be used to monitor them. Examples of how animals use plant communities are discussed in the *Functional Characteristics of Coastal Marshes: Habitat* section below.

[13]Living on the surface of the sediment.


Figure 6. Cattails (*Typha spp.)* are an example of persistent vegetation. These two photos were taken of the same marsh in summer and spring of the following year. Photos by David H. Merkey, NOAA Great Lakes Environmental Research Laboratory.

persistent vegetation and low marshes by non-persistent (Odum 1988; Khan and Brush 1994). Tidal ranges in the Gulf of Mexico are not large enough to create distinct high and low marshes, nor are high and low marshes found in the non-tidal Great Lakes. Marshes in these areas can be made up of persistent or non-persistent vegetation or a mix of the two depending on the particular species present, water depth, and characteristics of the substrate. Whether a marsh is dominated by persistent or non-persistent species has implications for how wildlife use the marsh, certain water quality and nutrient cycling functions as well as the type and timing of sampling that can be done as part of monitoring.

The relationship that different types of marshes have with other habitats also affects the habitat function of coastal marshes. Salt and freshwater marshes differ in their relationship with submerged aquatic vegetation (SAV) habitats[14]. In freshwater areas, SAV is a common component of marshes in deeper areas and large SAV habitats often occur adjacent to marshes (Figure 7). Salt marshes, on the other hand, generally lack dense beds of SAV in adjacent, shallow subtidal areas (Yozzo and Smith 1998). This difference changes the way animals use marsh habitats. Estuarine animals such as mummichogs often stay in salt marshes during low tide by sheltering in pools (Yozzo and Smith 1998). In freshwater areas, animals tend to leave the marsh completely and move to adjacent SAV habitats (Rozas and Odum 1987b; Rozas and Odum 1987a; Yozzo and Smith 1998). As these areas provide similar levels of protection from predation and food availability as marshes do without the added stress of high salt concentrations and potential desiccation (Yozzo and Smith 1998).

Salt marshes

Although salt marshes may have a very high number of algal species within them, the diversity of vascular species is quite low compared to freshwater marshes (Wiegert and Pomeroy 1981). Some of the common dominant plant species of estuarine salt marshes along the Atlantic coast and the coast of the Gulf of Mexico include:

Smooth cordgrass
Saltmeadow cordgrass
Big cordgrass (*S. cynosuroides*), and
Black needlerush (*Juncus roemerianus*)

On the Pacific coast, California cordgrass (*Spartina foliosa*) is the dominant species with:

Salt grass
Sea blite (*Suaeda californica*), and
Arrow grass (*Triglochin maritima*)

[14]See Chapter 9: Restoration Monitoring of Submerged Aquatic Vegetation.

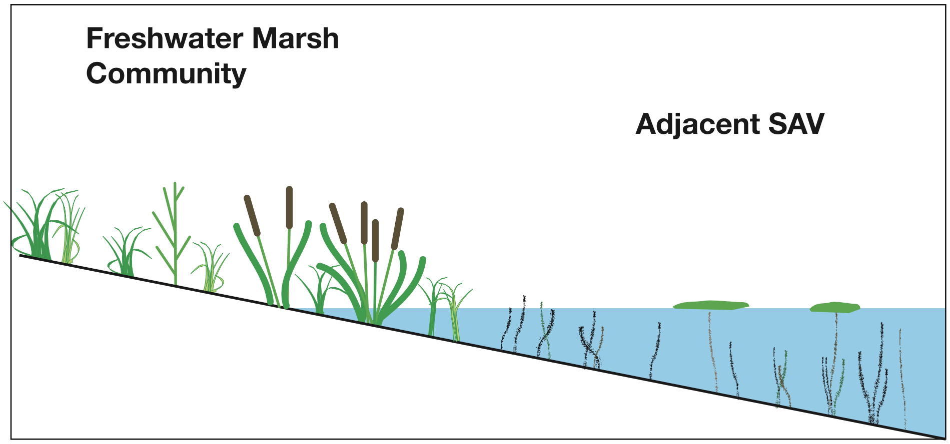


Figure 7. In freshwater areas, SAV grows adjacent to and sometimes within marsh communities. Modified from Maynard and Wilcox 1997.

(Cowardin et al. 1979; Seliskar and Gallagher 1983; Adam 1990 and literature cited therein)

Other common species of salt marshes include:

Saltwort (*Batis maritima*)
Pickelweed, and
Salt marsh plantain (*Plantago maritima*) (Cowardin et al. 1979; Adam 1990)

These plants and the various forms of algae found in salt marshes provide organic matter that supports a host of invertebrates, fishes, and resident and migratory birds (Kwak and Zedler 1997). Smooth cordgrass seeds and rhizomes, for example, are consumed by birds such as ducks, geese, and shore birds (Vivian-Smith and Stiles 1994). When plants die, leaves and stems settle on the sediment surface where they are broken down by bacteria and fungi. This detritus[15] is then eaten by bottom dwelling scavengers such as worms, fish, and crabs (Darnell 1967; Odum 1980).

Of the species listed, smooth cordgrass is the most important species in salt marshes of the eastern United States. Two growth forms are commonly found throughout its range. A tall form that can grow up to 3 m tall is found along tidal creeks and in low marsh areas. A short form, normally 10-40 cm tall, grows on upper levees and in pans between tidal creeks (Adam 1990). The short form is stunted from a general lack of available nutrients in upper levees and pans (Shea et al. 1975). Smooth cordgrass is not native to the west coast and is considered an invasive species there.

Seedling survival in salt marshes is extremely low (~5% - Allison 1996). The successful establishment and expansion of salt marshes is therefore dependent upon the few individuals that do survive, spreading by vegetative growth. Huge sections of marsh can in fact be made up of single, interconnected clones (Miller and Egler 1950; Ranwell 1964; Redfield 1972; Neiring and Warren 1980; Hartman 1988). Unlike freshwater marshes that have large, diverse seed banks, the seed banks of salt marshes have generally low density of seeds and low diversity of species (Hartman 1988). This is due, in part, to the dominance of these habitats by long-lived perennial species (Hopkins and Parker 1984).

Brackish marshes

Some plant species of tidal brackish low marshes include:

Marshhay cordgrass (*Spartina patens*)
Bulrushes (*Scirpus* spp.)
Salt grass (*Distichlis spicata*)
Salt meadow cordgrass
Spikerushes (*Eleocharis* spp.)
Broad-leaved cattail (*Typha latifolia*)
Narrow-leaved cattail (*T. angustifolia*)
Black rush (*Juncus roemerianus*)

[15] The mix of decayed plant material and nutrient-rich microorganisms.

Pickerelweed (*Pontederia cordata*)
Three-cornered grass (*Scirpus olneyi*)
Smooth cordgrass (*Spartina alterniflora*)
Widgeon-grass (*Ruppia maritima*)
Phragmites, and
Southern wild rice (*Zizaniopsis miliacea*) (Cowardin et al. 1979; Adam 1990)

Plant species found in brackish high marshes also often include smooth cordgrass and saltmeadow cordgrass (Adam 1990). On the northwest Pacific coast, Lynbei's sedge (*Carex lyngbei*) is also a common dominant species of brackish marshes (Seliskar and Gallagher 1983). Of the species listed, marshhay cordgrass is the most important species in brackish marshes of the Atlantic Ocean and Gulf of Mexico (Chabreck 1970). This species makes up over 24 percent of the vegetative composition and almost doubles the values for its nearest competitor, smooth cordgrass in coastal brackish marshes in Louisiana (Chabreck 1970).

Freshwater marshes

On the coasts of the Atlantic Ocean, Gulf of Mexico, and in the Great Lakes, freshwater marshes with persistent vegetation are often dominated by:

Narrow-leaved cattail
Sedges (Family Cyperaceae)
Phragmites, and
Southern wild rice

On the Pacific Coast, cattail (*T. domingensis*) and the California bulrush (*Scirpus californicus*) are common dominants. There are also a variety of broad-leaved persistent emergents common to these systems such as:

Purple loosestrife
Dock (*Rumex* spp.), and
Waterwillow (*Decodon verticillatus*) (Cowardin et al. 1979)

Freshwater marshes with non-persistent vegetation often include species such as:

Arrow arum (*Peltandra virginica*)
Wild rice (*Zizania aquatica*)
Pickerelweed
Arrowheads (*Sagittaria spp*.), and
Smartweeds (*Polygonum* spp.)

Due to lower levels of environmental stress, freshwater wetlands have a much greater diversity of species than salt or brackish water marshes (Odum et al. 1984). In tidal areas, this diversity is derived in part from a large, diverse seed bank with an abundance of annual species (>85% of the seed bank - Leck and Graveline 1979; Parker and Leck 1985; Leck and Simpson 1987). In coastal marshes of the Great Lakes, however, the seeds of perennial species tend to be more dominant (Keddy and Reznicek 1982). The large seed bank diversity of freshwater marshes may make construction and restoration easier as there may not be as great a need for planting if the hydroperiod can be manipulated to allow germination from the seedbank to occur (Odum 1988).

Potential variability

Coastal marsh plant communities can be very dynamic. Seasonal and annual changes in climate and large, coastal storms play an important role in these dynamics. The vegetation of salt and brackish marshes, for example, is adapted to a range of soil salinities that can change as a result of differences in climate-driven freshwater flows (Zedler et al. 1986). The vegetation of freshwater marshes, on the other hand, is adapted to and dependent upon periodic, water level fluctuations also related to climate (Keddy and Reznicek 1986; Wilcox 1995; Wilcox and Meeker 1995). Hurricanes and changes in land use practices can completely alter marsh vegetation communities from salty to fresh and vice versa (Clark and Patterson 1985).

Freshwater marshes, in particular, exhibit considerable changes in vegetation both seasonally and from one year to the next (Odum et al. 1984; Odum 1988; Leck and Simpson

1995; Wilcox et al. 2002). A common pattern is for broadleaved emergents to dominate in the spring and early summer. By late summer, grasses and other herbaceous vascular plants come to dominate (Odum 1988; Yozzo and Diaz 1999). Because of the inter-annual variability of Great Lake's water levels, the marshes that are directly dependent on them also vary from year to year. If water level changes from one year to the next, slight differences in species composition may result. If water level changes are more drastic, entire habitats may change from marsh to upland or submerged aquatic vegetation depending on the direction of the change (Wilcox et al. 2002).

Sampling and Monitoring Methods

Some parameters that have been suggested for use in monitoring restoration (revegetation) projects include species composition, percent survival over time, percent cover relative to wetland area, rate of expansion, ratio of vegetation to open water, and percentage of gaps that have grown in with vegetation (Levine and Willard 1990). Stem density and plant health/survival are also commonly measured parameters in restoration monitoring projects. Measurements should be conducted quarterly for the first year, and in the early summer and early fall of the following two years (Levine and Willard 1990). Monitoring at a high frequency soon after implementation of the restoration helps ensure that plants are successfully germinating and becoming established. If they are not, adaptive management strategies may be identified and implemented to assist the process (Thayer et al. 2003). Additional monitoring should also take place after large storms as, in certain coastal areas, these can be extremely stressful on marshes (Levine and Willard 1990).

Numerous sampling and measurement methods are available to evaluate plant communities in marshes. Examples of remote sensing and line intercept methods are presented below but a variety of other methods exist such as quadrat sampling that allows for calculation of plant density and % cover. Practitioners should choose among available techniques based on a number of factors such as the size/accessibility of their project area, the type of technique(s) previously used in their area (the data from which might be used for comparison), the particular aspect of plant community that will be measured (aerial extent, productivity/biomass, species richness/diversity/etc.), and the particular statistical question(s) to be answered. Therefore, a statistician should be consulted during the planning stages of a restoration project to help practitioners determine appropriate sampling strategies and techniques for their restoration project. The second appendix of this chapter, *Appendix II: Review of Technical Methods Manuals* provides additional resources on sampling and planning issues.

Remote sensing - Remote sensing, in the form of aerial photographs or satellite imagery, can be a very effective tool for monitoring changes in the characteristics of marsh vegetation such as % cover, dominant species, plant health, productivity, and biomass over very large areas (Gross 1987; Thomson et al. 1999; Shuman and Ambrose 2003; Berberoglu et al. 2004). Satellite imagery can also be gathered at regular intervals during a growing season and used to derive estimates of primary productivity for a whole marsh (Hardisky et al. 1984; Gross 1987). Remote sensing data is most useful when it has been ground-truthed by physically sampling plots that have been remotely sensed. This allows for a greater degree of certainty when interpreting remotely sensed data and verifies that what is seen in the imagery is what is actually present on the ground (Windham and Lathrop 1999).

Line intercept - Line intercept sampling is a measurement of plant communities along straight lines (usually a tape measure, cord, or length of rope). Lines are laid out over a gradient such as upland to open water and any plant that touches the line is recorded. The number of replicate lines needed depends, in part, on the complexity and size of the marsh being studied. This method of sampling can be used to quantify both the distribution and abundance of plant species within a marsh. The placement of permanent stakes or other markers to identify the beginning and end of the line may be used if particular areas are to be resampled over time[16]. In Laguna Atascosa National Wildlife Refuge in southern Texas, the line intercept method was used to analyze the change in plant species over time in salt and brackish marshes (Judd and Lonard 2002). Each marsh was sampled using three line transects in 1996 and 1999 to compare plant species variation between transects, years, and marshes. Although no difference in species diversity was noted from one sample time to the next, the vegetation was clearly zoned along an elevation gradient. Studies such as this can be used to help identify which plant species should be planted where during a marsh restoration.

PHYSICAL

The physical characteristics of marshes such as the size of the marsh, sediment grain size and organic content, and topography/bathymetry are separated from the hydrologic characteristics of marshes discussed in a later section. Marsh size is included as a physical characteristic as it determines the limits of the area under study, how much habitat is available to wildlife, and helps identify all of the potential inputs to the system. Soil characteristics such as grain size and organic content direct the types of restoration strategies that can be considered. Marsh topography/bathymetry determine marsh plant community distribution and marsh function. Although many hydrologic characteristics of marshes are ‘physical’ in nature, they are important enough to warrant a separate discussion.

Size

In general, large marshes with many different vegetation communities provide higher quality habitat for a larger number of species than do smaller, less complex wetlands (Hemesath and Dinsmore 1993; Merendino and Davison 1994). This is particularly true for birds as very few species use marshes as small as 0.10 ha. The number of bird species dramatically increases with marsh size, particularly in the 1 to 5-ha range (Watts 1992). That does not mean that smaller marshes are unimportant. Small marshes provide critical amphibian habitat, maintain landscape-level diversity, and provide recruits to new marsh areas following disturbance (Semlitsch and Bodie 1998). If a large, diverse, productive marsh is severely disturbed or degraded, smaller marshes, even inland ones, scattered throughout the landscape could escape the disturbance and provide seed sources and wildlife to recolonize the larger wetland. In addition, some animals and birds require large continuous blocks of a single habitat type that are at least as large as their territorial range. The amount of flood/storm water a marsh is able to retain is also size related. Larger marshes can store larger volumes of flood/storm water than smaller marshes thus increasing the amount of flooding protection provided to downstream areas.

Sediment

Sediments are brought into coastal marshes by river flows, tides, and storms carrying marine deposits (Meade 1969; Chabreck 1988). The grain size of marsh sediments and their associated nutrient content is dependent upon the:

- Parent material
- Method of transport
- The geologic and hydrologic characteristics of the marsh itself

[16]If particular areas are to be sampled in this manner, care must be taken to ensure that sampled areas do not become impacted (i.e. trampled) by repeated site visits.

- Current velocity
- Plant density
- Water volume
- The area over which sediment spreads, and
- Watershed characteristics such as size, geology, and discharge (Seliskar and Gallagher 1983; Cahoon and Reed 1995; Cahoon et al. 1996; Leonard 1997; Pasternack and Brush 2002).

Freshwater marshes typically have soils deposited by river flow from upland sources. These tend to be a mix of clays, silt, and fine organic matter with some sand and can be quite variable depending on the characteristics of the watershed (Meade 1972). Salt and brackish marsh soils consist of silt, sand, or clay derived from both upland sources and marine deposits (Redfield 1972; Nixon and Oviatt 1973).

Three characteristics of sediments important to restoration monitoring are grain size, organic matter content, and the rate of accretion or sedimentation. Each is a key structural component of marshes that will often need to be monitored closely after the implementation of restoration projects. As will be discussed below, sediment grain size affects nutrient availability (Hausenbuiller 1972; Andrieux-Loyer and Aminot 2001; Koch 2001; Jahnke et al. 2003; Steiger and Gurnell 2003). Sediment organic content affects the ability of a restored marsh to act as a nutrient sink and the use of sediments as benthic habitat (Cole and Weigmann 1983; Craft 2000). Sedimentation rates that are too high or too low can alter the elevation of the substrate or bury the seed bank and lead to changes in vegetation communities (Jurik et al. 1994; Wang et al. 1994).

Grain size

Marsh vegetation obtains a majority of its nutrients from sediments (DeLaune et al. 1981). Plant productivity and biomass is therefore related to soil nutrient content (Broome et al. 1975; DeLaune and Pezeshki 1988). Sediment grain size also has direct effects on nutrient levels available to marsh plants. Different grain sizes such as clay (below 0.002 mm), silt (0.002 to 0.05 mm), sand (0.05 to 2.0 mm), and gravel (above 2.0 mm) supply different levels of nutrients and support different plant communities (Hausenbuiller 1972; Andrieux-Loyer and Aminot 2001; Koch 2001; Jahnke et al. 2003; Steiger and Gurnell 2003). Fine sediments, such as silts and clays, have greater nutrient content than do coarse, sandy soils. This is due in part to the increased surface area to volume ratio of fine sediments compared to larger particles (Andrieux-Loyer and Aminot 2001; Pasternack et al. 2001; Steiger and Gurnell 2003). This effect can be offset, however, by the poor drainage that fine sediments suffer from (Clarke and Hannon 1967; Clarke and Hannon 1969). Fine-grained, poorly drained, waterlogged soils can be low in oxygen. This negatively affects plant growth and has a variety of other effects on sediment chemistry that will be discussed in the section on *Chemistry: dissolved oxygen and redox potential* below (Long and Mason 1983; Portnoy 1999).

Soil bulk density[17] can also be used as an indicator of the relative amount of mineral sediment (Hatton et al. 1983) and has been related to the amount of aboveground plant biomass in salt (DeLaune and Pezeshki 1988) and brackish marshes (Nyman et al. 1994). Soils with higher bulk density typically contain higher concentrations of phosphorus, an important nutrient to marsh plants (Patrick and DeLaune 1976).

Sampling

Sediment grain size or bulk density can be monitored to determine if the rooting medium for emergent plants is adequate for establishment and/or if sedimentation rates are keeping pace with coastal subsidence for the long-term survival of the marsh. Sediment grain size can

[17]The dry weight of the sediment per unit of volume.

be measured directly by drying and sifting samples through a series of different sized sieves or indirectly through measuring bulk density. It is generally low (e.g., 0.2 to 0.3 g/cm^3) for sediments with high organic matter content and high (e.g., 1.0 to 2.0 g/cm^3) for sediments with high mineral content. These and other methods to measure sediment characteristics are reviewed by Poppe et al. (2003).

Organic content

Sediment organic matter comes from two sources: upland drainage (more important in freshwater marshes than salt marshes) and from marsh plants. The dead leaves, stems, seeds, roots, rhizomes, and other parts of marsh plants lay in or on the sediment where animals, bacteria, and fungi break them down. This material can then be worked into the sediments by burrowing animals or covered over with new mineral sediments deposited from storms or upland drainage. The amount of plant material in the soil depends upon the plant community, frequency and duration of flooding, and the magnitude of tidal and other surface water currents, as well as the burrowing activity of benthic organisms (Chabreck 1988). As such, the amount of organic matter in the soil generally increases inland from the sea (Chabreck 1970). For example, freshwater marshes tend to have higher organic content than brackish or salt marshes (Odum 1988 and literature cited therein). Percent organic matter for tidal freshwater marshes ranges between 20% and 70% with a mean of 35%, though much variability between and within sites should be expected (Odum 1988). In addition, in marshes that have distinct high and low marsh communities, high marshes tend to have higher amounts of sediment organic matter than low marshes (Khan and Brush 1994). This is partially due to the increased exposure to wave energy low marshes are subject to, as well as an increased frequency of inundation (Whigham and Simpson 1975; Gosselink et al. 1977). Marshes in protected bays or behind barrier beaches may accumulate thick deposits of organic sediments, while open marshes in wave exposed areas typically have little sediment organic matter (Keddy 1985; Burton et al. 2002).

Many of the chemical functions marshes provide such as nutrient cycling and retention and conversion of metals and pesticides as well as some habitat functions are affected by the amount and type of organic matter in the sediment (Simpson et al. 1978; Cole and Weigmann 1983; Orson et al. 1992; Khan and Brush 1994). Marshes with higher amounts of sediment organic matter retain greater amounts of nutrients and metals than marshes with lower concentrations of sediment organic matter (Simpson et al. 1978; Khan and Brush 1994). Benthic invertebrates such as worms (polychaetes and oligochaetes) and midge larvae (chironomids) are also strongly related to amount of organic matter in the sediments (Cole and Weigmann 1983; Moy and Levine 1991; Craft 2000). These invertebrates are also important sources of food for bottom feeding fish and shrimp (Weisberg and Janicki 1990; Swenson and McCray 1996).

The amount of organic matter deposited in marsh soils can vary over time. This is particularly true in coastal marshes of the Great Lakes. During years with low lake levels, barrier beaches may form over the outlets of some marshes, limiting exchange of water with the lake, fostering the accumulation of organic sediments. During prolonged high water levels, these protective structures may erode and organic sediments might wash away (Wilcox 1995). Thus the ability of a Great Lake coastal marsh to function as a sink or source of organic material and nutrients to the associated lake varies from year to year depending on the water level fluctuations of the lake and its affect on marsh geomorphology and hydrologic characteristics. The amount of organic matter also changes in salt marshes over time but over much longer time scales. Young marshes accumulate sediments, organic matter, and the nutrients and contaminants adhered to them. As the marsh ages, these materials are exported out of the marsh. Thus the ability of a marsh to act as a source or sink depends upon the age of the marsh as well (Leendertse et al. 1996). As with natural marshes, organic matter content will vary with restored marshes according to marsh type and the age of the restoration project (Craft 2000).

Sampling

A common method of measuring soil organic matter involves freeze drying the samples, then grinding them and applying hydrochloric acid (HCl) overnight to remove any calcium carbonate. The samples are then dried at 70˚C to remove any water and weighed. They are then dried at 550˚C for 1.5 hr to burn off all of the soil organic matter (Davies 1974). Samples are allowed to cool and then re-weighed. The difference in weights is the amount of organic matter in the soil. Although this method is widely used in laboratories, it may require a significant investment in equipment. Smaller, less expensive chemical methods are also available from environmental and aquaculture suppliers that can provide similar results (Queiroz and Boyd 1998). Bulk density can also be used to determine the amount of organic and inorganic matter in sediments (DeLaune et al. 1983b).

Accretion[18]

Sea level rise, natural subsidence, and changes in land use have increased mean water level in many coastal marshes, making it more difficult for emergent vegetation to survive (Hatton et al. 1983; Baldwin et al. 1996). The continued existence of coastal marsh habitat depends on whether the substrate can maintain an elevation above relative sea level. The annual increase in marsh elevation, referred to as accretion, is accomplished through a combination of processes including mineral sedimentation and organic matter production. While mineral sediment supply has long been considered the primary control of vertical marsh accretion and marsh stability (Hatton et al. 1983; Baumann et al. 1984), several other factors can also influence the accretion of coastal marsh soils including pulsed storm events (Reed 1992), local subsidence (DeLaune et al. 1983b), and the oxidation and compaction of organic matter (DeLaune et al. 1990). These processes link soil formation to the stability of marsh wetlands. The conversion of marshes to open water habitats can occur where accretion is less than the relative rise in water level causing excessive flooding and marsh loss.

Soil formation and accretions are controlled by the contribution of biomass production and the loss of organic matter through decomposition. An increase in accretion can occur by either an increase in belowground plant production or by a decrease in decomposition rate; either of which increases the accumulation of organic matter in marsh soils. The balance between these two processes is controlled by a myriad of factors including mineral sediment and nutrient supply, freshwater delivery, and hydroperiod (Mendelssohn et al. 1983; Mendelssohn and McKee 1988; Reed and Cahoon 1992). The interactions of these factors are very complex and can vary spatially across a coastal landscape.

Deposition of sediment on the marsh surface can only occur when the marsh is flooded and requires both the availability of suspended sediment and the opportunity for that sediment to be transported by floodwaters over the marsh (Reed 1989). Freshwater tidal marshes, for example, often occur where the highest rates of sediment deposition are found (Meade 1972). These marshes often act as sedimentation basins, protecting downstream water bodies from turbidity and other problems associated with sediment deposition. The high stem density of emergent vegetation also contributes to sedimentation on the marsh surface by slowing water velocity and allowing suspended sediments to fall out of suspension.

[18]Sedimentation rate is equal to accretion minus erosion.

Too much sediment, however, can also be a problem as water level/substrate elevation relationships are altered and existing sediments are smothered. These changes in sediment type and substrate elevation can lead to changes in marsh vegetation communities. Heavy inputs of sediments from agricultural areas can create mudflats along shorelines, creating habitat for annual, freshwater, pioneer species such as nodding smartweed (*Polygonum lapathifolium*), bur-marigold (*Bidens cernuus*), and soft stem bulrush (*Scirpus validus*) and smothering the perennial species that may have once dominated the area (Minc 1997). Heavy sediment inputs can also alter the physical and chemical characteristics of the substrate, further impacting vegetation communities. Wild rice, for example, grows best in rich, organic deposits and once dominated some coastal marshes in the Great Lakes. Sediment-laden runoff from agricultural areas, however, has covered over the original organic deposits and eliminated wild rice habitat (Minc 1997).

Variability in Sedimentation Rates

There can also be considerable variation in sedimentation rates (Harrison and Bloom 1977). Characteristics of the plant community, distance from creek channels and inlets, frequency and severity of storms, and water level fluctuations can all affect the amount of sediments deposited in the marsh (Roman et al. 1997; Boorman et al. 1998; Pasternack and Brush 2002). The amount of sediments delivered to a marsh from upland sources can also be quite variable over time (McManus 2002). Hurricanes and large storms can cause tremendous amounts of erosion in the low marsh (Ranwell 1961) and can greatly increase sedimentation in the high marsh (Stumpf 1983). A major flood in 1936 and Hurricane Agnes in 1972, for example, accounted for half of the sediment deposited in the upper Chesapeake Bay between 1905 and 1975 (Schubel and Hirschberg 1978). The type of marsh also affects sedimentation patterns. High marshes tend to accumulate and retain sediments better than low marshes (Craft et al. 1993). These sources of potential variability will need to be accounted for when developing a restoration monitoring plan requiring measurement of sedimentation rates.

The Role of Algae

Although studies often focus on the role of vascular plants in increasing sedimentation in marshes, algae can also play a crucial role (Adam 1990). Algae (particularly diatoms) are often the first plants to colonize and stabilize newly exposed mudflats. These microscopic plants produce large amounts of mucus-like material that holds loose sediments together, eventually allowing vascular plants to colonize the area (Coles 1979).

Sampling

Various methods have been employed to measure the rate of vertical accretion in coastal marshes. Commonly used techniques involve the use of a 'marker layer' of brick dust, feldspar, or some other easily identifiable substance spread along the soil surface. In some cases, natural markers such as a layer of sand deposited by a particular storm can also be used. Once the marker layer is deposited, sediment cores can be taken to measure the rate of accretion over time (Adam 1990 and literature cited therein). Stakes can also be driven into the sediment for shorter-term studies. High current velocities, however, may lead to scour around the stake and complicate measurements using this technique (Adam 1990). Accretion can also be determined by measuring the concentration of radioactive materials such as Pb-210[19] at specific depths in the soil (French et al. 1994; Cochran et al. 1998; Anisfeld et al. 1999; Brenner et al. 2001).

When measuring rates of accretion, infrequent measurements over longer periods of time may be more informative than repeated measurements at short time intervals. Frequent, short-term measurements tend to show a more complicated

[19] A naturally occurring radionuclide supplied to marshes from the atmosphere.

picture of highly variable sedimentation and accretion rates over time. This is particularly true in lower marshes, due to the increased time of inundation. Short-term measurements may also over estimate accretion as they do not allow for sediments to settle and consolidate (Adam 1990).

Bathymetry/Topography[20]

The topography and bathymetry of marsh sediments, in relation to water level, influences the types of plants and animals that live in the marsh. Changes in topography through erosion, subsidence, or sediment deposition, even of a few centimeters (microtopography), can alter plant and animal communities and plant productivity (Adam 1990; Morris et al. 1990; Morris 2000). This is because each plant species is adapted to germinate and grow under a specific tidal regime or hydroperiod as it relates to water depth (van der Valk and Davis 1978; Keddy and Reznicek 1982). Changes in sedimentation rates, water level fluctuations of the Great Lakes, sea level rise, and subsidence of coastal areas can all change the depth of water to the substrate and thus change the vegetation community (Hatton et al. 1983; Wilcox and Whillans 1989; Adam 1990; Wilcox and Meeker 1995; Minc 1997; Baldwin and Mendelssohn 1998). The topographic diversity of marsh sediments also increases the diversity of the plant community. All other things being equal, marshes with uniform substrate elevations should have a much more uniform vegetative community with lower species diversity than a marsh with more topographic diversity. The presence of channels in the marsh also increases the ratio of edge to area and allows greater access to the marsh surface by fish and crustaceans, thus increasing the habitat value of the marsh (Rozas et al. 1988). In addition to elevation, microtopography, and channels, other ecologically important characteristics of marsh topography for monitoring include pans, slope and geomorphology.

In any restoration project involving planting or seeding, careful measurement of depth to substrate, substrate elevation, and topographic diversity will need to be done in order for the proper plant species to be selected. During the planning stages of any restoration projects requiring earth moving or the use of dredge material, soil engineers will compare the size of the project area with the source area to determine a settlement curve prior to restoration activity. Practitioners may still need to monitor substrate elevations and topographic diversity for a period after implementation and before planting to determine if the planned-for elevations have been achieved. Once sediments have settled into place and final elevations of the marsh substrate are known, final selections of plant species can be made and placed in the field.

Elevation and microtopography

Mean water level, as it relates to elevation of the marsh surface, is one of the most important factors affecting marsh productivity (Morris et al. 2002). Mean water level determines the frequency and duration of flooding of marsh soils. In salt marshes, mean water level (sea level) also determines soil salinity. The frequency and duration of flooding and soil salinity directly impact the health and productivity of marsh vegetation (Phleger 1971; Morris 1995). For example, changes in mean sea level from year to year as small as 5-10 cm have been shown to greatly impact the productivity of smooth cordgrass marshes on the east coast of the United States (Morris et al. 1990; Morris 2000). Increases in relative mean sea level through subsidence of coastal areas or increases in actual sea level through global warming can be potentially problematic for salt marsh restoration efforts. While the processes of subsidence and erosion constantly decrease

[20]Unless otherwise noted, the discussion of topography and bathymetry as it relates to wetland geomorphic features has been developed using Keough, J. R., T. A. Thompson, G. R. Guntenspergen and D. A. Wilcox. 1999. Hydrogeomorphic factors and ecosystem responses in coastal wetlands of the Great Lakes. *Wetlands* 19:821-834.

marsh surface elevations, healthy marshes with adequate sediment inputs are able to constantly modify marsh elevations toward equilibrium with mean sea level (Morris et al. 2002). Other topography-related factors that affect plant growth include soil salinity, soil aeration and drainage, sediment grain size, and nutrient availability (Gray and Bunce 1972).

Small changes in topography (microtopography) on the marsh surface are extremely important in maintaining plant species diversity and providing refuge areas for juvenile animals. Since each plant species is adapted to growing within a certain depth or elevation, small changes in the vertical structure of marsh substrates such as depressions or mounds can greatly increase the diversity of the plant community (Werner and Zedler 2002). Fish and invertebrates commonly use pools of open water on the marsh surface to wait out low tides and escape predations while hummocks created by different vegetation types make excellent hiding spaces for these animals during high water levels (Havens et al. 1995).

Pans

Pans are a characteristic feature of coastal salt marshes. They are slight depressions in the marsh surface often located between tidal channels. Seawater from high spring tides can become trapped in these areas and, over the growing season, become increasing salty as the water evapotranspirates away. These high salinity conditions limit seedling germination and plant growth. Without precipitation or additional tidal flooding, salt concentrations in pans may reach levels high enough to kill marsh plants and form a salt crust over the soil surface, limiting future recolonization of the area (Figure 8 - Adam 1990).

Marsh Creeks[21]

Water channels through a marsh are important corridors for water, materials, and animals to move from the marsh to open water areas and back (Mitsch and Gosselink 2000). Water carrying suspended and dissolved material moves downstream during periods of low water levels and inland with tides and seiches. Marsh creeks also facilitate the draining of the marsh during low tide, a process essential to the survival of many marsh plant species (Teal and Weinstein 2002). The more channels a marsh has also increases the exchange of animals, nutrients, sediments, and other materials between the marsh and downstream water bodies (Figure 9). Animals such as fish and shellfish find refuge in creeks during low water levels and then enter marshes to forage during times of high water levels (Weinstein 1979; Rozas et al. 1988; Laffaille et al. 2001; Hampel et al. 2003; Teo and Able 2003b; Teo and Able 2003a). In fact, most of the shrimp, crabs, and fish that use salt marshes are found within 5 meters of open water or marsh creeks so they can quickly return to lower areas at low tide (Minello et al. 1991; Peterson and Turner 1994).

A dense network of creeks maximizes the amount of marsh edge that can be accessed by animals increasing the use of marshes for feeding, breeding, and nursery purposes (Kneib 1994; Minello et al. 1994; Minello and Rozas 2002; Whaley and Minello 2002). The exact effect of animals' use of marsh creeks to access the marsh surface is also dependent upon the:

- Marsh slope
- Elevation
- Tidal dynamics
- Vegetation type and density
- Sediment grain size, and
- Drainage characteristics of the sediment (Minello et al. 1994)

Studies comparing natural versus constructed marshes in southern California also suggest that the creek characteristics most important in determining fish use of coastal marshes are:

[21]Often referred to as 'tidal creeks' in tidal marshes. The more generic 'marsh creeks' term is used here to include creek channels flowing through non-tidal Great Lake coastal marshes.

Figure 8. A salt crust (white areas) has formed on the soil surface of this tidal marsh pan on Whidbey Island, Washington. The vegetation in the pan has also turned red in response to salinity stress. Photo by David H. Merkey, NOAA Great Lakes Environmental Research Laboratory.

Figure 9. An aerial view of the meandering tidal creeks and extensive pristine marshes in North Inlet Estuary North Inlet - Winyah Bay National Estuarine Research Reserve, South Carolina. Creeks such as these increase the amount of edge habitat and allow fish and other animals access to the marsh surface during high water levels. Photo from the NOAA National Estuarine Research Reserve Collection.

- Water depth
- Temperature
- Dissolved oxygen
- Channel width
- The presence of smaller creeks, and
- Salinity (in tidal areas) (Zedler et al. 1997; Williams and Zedler 1999)

Slope

Since each plant species is adapted to a certain depth of water, the slope of the marsh surface can also influence plant communities. In freshwater marshes, differences in slope dictate the width of various vegetation zones as plant species adjust spatially in response to water level fluctuations. In salt marshes, differences in the slope can also influence salinity levels that dictate plant zonation (Dreyer and Niering 1995). This is more often an issue in high marshes where tidal waters may become trapped in poorly drained areas[22]. In tidal areas that are poorly drained or lack sufficient groundwater or fresh, surface water flows to flush sediments, salts brought in with the tide can accumulate

[22]Practitioners should also ensure that selected elevations and slopes will actually be inundated long enough that marsh vegetation will grow instead of upland or scrub-shrub species.

in the sediment through evapotranspiration (Valiela et al. 1978; Adam 1990; Thibodeau et al. 1998; Mitsch and Gosselink 2000). As soil salinities increase, plant productivity diminishes and fewer and fewer species are able to tolerate the increasingly saline conditions (Zedler et al. 1999; Mitsch and Gosselink 2000). Increasing the slope of and creating channels through a marsh to help salt water drain out during low tide can help minimize this problem (Zedler et al. 1999).

Geomorphology

Geomorphology is the study of the physiographic features of the earth's surface. By understanding the shape of a particular feature on the landscape and how it was formed, insights can be gained regarding the functions that area can perform (Valiela et al. 1978; Odum et al. 1979). Geomorphic features are determined based on the:

- Shape and geologic history of an area
- Degree of protection from wave energy, and
- Amount of hydrologic exchange with their receiving water body

These basic structural characteristics are outlined in Figure 10 for three different types of coastal wetlands: open wetlands, drowned river mouths, and protected wetlands (Roy 1984; Keough et al. 1999).

Open Coastal Wetlands

Open coastal wetlands are located directly on the shores of lakes, bays, or the open ocean (Figure 11). They and their associated marsh habitats are subject to more wave energy and hydrologic exchange than drowned river mouths or protected wetlands. Open marshes are chemically and hydrologically directly connected to the water body they discharge into. They may also have upland water sources such as small streams. They typically do not have as much sediment organic matter accumulated as drowned river mouths or protected wetlands. Plants and animals that live in open marshes must be tolerant of daily water level fluctuations from tides or seiches and higher rates of erosion caused by waves and ice.

Drowned River Mouths

Drowned river mouths were formed during the last ice age when water levels of the Great Lakes and oceans were much lower than they are today. As the lakes and oceans rose to present levels, deep river valleys filled with sediments creating linear wetland complexes dominated chemically and hydrologically by both the rivers moving through them and their receiving body of water (Figure 12). Many of the estuaries in the United States such as the Chesapeake and Delaware Bays on the east coast, Coos and Siletz Bays in Oregon, and those in the Great Lakes such as Muskegon Lake in Michigan are drowned river mouths. Marshes of drowned river mouths are usually long, linear, and run perpendicular to the coast. Unlike open or protected marshes, drowned river mouths are heavily influenced by physical and chemical processes of both the river and the receiving body of water. During periods of low flow or the presence of a barrier beach, retention time of water in the marsh is increased, and sediments and nutrients are held in the marsh as well (Reeder and Mitsch 1989). During severe storm events or high water levels, protective structures can be eroded away reducing retention time of water and flushing accumulated sediments, nutrients, and organic matter out of the marsh.

Protected Wetlands

Protected wetlands and associated marshes are located behind some sort of barrier (often an island) that protects them from the full force of waves coming off a water body (Figure 13). Barriers for protected marshes, as well as those occasionally associated with drowned river mouths, can be completely isolating or can be open to allow some hydrologic exchange with the receiving body of water. The extent of the barrier has direct effects on the accumulation

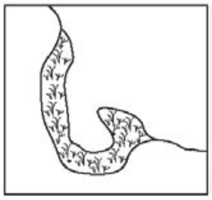
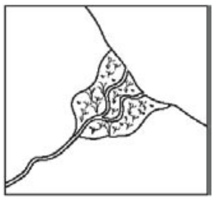
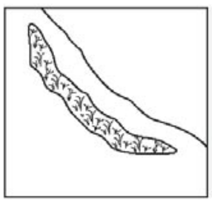
Type	Physical	Hydrologic	Biological	Chemical
Open 	Variable inorganic substrate (clay to gravel). Thin to non-existent organic substrate. Moderate to high wave climate. Low rate of sediment supply. Gentle offshore and underlying-surface slopes. May or may not have offshore bars of sand to gravel.	Direct surface-water connection to the receiving body of water. Ground-water flow-system directly influenced by elevation of receiving body of water.	Plant morphometry adapted to hydraulic stress. Vegetation aligned with shoreline bars and dunes. Vegetation sensitive to wave climate and protective dunes, ridges, bars, and points. Plant species preferring inorganic substrates. Stray estuarine fauna. Biota tolerant of ice action.	Strongly influenced by constituents of the receiving body of water. Low turbidity. Vegetation may isolate nearshore water from mixing with the receiving body of water.
Drowned River 	Variable inorganic substrate (clay to gravel). Variable thickness of organic substrate. Low to moderate wave climate. Low to moderate rate of sediment supply from coast and river.	Direct surface-water connection to river and the receiving body of water. Ground-water flow-system influenced by elevation of the receiving body of water and the river. Many local flow systems. Seiches transmitted upstream.	Plants and animals of riverine, lagoonal, and coastal habitats. Mud-flat annuals, and plants preferring organic sediments. Warm-water fish. Biota tolerant of flooding and high turbidity.	Upstream-downstream gradient in water constituents caused by seiches mixing of river water with water from the receiving body of water and reversal of currents. Variable turbidity.
Protected 	Uniform inorganic substrate (sand to gravel). Thick organic substrate. High rate of sediment supply to shoreline.	May or may not have a surface-water connection to receiving body of water. Ground-water flow-system may or may not be influenced by the elevation of the receiving body of water. Many local flow systems.	Peatland vegetation is often present in northern areas. Ridges and swales show successional patterns. Warm-water fish in lagoons. Plants preferring organic substrates.	Organic matter may dominate water chemistry if limited riverine inflow. High water temperatures in summer. Ground-water seepage may cause temeprature gradients. Low turbidity. Ground water may dominate chemistry where inputs are high.

Figure 10. Three main types of coastal wetland geomorphology: open, drowned river mouth, and protected. The specific type of geomorphic feature a marsh is part of has direct effects on the physical hydrological, biological, and chemical characteristics of the marsh. Modified from Keough et al. 1999).

Figure 11. Braddock Bay, an open embayment on the shore of Lake Ontario. Photo courtesy of Doug Wilcox, United States Geological Survey.

Figure 12. Beaver Creek, a drowned river mouth marsh in the Great Lakes. Photo courtesy of Doug Wilcox, United States Geological Survey.

of organic matter, water chemistry, and other physical and biological characteristics as well by altering the flow and retention time of water through the marsh. If the barrier is complete, it may isolate them from tides, seiches, and other water level fluctuations of the receiving body of water. In the Great Lakes, the extent of the barrier can change from year to year with lake level fluctuations, thus changing many of the structural and functional processes within the marsh.

Sampling

Traditional methods for obtaining topographic information in enough detail for plant studies requires detailed field surveys of marshes. Although they provide definitive information of marsh topography for baseline information, field surveys can be costly and time-consuming and, depending on the variability in sedimentation and erosion in the marsh, the expense may not be warranted on a repeated basis. Newer technologies using aerial and satellite remote sensing or hand-held global positioning systems (GPS) may provide information in

Figure 13. South Colwell Pond, a barrier protected marsh on the shores of Lake Ontario. Photo courtesy of Doug Wilcox, United States Geological Survey.

sufficient detail for monitoring purposes. These technologies have been successfully demonstrated in mapping coastal topography (Blomgren 1999; Van de Kraats 1999; Parker et al. 2001; Brock et al. 2002; Ozesmi and Bauer 2002). Other geomorphic features of marshes such as tidal creeks and barrier beach formation can be monitored during site visits or with aerial photography. Aerial photography has the added benefit of creating a comparable physical record of changes in the marsh over time (Weinstein et al. 2001).

HYDROLOGICAL

As long as there is a direct, open connection between a marsh and its receiving body of water, the hydrological characteristics of the marsh will be dominated by the hydrodynamics[23] of the receiving basin, be it a Great Lake, open ocean, or the Gulf of Mexico. This occurs even when the marshes and open water bodies are not directly adjacent to one another. Because of this relationship, marshes are very dynamic places and the specific location of the habitat can move spatially over time. A strong storm surge that brings saltwater upstream coupled with low flushing potential can replace freshwater marshes with brackish and salt marsh habitats or remove marshes entirely. Increases in the water level of the Great Lakes can also push freshwater marsh habitats inland, replacing them with submerged aquatic vegetation (SAV) or open water habitats. During periods of high precipitation in headwater areas coupled with little storm activity at sea or during low water-level periods of Great Lakes, freshwater marshes may expand farther downstream (Zedler et al. 1986; Maynard and Wilcox 1997).

The Role of Climate

The particular species of plants growing in a marsh are ultimately dependent upon climate and can thus be quite variable over time. Vegetation communities in Great Lakes and tidal freshwater marshes are adapted to and dependent upon periodic, natural water level fluctuations (Keddy and Reznicek 1986; Wilcox 1995; Wilcox and Meeker 1995). These water level fluctuations are brought about by changes in long-term climate patterns and short-term freshwater flows (droughts and flooding). In salt and brackish marshes, soil salinity is the mechanism responsible for most changes in vegetation communities[24] (Zedler et al. 1986). Soil salinity is, in turn, dependent upon tidal exchange and upon the climate-related factors of freshwater flows and storm activity. Thus soil salinity can also be highly variable over time (Zedler et al. 1986).

With all of this variability coastal marshes can be extremely stressful environments for plants and animals. In addition to periodic water level fluctuations caused by seiches, tides, storm surges, and differences in soil salinity in coastal areas, marshes are often exposed to the erosive energy of waves and ice (in northern climates). These physical stresses, however, also help to create diversity in the plant and animal communities of marshes (Odum et al. 1984). Therefore, hydrologic characteristics such as tidal regime, hydroperiod, water velocity, water sources, and wave energy are important structural characteristics of marshes that need to be taken into consideration when preparing restoration project goals and monitoring plans (Wilcox et al. 2002).

Tides/Hydroperiod

Tidal regime and hydroperiod refer to the depth, duration, frequency, and timing of inundation. Tidal regime commonly refers to the pattern of these water level fluctuations in ocean and Gulf coast areas. Hydroperiod is commonly used for Great Lake or other freshwater habitats.

[23]Vertical water level fluctuations.

[24]Changes in salt marsh vegetation also occur in relation to changes in sea level but these effects are seen over much longer periods of time Clark, J. S. and W. A. Patterson, III. 1985. The development of a tidal marsh: Upland and oceanic influences. *Ecological Monographs* 55:189-217.

Water level fluctuations vary by region and on daily, seasonal, and on annual/decadal cycles, driven by changes in climate. Tidal regime and hydroperiod are the most important factors in determining the dominant vegetation and habitat found in a given area (Keddy and Reznicek 1986; Chabreck 1988; Wilcox 1995; Wilcox and Meeker 1995; Baldwin et al. 2001). Therefore, they are strongly suggested as parameters to be measured during any restoration monitoring program.

Tides have a variety of effects on coastal marsh vegetation and influence a variety of physiographic, chemical, and biological processes including transport, deposition, and erosion of mineral and organic sediments, flushing of toxins, and controlling sediment salinity, pH, and redox[25] potential (Mitsch and Gosselink 2000). During spring high tides, the entire surface of even the high marsh can be inundated and low marshes are completely submerged for the duration of the tide (Adam 1990). This changes the amount and quality of light available for photosynthesis. Once tides recede, they often leave a coating of sediment on plant leaves that may further limit photosynthesis and productivity if not washed off by rain (Adam 1990). As tides rise and fall, marsh plants are also exposed to the erosive forces of waves action and tidal currents. Well-established vegetation, with a developed system of roots or rhizomes, is usually able to tolerate the extra stress of tidal currents on sediments but the combined stress of high water levels and increased wave action can lead to erosion (Adam 1990). Germinating seedlings and young plants without well-developed root systems are particularly vulnerable to erosion during these times (Adam 1990).

Tidal marshes can be salty, brackish, or fresh depending on the relative inputs of seawater and upland freshwater to them. Freshwater tidal marshes develop where incoming tides prevent the continued flow of freshwater downstream so river flows pile up. Once the tide subsides, downstream flow of freshwater can continue. This phenomena has been noted as far as 80 km (50 miles) inland from the coast (Mitsch and Gosselink 2000) and occurs most readily in areas where there is a diurnal tide greater than 0.5 m, a flat gradient from the ocean inland, and enough precipitation or river flow to maintain salinities below 0.5 ppt (Odum et al. 1984). These conditions are more commonly found along the Atlantic Ocean and Gulf of Mexico than the Pacific coast of the United States (Odum et al. 1984). Seiches are wind-driven water level fluctuations that occur in tidal areas of the Gulf of Mexico, large bays, and other large open bodies of water on the ocean coasts as well as in the non-tidal coastal marshes of the Great Lakes (Wax et al. 1978; Muller and Willis 1983; Herdendorf 1990; Bedford 1992; Trebitz et al. 2002). By temporarily raising and lowering water levels and moving water in and out of marshes, seiches have many of the same characteristics and functions as tides without the regularity (Bedford 1992).

The hydrodynamics of coastal marshes can be divided into three types corresponding to their geographic location: *Tidal - Ocean Coasts, Tidal - Gulf Coast,* and *Non-tidal Great Lakes*. Due to significant regional differences, the type and timing of tides and hydroperiod will be described for each location.

Tidal: ocean coasts

Tides on the ocean coasts can be as large as 3 meters or more (Chabreck 1988 and literature therein). Regional subclasses of tidal ranges can be identified and used to allow practitioner to anticipate conditions they may encounter (Shafer and Yozzo 1998). Tides on the North Atlantic coast (Eastport, Maine to Cape May, New Jersey) experience the largest tidal range (>3 m). Tides in the Mid-Atlantic region (Cape May to Virginia Beach, Virginia) range from 1 to 2 m. While tides in marshes of the South Atlantic coast can be broken into two classes,

[25]Stands for ‘oxidation-reduction’ potential. This influences nutrient cycling and other chemical processes in marsh sediments and will be discussed in greater detail with other chemical characteristics of coastal marshes below.

a microtidal with tides less than 0.5 m and a macrotidal class with tidal ranges between 1 to 2 m depending on characteristics of the estuary. The Pacific coast can be broken into two subclasses. The South Pacific (Baja Peninsula to Cape Mendocino, California) has a tidal range of 1 to 2 m. The North Pacific (Cape Mendocino to southeastern Alaska has moderate (1 – 2 m) to large (> 3 m) tidal ranges. Along the Pacific northwest, daily and semi-daily tides result in two unequal high and low tides per day (Oceanographic Institute of Washington 1977). The highest tides occur in the Pacific northwest in the fall and winter when plants are dormant (Seliskar and Gallagher 1983).

In areas with tides of ~0.7 meters or more (Simpson et al. 1983; Baldwin et al. 2001), two distinct vegetation zones can be found; a high marsh, with saturated soils that may be shallowly inundated for up to 4 hours and a low marsh, inundated for a longer period of time and to a greater depth (Chapman 1960). The transition line between high and low marsh is roughly equal to the elevation of the mean water level. These differences in the depth, duration, and timing of flooding affect not only the plants but other marsh functions such as decomposition, nutrient cycling, and heavy metal retention as well (Simpson et al. 1978; Khan and Brush 1994)[26]. Accurate measurement of basin topography and the elevation and duration of tides must be a part of any pre-restoration planning in order for selection of appropriate plant species for revegetation projects.

Tidal regime will also influence the sampling times and selection of other characteristics to be monitored, to ensure that appropriate comparisons are made. For example, nitrogen levels in tidal freshwater marshes can range from barely detectable levels at low tide to nearly 120 μg per L at high tide (Simpson et al. 1978). Similar patterns have also been found for phosphorus and dissolved oxygen concentrations. If accurate comparisons of nutrient levels in a marsh are to be made over time, then samples will need to be taken at the same point in the tidal pattern and over a range of tidal cycles as well.

Tidal: Gulf of Mexico

The hydrology of marshes along the northern Gulf of Mexico is dominated by rivers in the winter and spring and by shallow tides in the fall (Stern et al. 1986). Seasonal wind patterns are also an important influence on marsh hydrodynamics. This is due to the small tidal range (often < 0.5 m), shallow marsh depth, and low elevation of Gulf coast marshes (Marmer 1954; Stern et al. 1986; Shafer and Yozzo 1998). High Mississippi River flows in the late winter and spring, followed by steady winds from the south and east during the summer (Muller and Willis 1983; Gosselink 1984), raise water levels in the estuaries and marshes (Wax et al. 1978). By late summer, river flows typically subside and in the late fall and early winter winds come predominantly from the north, pushing water out of the coastal marshes (Muller and Willis 1983; Gosselink 1984). Although these patterns are the predicted ideal, actual water level fluctuations in the Gulf of Mexico are heavily influenced by changes in weather patterns and can be quite variable (Gosselink 1984).

Changes in seasonal hydrodynamics are reflected in seasonal changes in nutrient concentration (Stern et al. 1986; Stern et al. 1991), suspended solids within the marshes (Stern et al. 1986), and in vegetation communities (Mitsch and Gosselink 2000). Suspended sediment and nutrient values are highest during high river flows in the winter and spring and decrease in the summer as river flows subside (Hem 1970; Dunne and Leopold 1978). Due to low topographic relief[27] and differences in the timing and frequency of inundation, coastal

[26]See Chapter 2 for a broader discussion of tidal processes.

[27]An exception occurs where natural levees have formed along the bayous. During spring overbank flooding events, heavier sediments drop out as floodwaters leave river channels, forming levees (ridges) parallel to the waterway. These features form definite elevational gradients within coastal Louisiana with high ground adjacent to bayou and low ground on the opposite, marsh side of the ridge.

marshes along the northern Gulf of Mexico do not exhibit the high and low marsh zonation commonly found in coastal marshes along the Atlantic Ocean (Shafer and Yozzo 1998) and are much more diverse. Vegetation species in the area are also commonly adapted to salt and freshwater conditions, making separation of plant communities along a salinity gradient challenging (Shafer and Yozzo 1998).

Non-tidal: Great Lake coastal marshes

Great Lakes coastal marshes are subject to short-term (i.e., daily) and long-term (i.e., annual or decadal) changes in water level. Seiches move sediments, nutrients, and organic material back and forth throughout the marsh-lake system and can mix lake water far into coastal marshes (Figure 14 - Bedford 1992). Particularly strong seiches have even been shown to reverse the flow of connecting channels between the lakes (Derecki and Quinn 1990). Since they are caused by weather patterns, seiches do not occur at regular intervals nor develop to consistent depths, as do lunar tides. Since seiches can stress germinating plants (Fenner 1985; Lenssen et al. 1998; Middleton 1999), water levels need to be monitored to ensure successful plant establishment.

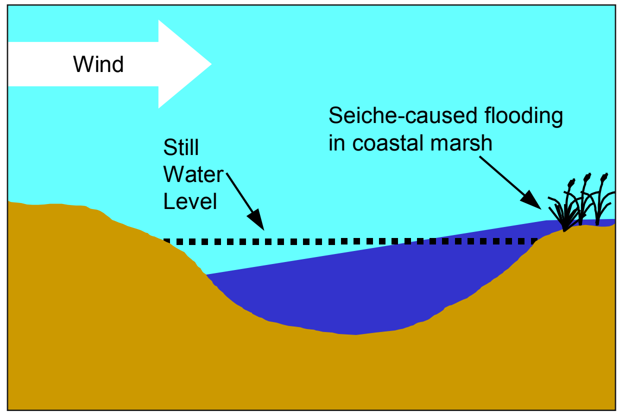


Figure 14. A seiche causing high water levels in a coastal marsh. If the wind were still or blowing the opposite direction, water levels would be lowered in the marsh. Graphic by David H. Merkey, NOAA Great Lakes Environmental Research Lab.

Long-term, climate-driven changes in water-levels of the Great Lakes also have an effect on coastal marshes (Keddy and Reznicek 1986). As Figure 15 illustrates, during years when lake levels are high, marsh vegetation is pushed inland. During low-water years, marsh vegetation expands out toward the lake (Mitsch 1992; Wilcox et al. 2002). Great Lakes coastal marsh communities are composed, almost exclusively, of species tolerant of these variable water level fluctuations (Odum 1988; Maynard and Wilcox 1997). The plant species of coastal marsh seed banks can be extremely diverse, allowing a different plant community to germinate in response to whatever hydrologic conditions exist (Keddy and Reznicek 1982). Restoration project goals and monitoring programs need to account for these long-term changes in lake water levels since an area that was planned and planted as emergent marsh one year might be too dry to maintain emergent vegetation, or completely inundated and dominated with submersed aquatic vegetation, the next.

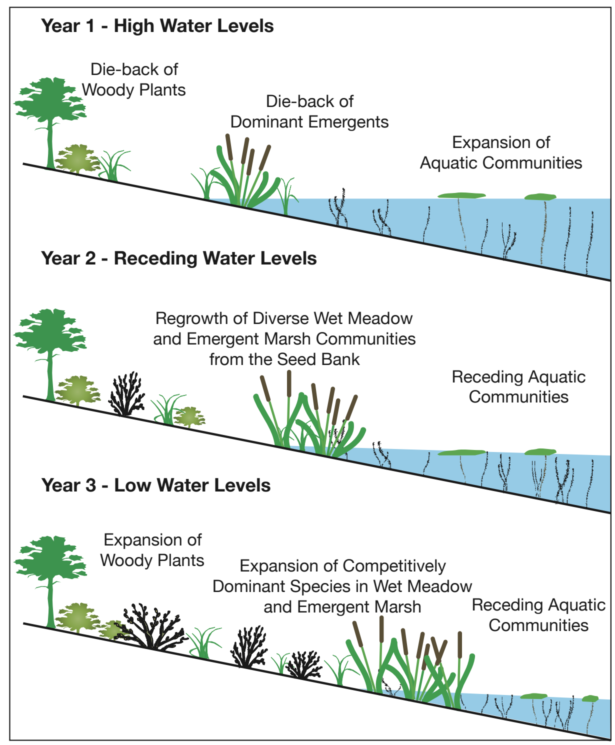


Figure 15. Simplified diagram of water-level fluctuation effects on coastal marsh vegetation communities of the Great Lakes. Modified from Maynard and Wilcox 1997.

Sampling

The patterns in climate and water level described above highlight the need for restoration monitoring to occur for more that a single season or year and in comparison to reference sites[28] whenever available. A monitoring project that only samples water level fluctuations for one year after project implementation might conclude that changes in suspended sediment and nutrient concentrations were a result of restoration activities. These changes may, however, be the result of regional hydrologic patterns unaffected by a particular restoration activity. Only through monitoring for multiple years after restoration implementation, as well as at appropriately selected reference sites can one separate the effects of the restoration activity from the background affect of large-scale, non-restoration related hydrologic patterns.

Tide tables for most of the United States and its protectorates are available from the National Oceanic and Atmospheric Administration (NOAA) at http://tidesonline.nos.noaa.gov/. If the restoration site is reasonably close to a currently monitored site, measuring tidal- or hydroperiod as part of the restoration monitoring may not be necessary (U.S. EPA 2001). The United States Geological Survey (USGS) also operates a series of gaging stations on rivers throughout the United States. Historical and real-time data on hydroperiod and characteristics of the watershed for many of these sites are available at http://water.usgs.gov/waterwatch/. Smaller, coastal rivers may not have a gaging station and may require that restoration practitioners implement another methods to collect this information. In addition, the tidal regime experienced within a marsh is not necessarily the same as that of the open ocean or coasts. The geomorphology of the estuary or individual marsh can magnify or dampen the tidal range. Funnel shaped estuaries tend to magnify the tidal range while restrictions such as barrier beaches can lessen tidal ranges (Adam 1990). An initial set of measurements to compare NOAA- or USGS-recorded tidal regimes with those actually measured in the marsh would dispel most uncertainty in using these less expensive, publicly available data.

A variety of manual and electronic gages are commercially available in different lengths and measurement intervals. Manual gages, also called staff gages, can be attached to metal poles driven into the substrate. Water levels are simply read off the gage during site visits (Figure 16). Electronic gages, however, can be set up and left in place to continually record water level fluctuation, thus recording data that would otherwise be missed by manual sampling alone. Monitoring wells can also be installed for measuring the depth of water below the soil surface (Sprecher 2000). Regardless of the type of equipment used to monitor water level, the precise location of where it is placed should be surveyed or determined with a GPS so that the exact elevation and location is known. This will allow for the construction of detailed maps showing the relationship between plant species and water level patterns.

Care should also be taken when selecting the placement of gauges and other equipment to be left in the field over extended periods of time. Equipment should be placed where it is hidden from the general public to avoid random vandalism but where those taking measurements can still readily find it. The use of a Geographic Positioning System (GPS) could facilitate this in areas without readily available landmarks. Equipment also needs to be protected from damage caused by animals. Large animals such as deer may rub on equipment dislodging it, and even smaller animals can chew on and damage plastic fixtures as well. If damage from animals is a persistent problem, monitoring equipment may need to be fenced off for protection.

[28]See Chapter 15 for a discussion on the selection of reference sites.

Figure 16. An extra length of gage is being added to this pole to measure higher water levels. Photo by David H. Merkey, NOAA Great Lakes Environmental Research Lab.

Water Velocity

The velocity of water moving through a marsh directly affects a variety of coastal marsh functions including primary productivity, erosion protection, provision of benthic habitat, and sediment deposition. The velocity of water, ideally moving as sheet flow, affects the ability of water to carry suspended particles (i.e., sediment) and dissolved nutrients (Margalef 1968). Faster currents have more energy and are able to carry larger sediment loads and particle sizes than slower moving water. As flood- or tidewaters spread out over a marsh, its velocity slows and much of the suspended sediment is deposited on the marsh surface. If wetland substrates are saturated long enough, they become anaerobic and the phosphorus bound to the sediment particles becomes soluble in water[29]. Thus, the soluble phosphorus can then be taken up by plants contributing to primary productivity. The availability of nitrogen, a nutrient soluble under aerobic and anaerobic conditions, is also affected by water velocity. If nitrogen rich water is constantly flushed through a marsh system, then there should always be enough nitrogen available for plant production. If, however, water moves slowly through a marsh, the nitrogen carried in the water might be used up, eventually limiting plant production in the more downstream portions of the marsh. If velocities are too high, marsh sediments may be eroded away. High velocities can also carry large sediment loads that can smother benthic habitats and bury plants, thus destroying marsh habitats instead of enriching them. Moving water also tends to have higher oxygen concentrations than stagnant water (Sparling 1966), this also benefits the plants and animals that live in the marsh.

Renewal rate

An important hydrologic parameter related to velocity is the renewal rate of water moving through a marsh. The renewal rate is a measure of the frequency water is replaced. It is dependent upon water depth, volume, frequency of inundation, and velocity (Margalef 1968). Although extremely important, renewal rate can be difficult to measure. In some cases, a useful surrogate may be the ratio of marsh to watershed area. Water in a large marsh with a small watershed should have a low renewal rate. Low renewal rates foster increased nutrient uptake by plants, biochemical transformation by microbes, and retention of nutrients in and build up of sediment organic matter (Eger 1994; Raisin and Mitchell 1995). Structures related to basin geomorphology, such as barrier beaches, can decrease renewal rates, thus increasing the

[29]Under aerobic (oxygenated) conditions, phosphorus is bound to sediment particles.

uptake and transformation of nutrients while protecting water quality of other coastal areas (Heath 1992).

Monitoring sheet flow and renewal rate before and after a restoration project is critical when setting project goals and determining whether or not they are being achieved. If, for example, the goal of a restoration project is to remove nutrients from the water column to protect downstream water quality, then having a slow water velocity[30] and low renewal rate through the marsh is important. If, on the other hand, the goal of a project is to increase biomass production then a higher flow rate of water through the marsh might be important so that plant productivity is not limited. The goal of preserving downstream water quality by restoring marsh in a high velocity area will have only limited effectiveness.

Sampling

A variety of manual and automated methods are commercially available for use in determining water velocity within and around vegetated areas. Equipment costs range from tens to several hundreds of dollars depending on whether you use low-tech, manual methods that measure flow at one point and time or hi-tech electronic meters that can be left in place for many weeks or months. Careful consideration of the project goals and data required to assess them needs to take place before any equipment is purchased. Local or regional experts can assist in this process and should be consulted as to the precise method and equipment that could or should be used in any given location.

Water Sources

The sources of water to the marsh need to be understood early in the restoration plan development phase. If they are not, then parameters selected for monitoring may be poorly chosen or altogether inappropriate for the monitoring effort. In addition, it may be that factors upstream from the marsh are directly responsible for impacting the health of the marsh. Any restoration effort within the marsh itself that does not account for upstream impacts will have limited value or success. By understanding the sources and timing of water entering the marsh, restoration practitioners will be better able to address impacts to their specific system and select parameters that best track the progress of their restoration effort over time.

Water quality and quantity from various sources can have direct effects on a variety of marsh functions. Water source determines nutrient concentration, toxin load, oxygen saturation, and suspended sediment load (Margalef 1968). The chemical concentration and physical nature of water entering coastal marshes is influenced by:

- Tidal regime (as previously discussed)
- Amount of groundwater entering the system
- Regional climate
- Geology
- Surface water flow, and
- Human inputs (Valiela et al. 1978; Mitsch and Gosselink 2000).

The precise combination of factors delivering water to a marsh dictates what parameters are measured as part of a restoration monitoring project.

Groundwater

The type of substrate groundwater moves through before it enters a stream, river, or coastal marsh and how long it has been in contact with mineral soil determines the type and concentration of minerals dissolved in it (Langmuir 1997; Seelbach and Wiley 1997). Water that passes through limestone or dolomite typically has higher dissolved ion concentrations

[30]Although increased retention time does increase nutrient uptake, retention times that are too long or conditions of persistent non-flowing, stagnant water can be harmful to plants and decrease nutrient uptake.

(e.g., calcium and magnesium) and a more neutral pH (~7.0) than water that has passed through less soluble rock such as granite or sandstone (Langmuir 1997). Groundwater can also provide marshes with significant amounts of soluble nutrients such as nitrate (NO_3) and dissolved organic nitrogen (DON) (Valiela et al. 1978; Page et al. 1995; Tobias et al. 2001).

In brackish and salt marshes, groundwater discharge can also play a significant role in controlling the distribution of soil salinities (Thibodeau et al. 1998; Tobias et al. 2001; Gardner et al. 2002). Groundwater is freshwater and discharge through marsh sediments can moderate pore water salinities (Tobias et al. 2001). Although the relative amount of groundwater discharge to a marsh can change seasonally (Tobias et al. 2001), it is often higher in areas with porous soils and steep topography compared to flatter, less porous areas (Bedient and Huber 1992). Marshes adjacent to upland forests have also been shown to have higher rates of groundwater discharge and lower pore water salinities than those adjacent to other types of land cover (Thibodeau et al. 1998; Gardner et al. 2002). In marshes without strong enough groundwater discharge to flush sediments, evapotranspiration can concentrate salts in the sediment pore water (Thibodeau et al. 1998).

Sampling

Monitoring of groundwater discharge requires the installation of a series of nested piezometers or hydraulic potentiomanometers throughout the marsh and adjacent upland areas (Winter et al. 1998; Sprecher 2000). Once installed, these should be monitored on a regular basis. The exact frequency of which depends upon the goals of the restoration and monitoring effort (Shaffer et al. 2000). This level of effort may not be necessary for many marsh restoration projects, particularly those without pore water salinity problems. Regardless of whether or not groundwater discharge is actually measured, an understanding of the relative quantity of groundwater entering a system and the underlying geology through which water has passed before entering a river or marsh will be important to consider when choosing species for planting and chemical parameters to monitor.

Climate

Changes in weather and climate can alter the quality and quantity of freshwater entering a marsh (Dunton et al. 2001). Increases in precipitation create increases in surface water flow that dilute concentrations of chemicals such as salinity, nutrients, toxics, and other dissolved ions (Valiela et al. 1978; Page et al. 1995). On a seasonal basis, waters that enter freshwater marshes tend to have low chemical concentrations in the spring when precipitation is high and snowmelt (in northern or mountainous areas) is entering rivers. In the summer and fall, precipitation tends to lessen, decreasing the overall amount of water entering marshes and increasing the chemical concentrations (Hem 1970; Dunne and Leopold 1978). During droughts, the concentration of chemicals in the water also increases and tidal areas may experience increased salinity (Wicker 1980). Hypersaline conditions may result that can stress or kill salt marsh plants (Zedler et al. 1986).

Sampling

Regional climate information can be obtained from the National Oceanic and Atmospheric Administration (http://www.noaa.gov/climate.html or http://weather.gov) or other regional climate stations such as airports. If there are no public weather stations in the vicinity of the restoration project an inexpensive climate station or rain gauge can be used to obtain local precipitation and temperature data. Incorporating short-term precipitation data within the longer-term record will help practitioners better understand the results of chemical analyses taken as part of a monitoring program.

Geography

There are several geographic effects that impact the quantity and quality of water entering coastal marshes. Most are not parameters that will be routinely monitored as part of a restoration project but they need to be accounted for in order to accurately interpret collected chemistry data. Watershed size and slope, soil texture, underlying geology, upstream land use, and cover types all have direct impacts on the quantity and quality of water entering from upland sources (Seelbach and Wiley 1997). Watershed size and slope affect the timing and amount of freshwater discharged from upland sources into the marsh (Dunne and Leopold 1978; Newson 1994). Soil texture and underlying bedrock also affect the timing and delivery of water to the marsh as well as the suspended and dissolved content of the water that affects plant communities and species composition (Minc 1998).

Coastal position is another aspect of geography that affects water source. Along coastal areas where significant upwelling occurs, deep-ocean, nutrient-rich water may enter estuaries through gravitational mixing[31]. These nutrients may then be available for use in estuarine tidal salt marshes (Proctor et al. 1980). Nutrient input from the oceans is likely to be greatest during seasonal upwelling events, while nutrient input from upland sources will be greatest during peak seasonal runoff and after large storm events (Seliskar and Gallagher 1983).

Surface water flow

By definition[32], all estuaries have a combination of upland water mixed with water from the receiving body, be it a Great Lake, ocean, or Gulf of Mexico. Upland surface water flows bring to estuaries and their marshes not just freshwater but sediments and nutrients as well (Valiela et al. 1978; Page et al. 1995; Mitsch and Gosselink 2000). In general, high river flows carry large amounts of suspended material such as sediments and low concentrations of dissolved material such as salt and nutrients. Low flows carry smaller suspended loads and higher concentrations of dissolved material (Hem 1970; Dunne and Leopold 1978; Lerberg et al. 2000). These patterns can be reversed, however, in watersheds with large amounts of disturbance such as construction or active agriculture that allow sediments and nutrients to be eroded during storms, carried in a river, and deposited in downstream marshes (Wolman 1967; Omernik 1977). The diversion of freshwater flows through the use of dikes, dams, levees, and shipping canals can alter the amount of these materials deposited into coastal marshes (Gosselink 1984; Ambrose and Meffert 1999; Wilson et al. 2001) directly impacting marsh plant and animal communities (Gosselink 1984; Adams et al. 1992; Wortmann et al. 1998; Montagna et al. 2002).

The amount of surface water flow can be highly variable over time. Seasonal or annual patterns of flooding and drought and individual storms can dramatically alter the chemistry of coastal marshes which in turn influences patterns of plant growth (Zedler et al. 1986; Herdendorf and Krieger 1989; Stern et al. 1991). In a long-term study of the influence of flooding and drought on salt marsh vegetation in southern California, Zedler et al. (1986) found that overall increases in freshwater flow increased the productivity of California cordgrass. Decreases in freshwater flow during droughts increased soil salinities through evapotranspiration and decreased overall productivity (as measured by the total stem lengths per area).

The duration and timing of freshwater flows also influence how increases in productivity are measured (Zedler et al. 1986). Productivity in California cordgrass, as measured by total stem length per area, can be related to the season and length of time soil salinities are lowered, not to the absolute lowest salinity reached. High freshwater flows in the winter and spring, when plants are actively growing, leads to increases

[31]See Chapter 2: Restoration Monitoring of the Water Column for a discussion of gravitational mixing in estuarine systems.

[32]See Volume One for a definition of ‘estuaries’.

in stem length. High freshwater flows later in the growing season are too late to increase individual growth and instead stimulated vegetative reproduction, increasing overall plant (stem) density (Zedler et al. 1986).

Sampling

Information on the quantity and timing of surface water flows can often be obtained from USGS gaging stations located throughout the United States. Real-time data from some stations is available on-line at http://waterdata.usgs.gov/nwis/rt. Data from more remote locations may be obtained by contacting regional USGS offices. Where data from gaging stations are not available, shallow monitoring wells can be outfitted with electronic devices to continuously record water levels. Manual flow meter measurements can also be taken to provide similar data for restoration monitoring efforts.

Human inputs

The particular types of human land use upstream from a marsh can directly affect the timing, delivery, and chemical and physical composition of the water entering a marsh (Marsh 1978) and, therefore, the success of a restoration project. This will also affect the parameters selected for a monitoring effort. Runoff from agricultural land may carry pesticides, herbicides, increased sediment loads, high nutrient concentrations, and bacterial contamination. Runoff from urban landscapes may have elevated temperatures, increased sediment loads, as well as high concentrations of hydrocarbons and other contaminants washed off of parking lots and streets. Sewage treatment plants, for example, may also discharge high concentrations of nutrients and bacteria during overflow events to be carried into downstream marshes. Urban and agricultural land uses also alter hydrology by getting the runoff into streams and rivers faster than forested cover types (Omernick 1977). Forested land also tends to contribute less sediment and nutrients to downstream areas and slows the discharge of water during and after storms. Land use information can often be obtained from local watershed councils or planning agencies. If these resources are not available aerial photography can be used to assess the amount and location of various upstream land uses.

Wave Energy

Wave energy has many impacts (positive and negative) on marsh vegetation. Waves can alter the composition of marsh substrates (Minc 1998) and redistribute reproductive structures such as buds and tubers (Foote and Kadlec 1988). Wave energy can resuspend and move seeds once buried in shallow sediments to new locations where they can germinate (Kelly and Bruns 1975). Thus, seed banks in areas of higher wave energy are not only a source of propagules in the immediate area but to surrounding areas as well (Foote and Kadlec 1988). Excessive amounts of wave energy can, however, damage and uproot marsh plants (Jupp and Spence 1977).

In tidal areas with high and low marsh communities, low marshes are subject to greater wave action and erosion potential than high marshes (Chapman 1960). As a result, marsh sediments exposed to waves such as in low or coastal open marshes typically have very little organic matter (Burton et al. 2002). Any organic matter produced is transported out of the marsh to other adjacent systems, leaving mineral substrates behind (Keddy 1985; Burton et al. 2002). By resuspending and redistributing sediments, altering sediment grain size, and removing most of the organic matter, wave energy effectively changes the sediment nutrient content[33] and primary productivity (Kadlec 1962; Wilson and Keddy 1985).

Terracing of marsh restoration projects, as demonstrated at the Sabine National Wildlife Refuge in coastal Louisiana (Castellanos 2003),

[33]The relationship between sediment grain size and nutrient availability was discussed in a previous section of this chapter.

can be an effective technique for reducing wave energy and protecting adjacent upland areas and the marsh itself (Underwood et al. 1991). Earthen terraces planted with smooth cordgrass were used to disrupt the fetch across open water and mimic natural deltaic sedimentation patterns (Figure 17). The combination of transplanted vegetation along with shallow terracing prevented shoreline erosion by reducing wave energy and creating areas for sediment deposition to occur. The combined effect had a greater affect on reducing wave energy than simply transplanting smooth cordgrass alone (Underwood et al. 1991). The terraces effectively reduced the rate at which open water areas within the marsh were widening due to erosion and allowed for the reestablishment of marsh in an area that had been converted to open water.

Restoration projects using fences constructed of recycled Christmas trees have also been shown, in some cases, to be effective at reducing wave energy, increasing sediment deposition, and enhancing revegetation efforts in desired areas. These structures, however, are very susceptible to damage from storms and heavy boat traffic and need to be monitored to maintain proper functioning condition (Boumans et al. 1997).

Sampling and Measuring Methods

Wave energy can be determined by measuring the height and period of waves. Wave height and period can be directly measured using a wave buoy (Smith 2002). Wave buoys are weather stations that are fixed within the marsh and left in place to record information about tidal currents. Wave height, direction, and period can also be measured using electronic sensors placed on the sediment surface. The goal of monitoring wave energy is to determine the shear stress at the sediment surface. Shear stress is the effect that waves have on marsh sediments. This is more important to coastal marsh processes than wave height alone, as not all surface wave energy affects the sediment (Sanford 1994). A more detailed discussion of different measurement techniques and the effect of wave energy on sediments and plant communities in coastal areas can be found in Chapter 9: Restoration Monitoring of Submerged Aquatic Vegetation, Appendix IV.

CHEMICAL

Sources of water to the marsh determine what nutrients and chemicals are present in sediment

Figure 17. Two of the newly planted earthen terraces can be seen in the fore- and background of this photo. Terraces are only a few feet wide but that is sufficient to reduce wave energy and allow smooth cordgrass to become established, further reducing wave energy in the marsh. Photo by David H. Merkey, NOAA Great Lakes Environmental Research Laboratory.

pore water and in what quantity. In salt and brackish marshes, most plant nutrients such as calcium (Ca), magnesium (Mn), potassium (K), sulfate (SO_4^-) are derived primarily from sea water, while silicon (SiO_2), phosphate (PO_4^-), iron (Fe), Zinc (Zn), and copper (Cu) are derived from upland, freshwater sources. Nitrogen (N) is in approximately equal proportions in seawater and freshwater although considerable local variation may occur (Mitsch and Gosselink 2000). The amount of the other chemicals listed above depends, in part, on physical characteristics of the soil and the relative contribution of salt and freshwater to the marsh.

Tidal freshwater marshes receive the majority of their chemicals from upland river flows (Stern et al. 1991). As freshwater flows vary seasonally, so too does the amount of nutrients carried to marshes by stream flow (Stern et al. 1991; Page et al. 1995). The concentration of nutrients and other chemicals in the sediment can also vary seasonally (Stern et al. 1991; Thompson et al. 1995).

Coastal marshes of the Great Lakes receive their waters from both upland sources and the lakes themselves. The hydrologic, nutrient, and sediment characteristics of Great Lakes coastal marshes are, however, dominated by storms that add pulses of each to marshes over time (Herdendorf and Krieger 1989). As such, concentrations of nutrients and other chemicals in Great Lakes coastal marshes are highly variable (Krieger 1989).

Pore water chemical characteristics considered important structural characteristics of coastal marshes and that may be of use when designing and implementing a monitoring plan include:

- Nutrient concentration
- Salinity
- Dissolved oxygen, and
- Redox potential

Temperature can also affect primary production and plant species composition but is not considered a primary structural characteristic. Extreme heat in shallow areas with black sediments, however, can lead to metabolic stress, reducing primary productivity. Marshes in colder climates or that receive large amounts of cold, groundwater discharge may also experience reduced productivity (Wilcox 1995).

Nutrient Concentration

The emergent plants that dominate marshes obtain the majority of their nutrients from the soil and low nutrient supply can result in reduced plant growth (Valiela and Teal 1974; Paludan and Morris 1999; Tyler et al. 2003). Excess nutrients from industrial, agriculture, wastewater, and other chemical inputs can increase plant growth and may alter the species composition of marsh plant communities (Pennings et al. 2002). The type and concentration of nutrients available for plants to use depends on the sediment grain size, organic content of the soil, and hydrologic characteristics of the marsh such as water source and the duration of flooding.

Nitrogen and phosphorus are the two nutrients that most often control plant growth in coastal marshes. Nitrogen availability often limits plant growth in salt and brackish marshes (Valiela and Teal 1974; Van Wijnen and Bakker 1999; Tyler et al. 2003), whereas freshwater marshes tend to be phosphorus limited (Howarth 1988; Hecky et al. 1993). Phosphorus can, however, also become limiting in salt marshes if there is:

- An overabundance of nitrogen (Cargill and Jefferies 1984)
- A lack of soil organic matter (Van Wijnen and Bakker 1999)
- A relatively low clay[34] content (Froehlick 1988; de Olff et al. 1997; van Wijnen and Bakker 1997), or
- A lack of iron (King et al. 1982)

[34]Particularly gibbsite or other clays with natural oxide coatings. Pure clays such as kaolinite have limited ability to bind with phosphate (Froehlick, P. N. 1988. Kinetic control of dissolved phosphate in natural rivers and estuaries: A primer on the phosphate buffer mechanism. *Limnology and Oceanography* 33:649-668).

Compared to freshwater marshes there is often much more phosphorus available to plants in salt and brackish marshes (Froehlick 1988; Roden and Edmonds 1997). Increased nutrient levels, on the other hand, can increase primary productivity and change (often decrease) species abundance and community structure (Reader 1978).

Nitrogen[35]

Nitrogen is found in a variety of forms in marsh waters and soils: elemental, inorganic, organic, and total *Elemental* nitrogen (N_2) is abundant in the atmosphere but it is not usable by plants. Elemental nitrogen is, however, 'fixed' into *inorganic* forms by humans and certain types of bacteria and blue green algae into nitrate (NO_3^-), nitrite (NO_2^-), and ammonium (NH_4^+). These forms of nitrogen are then usable by plants. Vascular plants and algae take up these forms of nitrogen and use them to make amino acids and other biologically useful compounds. *Organic* nitrogen, as is often measured in marsh sediments and surface waters, is all of the nitrogen that is bound up with organic matter such as leaves, stems, roots, and dead animals or dissolved in the water column. Organic nitrogen plus all of the other forms together are referred to as *total* nitrogen.

The type(s) of nitrogen that is (are) monitored as part of a monitoring program will depend upon the:

- Inputs to the marsh
- Sediment grain size
- Amount of organic matter present in the soil
- Types of bacteria present, and
- Oxidation/reduction state of the sediments (see discussion of *Dissolved Oxygen and Redox* below)

Nitrate (NO_3^-) and nitrite (NO_2^-) are the oxidized forms of N and are found in aerobic sediments and in thin layers around the roots of healthy plants. Nitrate is the more abundant form of the two. Ammonium (NH_4^+) is the reduced form of nitrogen and is often the most abundant form of nitrogen in anaerobic marsh soils after total N. Both NO_3^- and NH_4^+ can be used by vascular plants although NO_3^- is generally the preferred form. Algae can use either of these forms and NO_2^- as well. When a marsh is 'nitrogen limited' at least one of these biologically available forms is lacking even though there may be abundant organic or total nitrogen present.

Phosphorus

Under aerobic conditions phosphorus is bound to iron and organic matter in the soil (Dolan et al. 1981). As sediments become anaerobic with inundation, phosphate (also referred to as orthophosphate, PO_4^-) becomes soluble and is released from the sediment (Mortimer 1941; Mortimer 1942). Phosphate is the only form of phosphorus that can be used by plants. Phosphate dissolved in pore water, together with phosphorus still bound to soil particles and organic matter is referred to as total phosphorus.

The process of phosphate becoming soluble and available to plants can be greatly enhanced by the presence of sulfate (SO_4^-) as sulfate competes with phosphate to bind with iron in the sediment (Roden and Edmonds 1997). Rates of phosphate release from the soil in the presence of sulfate can be five times greater than without it (Caraco et al. 1990). Sulfate is abundant in marine coastal areas but comparatively scarce in freshwater marshes. It is partly through the presence of sulfate that salt marshes are not phosphorous limited as compared to freshwater marshes (Odum 1988; Roden and Edmonds 1997).

Sampling and Monitoring Methods

There are a variety of ways to sample and measure the nutrient content of marsh sediment

[35]Unless otherwise cited, APHA (1999) and Mitsch and Gosselink (2000) have been used to develop this section. They are cited here, instead of liberally throughout the text.

pore waters. Syringes can be used to collect water at very specific depths. Monitoring wells can also be placed at different depths although they are not as precise at sampling at specific depths as syringes. If monitoring wells are used, wells should be within the depth of the rooting zone of marsh plants and pumped clear of water at least twice before the sample is collected to ensure that the water collected for analysis has not been modified by contact with the atmosphere (see discussion on the effects of dissolved oxygen on water chemistry below). A third method to sample pore waters involves the collection of sediment cores. Once taken, cores can be transported to a laboratory for dissection by depth and pore water extracted by centrifuging the sample. Portable labs can be used for quick analysis of nutrients in the field, but if precise measurements are required samples should be analyzed in a controlled laboratory environment. In addition, sandy sediments have greater drainage capacity and likely exhibit a greater variability of nutrient concentrations than clayey soils (Zedler and Lindig-Cisneros 2000). Thus marshes with sandier sediments or marshes subject to greater variability in water sources may require more frequent sampling to determine nutrient concentrations and availabilities.

Salinity

Salinity influences plant zonation and animal use of coastal marshes (Weinstein 1979; Adams et al. 1992; Wortmann et al. 1998; Mitsch and Gosselink 2000; Gelwick et al. 2001; Montagna et al. 2002; Bart and Hartman 2003). Each plant and animal species is adapted to living within a certain range of salinities and will use the various portions of a coastal marsh that have salinities within their specific tolerance (Weinstein 1979). Some plants and animals are tolerant of greater changes in salinity than others (Howes et al. 1986 and literature cited therein). Any change outside of the salinity range to which a plant or animal is adapted will cause stress. High salinity, for example, interferes with ammonium uptake in salt marsh plants, requiring them to expend more energy to incorporate nutrients; energy that could otherwise be spent on growth (Whitney et al. 1981). In response to salinity stresses, plants and animals that cannot migrate will decrease productivity (Weinstein 1979; Howes et al. 1986). Salinity stresses may be so great that plants, or animals that cannot migrate, will die.

The salinity level in salt and brackish marshes ranges from the salinity of the open ocean water (35 ppt) to almost freshwater (0.5 ppt). Occasionally, localized hypersaline conditions (> 35 ppt) can also occur with negative impacts on salt marsh vegetation. Salinities over 100 ppt have been recorded in coastal marshes in Texas during the summer months due to low freshwater inflow and high rates of evaporation (Montagna et al. 2002). Freshwater marshes have salinities below 0.5 ppt and salinity therefore, is typically not an issue in freshwater marshes. The amount of salt in any particular area depends upon the:

- Salinity of the flooding estuarine water
- Tidal elevation
- Climate as measured by:
    - Temperature
    - Evaporation, and
    - Rainfall
- Sediment grain size
- Specific evapotranspiration rate of local plant species (Gallagher 1980), and
- Freshwater inputs from groundwater and surface water (Odum et al. 1984).

Soil salinities in high marshes tend to vary over the growing season. As previously mentioned, seawater brought into the marsh by high spring water levels can get trapped in depressions (pans) between tidal creeks and evaporate away leaving higher concentrations of salt deposited in and on the soil. Soil salinities in low marshes tend to be more uniform throughout the year as these lower marsh areas are more frequently inundated and salts do not get concentrated through evapotranspiration (Beeftink 1965; 1977).

Measuring and Monitoring Methods

A variety of electronic meters for measuring salinity based on conductivity or density of the water sample (APHA 1999) are commercially available and range in price from tens to several hundreds of dollars. When purchasing a salinity meter, practitioners should note that most meters are designed for use within a given range of salinity. Use outside of this range will result in the collection of incorrect data if salinity levels are below that for which the meter is designed or permanent damage to the meter if salinity levels are too high.

Dissolved Oxygen and Redox

Bacteria in the soil preferentially use oxygen during the breakdown of organic matter. Once marsh soils are flooded, any oxygen in the soil is quickly used up. Bacterial communities then use a sequence of other chemicals in the soil as they continue to break down soil organic matter (see Figure 18 under Redox below). Many of these reactions are considered characteristic functions of marshes and will be discussed in a later section of this chapter. A few, however, have direct affects on plant growth and can be considered structural characteristics. These are briefly described here.

The amount of oxygen in marsh soils affects a host of chemical reactions related to nutrient availability, transformation, and uptake as well as the availability of toxic compounds in the soil. While low oxygen levels have been shown to directly limit plant productivity (Howes et al. 1986; Mitsch and Gosselink 2000), a host of associated factors brought about by anaerobic conditions can also limit plant growth. Anaerobic conditions can lead to increased levels of carbon dioxide (CO_2), and increased availability to plants of:

- Manganese (Mg)
- Boron (B)
- Copper (Cu)
- Lead (Pb)
- Mercury (Hg)
- Zinc (Zn), and
- Sulfide (S^{2-})
- Aluminum (Al)

All of these are toxic to plants in high concentrations (Long and Mason 1983 and literature cited therein). Under anaerobic conditions, nitrate (NO_3^-) is also converted to ammonia (NH_4^+). Some plant species have specific requirements for nitrate over other forms of nitrogen and thus suffer under anaerobic conditions (Long and Mason 1983). Marsh plants can, however, transport oxygen down to the roots where it diffuses out to the sediments creating a thin, oxygen-rich layer around roots where ammonia is converted to nitrate and taken up by plants (Howes et al. 1986 and literature cited therein; Chen and Barko 1988). This process is dependent upon the growth of healthy marsh plants. If plants are stressed from other factors, oxygen transport to the sediments may be limited (Howes et al. 1981). The burrowing of benthic invertebrates such as crabs and polychaetes can also increase the oxygen concentration of the sediment, thereby increasing plant productivity (Montague 1982; Bertness 1985).

One of the main problems associated with changing oxygen concentrations in marsh sediments is the formation of sulfide in salt and brackish marshes. Sulfate (SO_4^-) is abundant in seawater. When sulfate comes in contact with anaerobic marsh soils, bacteria reduce it to sulfide. Under anaerobic conditions sulfide bonds with iron to form insoluble pyrites and is thus removed from the water column. If there is not enough iron present hydrogen sulfide (H_2S) is formed. This is extremely toxic to marsh plants (Linthurst 1979). It also inhibits nitrogen cycling and uptake (Mendelssohn 1979; Morris 1980; Howes et al. 1981; King et al. 1982) and thus limits plant productivity. In addition, when tides or water levels recede and expose the soil to the atmosphere, hydrogen sulfide combines with oxygen to form sulfuric acid (H_2SO_4). This dramatically lowers soil pH and has been linked to the death of marsh plants (Cooper 1974; Mitsch and Gosselink 2000) and fish when areas are reflooded and the acid is leached from the soil (Soukup and Portnoy 1986). These conditions are more common in pans between tidal creeks than on creek banks. Creek banks tend to be much more well drained than pans and sulfide is continually washed away (King et al. 1982). In poorly drained pans, these acidic conditions will, however, remain until marsh soils are again inundated and the sulfuric acid is flushed from the system.

Redox

As previously mentioned, when soils are inundated most of the available oxygen is quickly used up as soil microbes break down organic matter. When the available oxygen has been depleted, bacteria need to use different chemicals in place of oxygen to make energy. As each new chemical is used up in the soil different bacterial communities are able to continue the decomposition process by using a different chemical. After oxygen is used up, nitrate is used first, followed in order by magnesium, iron, sulfate, and finally carbon dioxide (Mitsch and Gosselink 2000). Measuring the duration of inundation, however, to infer these chemical concentrations in the soil would require near constant water level measurements. Even when these data are available the rates at which these chemicals are used differs between marshes due to differences in microbial communities, the amount of organic matter, and relative amounts of each of the chemicals listed. By measuring the oxidation-reduction (redox) potential of the marsh soil practitioners get an indirect measure of the duration of inundation and a direct measure of which chemical forms are likely to be present in the soil.

Redox (also referred to as electronic potential or Eh) is measured in millivolts (mV) and can have positive or negative numbers, marsh soils range from +400 to -400. Highly oxygenated, upland soils have Eh values between +700 and +400 mV (Mitsch and Gosselink 2000). As soils are flooded and microbes use up oxygen this value begins to drop. At approximately +400 mV oxygen depletion begins and phosphate (PO_4^-), once attached to sediments, starts to become soluble and is then available for plants to use (Figure 18). At ~250 mV, soil oxygen has been depleted and bacteria begin to convert nitrate (NO_3^-) to ammonium (NH_4^+). At ~200 mV, manganic magnesium (Mn^{4+}) is converted to the manganous form (Mn^{2+}). Once NO_3^+ and Mn^{4+} are used up, ferric iron (Fe^{3+}) is converted to ferrous iron (Fe^{2+}), sulfate (SO_4^{2-}) to sulfide (S^{2-}), and finally carbon dioxide (CO_2) to methane (CH^4) (Mitsch and Gosselink 2000). Many of these chemicals are nutrients that are used directly by plants or that modify the nutrient cycling function of marshes.

As redox potential is related to duration of inundation there is also a relationship with soil depth. Deeper soils are inundated longer and typically have lower Eh values. Redox potential should therefore be measured at various depths within the root zone. Probes to measure redox potential, oxygen concentration, and pH can be purchased from commercial vendors or even made in a lab (Howes et al. 1981; Faulkner et al. 1989; Swerhone et al. 1999).

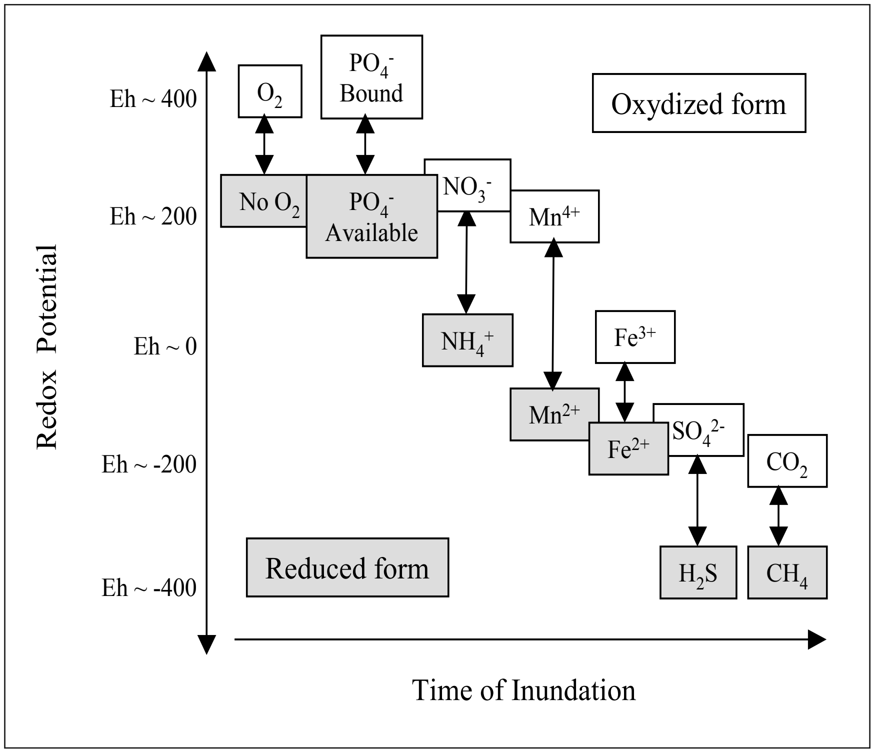


Figure 18. Redox potential of marsh soils changes with the duration of inundation. The longer soils are inundated, the lower the redox potential the soil has as bacteria reduce various chemicals during decomposition of soil organic matter. This process plays an important role in nutrient cycling processes and determines which nutrient forms are available for plants to use. Graphic by David H. Merkey, NOAA Great Lakes Environmental Research Laboratory.

FUNCTIONAL CHARACTERISTICS OF COASTAL MARSHES

The goal of many restoration projects, either directly or indirectly, is to restore function(s) to a degraded area, hopefully to a level comparable with reference standards[36]. Functions are things that marshes or other habitats do, whether or not humans derive any social or economic value from them. Temporary storage of flood and storm water is something that often occurs in marshes. If the marsh happens to be in an area where performance of this function prevents or minimizes flood damage to homes and businesses downstream, then a value can be placed on this function. The information provided in this section is organized around common functions of coastal marshes instead of values since values change from place to place and over time based on the needs and desires of the local community[37]. The functions of coastal marshes include:

Biological
- Contributes to primary productivity
- Provides habitat

Physical
- Alters sedimentation rate
- Reduces erosion potential and wave energy
- Temporary flood and storm water storage

Chemical
- Modified water quality
- Supports nutrient cycling

These and the parameters that can be used to monitor them are discussed below.

BIOLOGICAL

Contributes to Primary Productivity

Coastal marshes are extremely productive ecosystems. Tidal freshwater marshes have been shown to have net primary productivity ranges between 566 to 2,311 g/m^2 per year. Net productivity for brackish marshes are similar at 216 to 2,270 g/m^2 per year and salt marshes typically range between 830 and 2,900 g/m^2 per year[38] (Whigham et al. 1978; Mitsch and Gosselink 2000 and literature cited therein), although values as high as 8,000 g/m^2 per year have also been measured in salt marshes on the southern coastal plain of the United States (Mitsch and Gosselink 2000). These values put marsh productivity on par with tropical rainforests and intensively managed agricultural areas (Teal and Teal 1969; Whigham et al. 1978).

Marsh productivity is largely controlled by water depth, salinity (in tidal areas), and proximity to marsh creeks (Mendelssohn et al. 1982). High marshes also tend to exhibit greater productivity than low marshes. This may be related to the greater amounts of organic matter, higher nutrient concentrations, and differences in hydrology between high and low marshes. In high mashes, since wave and tidal energy is lower, plants can allocate less of their energy to belowground processes such as root production and maintenance and more to aboveground growth. In freshwater areas, for example, broad-leaved, low marsh plants, such

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[36]Sites or conditions that represent project goals (Brinson, M. M. 1993. A hydrogeomorphic classification for wetlandspp. U.S. Army Corps of Engineers Technical Report WRP-DE-4., Army Corps of Engineers, Vicksburg, Mississippi.). See also Chapter 15 of this volume.

[37]For a detailed discussion of the human dimensions values or benefits associated with coastal restoration see Chapter 14.

[38]Net primary productivity estimates for Great Lakes coastal marshes could not be found for comparison but probably vary widely based on differences in latitude and nutrient availability between the lakes as well as inter-annual differences in vegetation communities due to cyclical water level fluctuations.

as arrow arum and pickerelweed, allocate more energy to belowground rhizomes than to above ground stems and leaves. Freshwater, high marshes tend to be dominated by tall, grass-like perennials such as *Phragmites* and *Typha* and annuals that also exhibit greater aboveground productivity compared to the smaller low marsh species (Whigham et al. 1978; Doumele 1981). Marsh age also has an effect on marsh primary production and plant species composition. Younger marshes generally have lower productivity and accumulate organic matter and nutrients while older marshes tend to have higher rates of productivity and export nutrients and organic matter (Tyler et al. 2003).

Algae

In addition to the productivity of vascular plants, algae also contribute a significant portion of the overall marsh productivity, particularly in autumn and winter when vascular plants are dormant and grazers are less abundant (Zedler et al. 1978; Pomeroy et al. 1981; Adam 1990). Algae also decompose quickly due, in part, to their simple cell structure and are eaten more readily by fish and invertebrates than vascular plants (Polderman 1979). Thus, algae can play a significant role in nutrient cycling within the marsh as well (Adam 1990). There is strong evidence that the secondary productivity of coastal marshes is equally, if not more, dependent upon algae as a primary food source than detritus derived from vascular plants (Haines 1977; Thayer et al. 1978; Haines 1979; Haines and Montague 1979; Hackney and Haines 1980)

Detritus

Less than 10% of the production of vascular plants in coastal marshes is actually consumed by herbivores. The vast majority of biomass produced by vascular plants enters the food web through the detrital pathway (Figure 19 - Teal 1962; Pfeiffer and Wiegert 1981). As marsh vegetation dies and becomes incorporated in the marsh sediments, bacteria and fungi begin the process of decomposition. Bacteria, fungi, and the associated detritus are then fed upon by benthic animals such as nematodes and polychaetes (Kruczynski and Ruth 1997). Although these infauna[39] can be spatially and temporally patchy they can be an important food source for juvenile fish and crustaceans (Nixon and Oviatt 1973; Bell and Coull 1978; McTigue and Zimmerman 1998). They may also be sufficiently abundant to provide an important role in the secondary productivity of coastal marshes (Kreeger and Newell 2000).

Although direct grazing on marsh vascular plants is not the dominant way energy from the vascular plants enters the food chain, some species have been shown to consume large quantities of live vegetation. For example, the heavy marsh crab (*Sesarma reticulatum*) has been known to graze tall, creek side stands of cordgrass down to the ground (Kraeuter and Wolf 1974).

Sampling Methods

There are two main strategies for estimating productivity: sample once during the growing season or sample at multiple times throughout the year (Whigham et al. 1978). Sampling plants to estimate primary productivity is usually done during the time of peak growth for each species in the marsh. Unlike salt marshes that can be veritable monocultures, freshwater marshes tend to have very diverse vegetation communities, meaning that no single sample period will adequately capture the overall rate of productivity for the whole marsh for the year. Seasonal patterns of species dominance in freshwater marshes necessitate that multiple sample times be used (Whigham and Simpson 1975; Doumele 1981; Pickett et al. 1989). Perennials dominate in the early spring, die back and are then replaced by a succession of annuals with a few additional perennials that reach peak biomass later in the year (Whigham et al. 1978). Comparing productivity over longer periods of time in highly dynamic systems such as Great Lakes coastal marshes, where the entire

[39]Small invertebrates that live in the top few centimeters of the sediment.

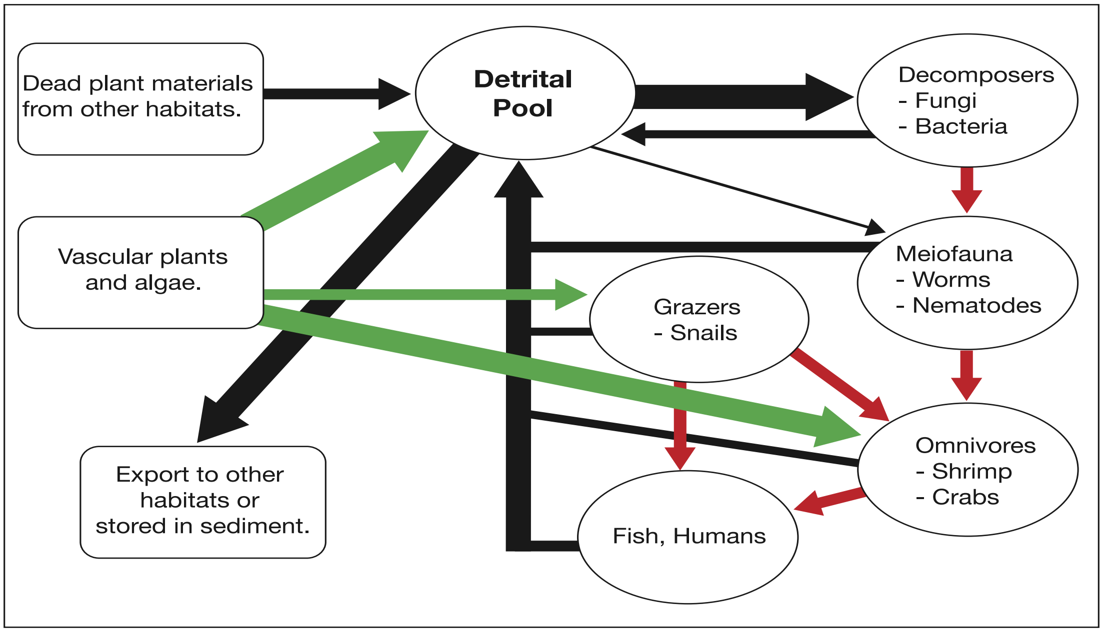


Figure 19. An example of a marsh food web. Green arrows represent the flow of live plant material, black arrows represent dead plant and animal material, red arrows represent predation. Although arrows are sized to represent relative amounts, exact amounts of energy moving from one component to the next will vary among individual areas. Graphic by David H. Merkey, NOAA Great Lakes Environmental Research Laboratory.

vegetation community may differ from year to year, is even more complicated.

A variety of techniques have been explored to measure marsh productivity. These include the simple measurement of plant height, harvesting of live peak standing crop, and more complicated procedures that account for growth, mortality, and decomposition (Keefe 1972; Kirby and Gosselink 1976; Linthurst and Reimold 1978; Shew et al. 1981; Long and Mason 1983; Gibson et al. 1994; Thursby et al. 2002). One common measurement often used is aboveground peak biomass production. Aboveground biomass production is, however, a good measure of just that, aboveground biomass production (de la Cruz 1978; Whigham et al. 1978). It is not a good measure of overall productivity because it does not account for belowground production, herbivory, or leaf mortality during the growing season. Aboveground biomass measurements may, in fact, underestimate overall productivity by 50 to 90 percent (Long and Mason 1983 and literature cited therein). It also leads to difficulties in comparing perennials to annuals and high marshes to low marshes as these vegetation types allocate plant productivity in different ways (i.e., aboveground vs. belowground).

In addition, plants respond to poor conditions by increasing growth and allocating energy to organs that acquire the most strongly limiting resource (Bloom et al. 1985). For example, marsh plants appear to put more energy into root production under unfavorable soil conditions (such as low nutrient availability - Mitsch and Gosselink 2000), perhaps because unfavorable soil conditions require more root surface to obtain the nutrients that are available and service each unit of aboveground biomass (Good et al. 1982). Without accounting for these shifts in relative production and not including belowground production, practitioners may inaccurately evaluate conditions of nutrient limitation.

If primary productivity is related to restoration project goals and is a desirable monitoring parameter, sampling techniques should be coordinated with other biomass monitoring efforts in the region to ensure comparability of data. Regional ecologists and botanists can also help by identifying peak productivity times based on species composition and vegetation dynamics of the restored system. The positives, negatives, and basic assumptions underlying a variety of standard techniques are also reviewed in Long and Mason (1983).

Provides Feeding, Breeding, and Nursery Areas

Coastal marshes provide feeding areas, breeding grounds, and protection for many species of animals such as:

- Fish (Vince et al. 1976; Kneib 1986; Bry 1996)
- Crustaceans and other invertebrates (Heck and Thoman 1981; Christy 1982; Christy 1983; Zimmerman and Minello 1984; Kneib and Knowlton 1995; McTigue and Zimmerman 1998)
- Birds (Weller and Spatcher 1965; Craig and Beal 1992; Prince et al. 1992; Brawley et al. 1998)
- Reptiles (Hurd et al. 1979; Gosselink 1984; Adamus et al. 2001), and
- Mammals (Magwire 1976a; Gosselink 1984; Ford and Grace 1998)

The tremendous diversity of microhabitats provided by marsh vegetation and small changes in topography provide animals with a range of habitats to exploit. The type and number of species, the abundance of individuals, and community composition may be useful parameters in restoration monitoring depending on the goals of the project.

What brings all of these animals into marshes is the high rate of primary and secondary productivity and protection from predators (Moy and Levine 1991 and literature cited therein; Teo and Able 2003b). The abundance of primary producers such as aquatic plants, epiphytes and periphytes, and benthic algae growing in the marsh, and phytoplankton growing in the water column provide animals with food, either directly through grazing or through the detrital food web. Leaf litter from upland sources and other inputs from the adjoining estuary supplement these food sources as well (Kreeger and Newell 2000). All of this organic matter leads to high rates of secondary productivity as various marsh omnivores and carnivores feed upon herbivores and one another.

Various amounts of information are available for the animal communities of salt-, brackish, and freshwater coastal marshes. Some groups such as the invertebrates are particularly well studied in salt marsh communities but not as well understood for freshwater areas. Other types of animals such as amphibians are more abundant in freshwater marshes than in saltwater areas. Thus an equal treatment of all animal types for each habitat across the entire United States and its protectorates is not possible even if it were within the scope of this document. Presented here is an introduction to the available information on the ecological role that some invertebrates, fish, birds, reptiles, amphibians, and mammals play in coastal marshes and how these organisms may be sampled in restoration monitoring. Although examples of how plants, animals, hydrology, water quality, and chemistry are related to one another are provided, practitioners interested in using animal communities to monitor restoration projects are strongly encouraged to follow up the reading of this section with resources in the literature cited and the chapter appendices.

Invertebrates

Invertebrates are a very broad and diverse group making up over 95% of known species of animals (Ruppert et al. 2003). A few of the myriad of possible examples include:

Segmented worms (Phylum Annelida) such as:

- Oligochaetes (Class Oliogchaeta)
- Bristle worms (Class Polychaeta), and

Leaches (Class Hirunidae)
Molluscs (Phylum Mollusca) such as:
- Snails (Class Gastropoda), and
- Oysters and clams (Class Pelecypoda a.k.a. bivalves)

Arthropods (Phyllum Arthropoda) such as:
- Crustaceans (Superclass Crustacea)
  - Amphipods (Order Amphipoda),
  - Shrimp, crabs, and crayfish (Order Decapoda), and
  - Isopods (Order Isopoda), and
- Insects (Class Insecta), such as:
  - Dragonflies and damselflies (Order Odonata)
  - True bugs (Order Hemiptera), and
  - True flies (Order Diptera)
    - Midges (Family Chironomidae)
    - Mosquitoes (Family Culicidae) (Davis et al. 1990)

In all of their forms, invertebrates form the link in the marsh food web between primary producers, decaying organic matter, and vertebrate predators such as fish, birds, and mammals including humans.

The positive and negative aspects of using some types of invertebrates (e.g., insects) in restoration and ecological monitoring of marshes has been covered in a thorough review by Batzer et al.[40] (2001). There are a number of taxonomic groups that respond well to environmental stressors, making them useful indicators of degradation. Invertebrates are also ubiquitous in marsh habitats making comparison from one marsh to another possible. The sampling of marsh invertebrates is also relatively straightforward, although the taxonomy of species can be somewhat difficult for some groups (e.g., chironomids).

Some of the disadvantages of using invertebrates are that species/impact relationships have not been worked out for many species. Abundance from one marsh to another and within-site patchiness can also vary greatly requiring a large sample size for accurate comparisons to be made. Collection of invertebrate data can be time-consuming compared to other types of wetland data such as plants and birds. Since many restoration projects already have tight budgets and monitoring of invertebrates can be time-consuming and expensive, their use should be carefully considered in conjunction with project goals (Brown and Batzer 2001).

Nonetheless, invertebrates can be very useful for indicating the rate at which restored marshes mature as invertebrates exhibit a variety of means for colonizing new habitats (Wissinger 1999). Adult dragon- and damselflies and the true bugs, for example, can fly from one wetland area to another to lay eggs in newly available habitats. Monitoring efforts will likely find these animals quickly after a restoration project has been implemented. Aerial colonizers such as these have been found in abundance only six months after some projects have been completed (Cramer 1998). Other invertebrates that colonize more slowly, such as molluscs (Wissinger et al. 2001), worms, and crustaceans, may take several years to reach abundance and diversity levels similar to reference sites.

Salt and Brackish Marshes

The invertebrate communities of salt marshes are particularly well studied in comparison to freshwater marshes. This is partially due to the economic importance of shellfish fisheries in marine coastal areas. An important difference, however, in the invertebrate communities on Atlantic and Gulf of Mexico coasts compared to Pacific coasts is that macroinvertebrates, particularly snails and crabs, are lacking in Pacific coastal marshes (Seliskar and Gallagher 1983). Infauna are, however, three times more abundant in Pacific coastal marshes compared to those on the east coast (Levin et al. 1998). Three groups of salt marsh invertebrates are discussed below: benthic macroinvertebrates, benthic infauna, and molluscs.

[40] The EPA publication *Methods for evaluating wetland condition: developing an invertebrate index of biological integrity for wetlands*, 57 pp. EPA-822-R-02-019, Office of Water, U.S. Environmental Protection Agency, Washington, D.C. also lists several advantages to using invertebrates in monitoring restoration efforts. This report and other wetland assessment materials can be found at: http://www.epa.gov/waterscience/criteria/wetlands/

Benthic Macroinvertebrates

Shrimp - The largest shellfish fisheries in the United States are for brown shrimp (*Farfantepenaeus aztecus*) and white shrimp (*Litopenaeus setiferus)* in the northern Gulf of Mexico (Zimmerman et al. 2000). Marshes play a more important role in the life cycle of shrimp in the Gulf of Mexico than in Atlantic coastal areas due to the longer duration of flooding Gulf coast marshes experience in the spring and summer giving shrimp greater access to the marsh surface (McTigue and Zimmerman 1998). In estuaries of the Gulf of Mexico, young brown shrimp are found in higher abundance in vegetated areas compared to mudflats or soft bottom habitats (Zimmerman et al. 2000 and literature cited therein). While juvenile white shrimp, are also found in and around coastal marshes, their linkage to the marsh surface is not as strong. Juvenile brown shrimp move into coastal marshes from late February to early April to feed on benthic infauna (particularly polychaetes) while juvenile white shrimp arrive in estuarine areas in late May or June to feed mostly on plant matter (Gosselink 1984; Minello et al. 1994; McTigue and Zimmerman 1998 and literature cited therein). Grass shrimp (*Palaemonetes* spp.) on the other hand, are year-round residents of coastal salt marshes, consuming smaller types of infauna (meiofauna[41]) than do brown shrimp (Bell and Coull 1978; Watts 1992).

Crabs - As with seasonal populations of commercially important shrimp, densities of blue crabs (*Callinectes sapitus*) can be almost ten times higher in vegetated versus non-vegetated habitats (Zimmerman et al. 2000). The high density of shrimps and crabs is due in part to the protection marshes provide from fish and other invertebrate predators (Zimmerman et al. 2000 and literature cited therein). Shrimp and crab are much more abundant near marsh edges than in interior portions of a marsh (Baltz et al. 1993; Minello et al. 1994; Minello and Rozas 2002). Marsh edges have less dense, albeit taller, vegetation than internal marsh areas. This allows invertebrates to burrow during the day and escape predation (Fuss 1964; Minello et al. 1987; Wilson et al. 1987).

Crabs have a special relationship with salt marsh plant communities and the density of crab burrows along the edges of marshes can be quite high. The Atlantic fiddler crab (*Uca pugnax*) is often found only in areas dominated by the tall form of smooth cordgrass as burrows cannot be maintained in soft, unvegetated sediments and root mats in the short form of cordgrass are too dense to burrow through (Bertness 1985). Burrowing by crabs increases plant productivity by increasing aeration of the soil during low tides (Clarke and Hannon 1967; Montague 1982; Bertness 1985). Although crabs are not found equally in all marshes, other burrowing animals may have similar effects on soil characteristics and plant growth (Adam 1990).

Benthic Infauna

Infauna are small invertebrates that burrow and live in the top few centimeters of the sediment (McCann and Levin 1989). These include various types of insect larvae, small crustaceans, and benthic infauna such as nematodes, worms (polychaetes and oligochaetes), and meiofauna, all of which are an important link in the detritus-based food web of coastal marshes (Levin et al. 1998 and literature cited therein). Infauna feed on dead algae and plant material in the soil and are in turn eaten by larger crustaceans and fish (Tenore et al. 1982; McTigue and Zimmerman 1998). Their burrowing through the soil also increases the porosity and aeration of the soils which benefits plants (Levin et al. 1998).

Infauna are dependent upon the presence of a certain amount of organic matter in the soil. As a result, they are often found in lower densities in created marshes with lower amounts of soil organic matter compared to natural reference sites (Matthews and Minello 1994). There are a variety of other factors that also influence

[41]A diverse group of microorganisms approximately 0.042mm and 1mm in size.

the composition and abundance of infaunal communities. These include:

- Sediment grain size
- Soil nutrient content
- Macro-organic matter
- Oxygen availability
- Hydroperiod (as it relates to desiccation)
- Sedimentation rates
- Disturbance, and
- Root density (Broome et al. 2000 and literature cited therein; Zedler and Lindig-Cisneros 2000)

These differences along with differences in marsh age bring about differences in the density, species composition, and diversity of infaunal communities (Goldberg 1996; Levin et al. 1998; Broome et al. 2000 and literature cited therein).

Molluscs

Snails such as the salt marsh snail (*Melampus bidentatus*) and periwinkle snails (*Littoraria irrorata*) graze on algae and are in turn eaten by crabs, fish, and some waterfowl and wading birds. Periwinkle snails often move up the stems of smooth cordgrass in advance of the incoming tide (Hamilton 1977) presumably to avoid predation from blue crabs (Warren 1985). Snail densities are often higher in areas where smooth cordgrass plants are tall or dense or where predators are less abundant (Lewis and Eby 2002).

Tidal Freshwater

The literature on invertebrate communities of tidal freshwater communities has been reviewed by Yozzo and Diaz (1999)[42]. Most of the information has been derived from studies conducted in the northeast and mid-Atlantic regions of the United States and the Columbia River on the west coast. Compared to the salt marshes, the invertebrate communities of tidal freshwater marshes are poorly understood and typically have lower species diversity. One reason for lower diversity is that only those freshwater organisms tolerant of a wide range of environmental conditions and resistant to disturbance and pollutants can dominate tidal areas. Yozzo and Diaz (1999) provide lists of taxa for some areas and include detailed discussions of the different types of organisms that inhabit marsh sediments, the water column, and those that are associated directly with different types of vegetation communities. These lists might be useful to practitioners trying to identify organisms or determine which types of taxa might be most useful for them to monitor depending on restoration project goals.

Non-tidal Freshwater

Invertebrate communities in coastal marshes of the Great Lakes have only recently come under consideration and are not well understood (Krieger 1992). More recent efforts have, however, begun to shed light on these organisms (Cardinale et al. 1997; Burton et al. 2002) and their possible use in biological assessment (Burton and Uzarski 2000; Kashian and Burton 2000; Wilcox et al. 2002). Programs that use invertebrates to monitor Great Lakes marsh restoration must also monitor water level fluctuations and the associated changes in vegetation community. As previously stated, long-term water level fluctuations of the lakes (e.g., inter-annual patterns of highs and lows) have tremendous effects on these plant communities (Keddy and Reznicek 1986). Since it is the plants that provide the habitat for invertebrates (Krieger 1992), changes in vegetation community may have tremendous effects on the invertebrates that can live in a particular area. Any changes in invertebrate community observed after a restoration project may have little to do with the act of restoration itself and may be due to variable lake levels influencing vegetation communities (Wilcox et al. 2002). The use of appropriately chosen reference sites will help elucidate the differences in restoration-induced changes in invertebrate community versus those associated with natural variation and lake level fluctuation.

[42]See summary in Appendix I of this chapter.

Sampling

A variety of methods to sample invertebrate communities are available. Rozas and Minello (1997) have reviewed the literature on methods to estimate nekton, including decapod crustaceans, in shallow habitats and Merritt and Cummins (1996) provide a review of gear that can be used for sampling insects and other smaller invertebrates. A few examples include:

- Corers
- Plankton nets
- Sweep nets
- Drop nets, and
- Small fyke nets

The selection of gear and sample design will depend upon the goals of the monitoring efforts and characteristics of the habitat. For example, a study of five marshes on the Swan Coastal Plain showed that invertebrate community composition collected with sweeps and tows was higher than collected with cores. Cores were not able to catch rapid swimming species such as hemipterans or less abundant species (Cheal et al. 1993). Plankton tows were used mainly when the time available for sorting species was restricted. This is because these samples were sediment-free and generally gave similar results to those obtained with sweeps. Plankton tows, however, cannot be used in areas with dense vegetation present. Sweeps appeared to be the most useful method for a large classification study as they collected more species and resulted in the best discrimination amongst marshes (Cheal et al. 1993). Recommendations on gear and sampling strategy can be found in the resources listed in the second appendix of this chapter, a *Review of Technical Methods Manuals*.

Fish

Coastal marshes provide important spawning, nursery, forage areas, and shelter for a wide variety of fish species (Vince et al. 1976; Keast et al. 1978; Gosselink 1984; Jude and Pappas 1992; Wilcox 1995; Craig and Crowder 2000 and literature cited therein). The particular species of fish present as well as how and when they use the marsh depends, in part, on whether the marsh is tidal (fresh-, brackish, or salt water) or non-tidal (freshwater Great Lake).

Tidal marshes

Tidal marsh communities are made up of a complex and variable mix of freshwater species tolerant of low salinity conditions, estuarine residents, juveniles of anadromous species or adults on spawning runs, marine juveniles using marshes as nursery areas, and marine transients (Odum et al. 1984). Some estuarine species such as killifish (*Fundulus* spp.), bay anchovy (*Anchoa mitichilli*), and the tidewater silverside (*Menida beryllina*) are commonly found foraging in freshwater tidal marshes (McIvor and Odum 1988; McIvor et al. 1989). Other estuarine fishes such as Atlantic croaker (*Micropogonias undulates*) and red drum (*Sciaenops ocellatus*) enter marshes to feed on juvenile brown shrimp (Minello and Zimmerman 1983). Commercially important anadromous fish such as herring (*Alosa* spp.), salmon (*Oncorhynchus* spp.), and striped bass (*Morone saxatilis*) use marshes as spawning and nursery areas before maturing and returning to the open ocean (Congleton and Smith 1976; Levy et al. 1979; Odum 1984; Miller and Simenstad 1997). Three families, cyprinids (minnows, carp, and shiners), centrarchids (sunfish, crappies, and bass), and ictalurids (catfish), spawn and complete their entire life cycle only in freshwater areas (both tidal and non-tidal) (Odum 1984).

The mummichog is an important resident fish of salt marshes on the East (*Fundulus heteroclitus)* and Gulf (*F. grandis)* coasts and is commonly studied for its role in marsh ecosystems (Teal 1962; Nixon and Oviatt 1973). Mummichogs use marshes for feeding, breeding, and refuge from predation (McIvor and Odum 1988; Rozas and Reed 1993; Able and Hagan 2000; Able et al. 2003) and are often found migrating between the marsh surface, marsh creeks, and small pools in response to tidal patterns (Weisberg and Lotrich 1982; Teo and Able 2003b). Mummichogs and banded killifish (*Fundulus diaphanous*) have been shown to enter marshes with almost empty stomachs on the high tide and leave almost full on the low tide (Rozas et al. 1988). While in the marsh, mummichogs feed on copepods, amphipods, insects, algae, and detritus (Fell et al. 2000). Once they leave the protection of the marsh surface, mummichogs are preyed upon by striped bass (Tupper and Able 2000), Atlantic croaker (Nemerson 2001), and flounder. Thus, this species serves as an important ecological link between the productivity of the marsh surface and commercially important estuarine species.

Non-tidal Marshes

In Great Lakes, northern pike (*Esox lucius*), long nose gar (*Lepisosteus osseus*), and bowfin (*Amia calva*) make extensive use of marsh habitats for feeding and spawning. Other species such as gizzard shad (*Dorosoma cepedianum*), carp (*Cyprinus carpio*), suckers (*Catostomus* spp.), and perch (*Perca* spp.) can be found seasonally in abundance in coastal wetlands (Jude and Pappas 1992). Though these species are not strictly dependent on coastal marsh habitats, the high productivity of freshwater marshes makes them efficient places to forage (Herdendorf 1992).

Seasonality

There is a strong seasonal component to fish use of coastal marshes, particularly in tidal areas. Anadromous and semi-anadromous fishes spawn early and their young begin using the marsh as a nursery area in the spring. Winter-spawning marine fishes also use freshwater marshes as nursery areas at this time. Later in the spring and summer as waters warm, freshwater species also begin to spawn in the marsh. Resident killifishes spawn in midsummer. In tidal freshwater marshes of the mid-Atlantic the greatest number of individuals and species are found in the summer and fall (Odum et al. 1984).

Effects of Hydroperiod

Hydroperiod and vegetation communities create opportunities and constraints to fish use of coastal marshes. The duration and depth of flooding are closely linked to marsh elevation and tidal regime (Rozas 1995). Fish can only access high marshes during high water periods or high tides. This means that shorter hydroperiods will limit the ability of estuarine fish to access marsh habitats (Teo and Able 2003b). While fish move into marshes on the high tide to feed and escape predation (Vince et al. 1976; Craig and Crowder 2000 and literature cited therein), patterns of fish movement at low tide often differ depending on the availability of adjacent SAV habitats (Rozas and Odum 1987b). In freshwater areas, where SAV is more likely to be adjacent to marshes, fish and crustaceans move out of the marsh into SAV during low tide (Yozzo and Smith 1998). In salt marshes where dense beds of SAV are not commonly as closely associated with marshes, fish and crustaceans stay in the marsh when possible. They are, however, restricted to deeper pools and channels, making them subject to predation from larger individuals and birds (Yozzo and Smith 1998 and literature cited therein). During neap tides, high marsh areas may not flood at all and are entirely unavailable for fish use (McIvor et al. 1989). These effects of hydrodynamics on fish use of marsh surfaces would also be present in Great Lakes marshes subject to large seiches. In addition, long-term water level fluctuations (e.g., 30 year patterns of highs and lows) that dramatically alter plant communities can have tremendous effects on the fish communities (Wilcox et al. 2002).

Response to Restoration

Fish can quickly colonize restored marshes if provided access through water level fluctuation, creek channels and other structures that provide 'edge' habitat, and the presence of sufficient vegetation to protect them from predation (Williams and Zedler 1999; Zedler and Lindig-Cisneros 2000; Roman et al. 2002). Just one to two years after implementation of a restoration project fish abundance, density, species richness, average size, and community composition can equal that of natural, reference marshes (Able et al. 2000; Roman et al. 2002). This does not mean that full functioning of the marsh has been restored as factors such as fish growth and survival may also need to be evaluated depending on the goals of the restoration project. In addition, the complete transformation of a fish community in restored marshes to one resembling a reference condition does not follow a linear trajectory. Although some utilization can be seen in a relatively short period of time, it may take several years (i.e., >15 years, Minello and Webb 1997) for restored communities to completely reflect those of reference marshes (Dionne et al. 1999).

Sampling

A myriad of techniques and equipment are available for sampling fish populations and each has biases toward sampling or missing different types and sizes of fish (Able and Hagan 2000). If sampling of fish is to be incorporated as part of restoration monitoring very specific questions about the goal of the project and the timing of sampling need to be answered before fieldwork is conducted (Rozas and Minello 1997). Pit traps, for example, cannot provide information on the relative abundance of animals occupying the marsh at low tide (Talbot and Able 1984; Kneib 1986; Yozzo and Smith 1998). They are only effective for sampling fish and invertebrates that stay in high salt marshes during low tide. Pit traps are also not as effective at sampling animals in high freshwater marshes as animals tend to move out of the marsh on low tide into adjacent SAV areas instead of waiting out low water levels in scattered pools and depressions on the marsh surface (Yozzo and Smith 1998).

Should fish be considered as part of a restoration-monitoring program, hydrologic patterns must be taken into consideration during the planning process. Multiple years of sampling may also be necessary to assess the change in fish communities over time with respect to the effect of restoration activities. Additional factors also need to be taken into consideration including:

- Depth of innundation
- Temperature of the water
- Salinity
- Seasonal shifts in marsh use by different species, and
- Daily behavior patterns

The use of appropriately chosen reference sites may also help differentiate between restoration-induced changes in fish communities and those associated with natural variation due to water level fluctuation, changes in vegetation community, or timing of sampling. Rozas and Minello (1997) provide an extensive review of sampling designs and gear suitable for sampling fish in marsh habitats. Additional resources may be found in *Appendix II: Review of Technical Methods Manuals*.

Birds

Coastal marshes are used for feeding, breeding, roosting, and resting by resident and migrating waterfowl, wading birds, shore birds, gulls and terns, raptors, and perching birds (Gosselink 1984; Odum et al. 1984; Herdendorf 1992). Wading birds such as herons (*Ardea* spp. and *Butorides* spp.) and bitterns (*Ixobrychus exilis* and *Botaurus lentiginosus*) often nest away from coastal marshes but use them to forage for fish and benthic invertebrates (Gosselink 1984; DuBowy 1996). Snowy egrets (*Egretta thula*), greater and lesser yellowlegs (*Tringa melanoleuca* and *T. flavipes*), glossy ibises (*Plegadis falcinellus*), and least and semipalmated sandpipers (*Calidris minutilla* and *C. pusilla*) frequently forage in and around large open pools within marshes

(Brawley et al. 1998). Rails (*Rallus* spp.) and other shorebirds feed on macroinvertebrates and seeds. Endangered and threatened species[43] such as the bald eagle (*Haliaeetus leucocephalus*) and whooping cranes (*Grus americana*), along with more common birds of prey, also use coastal marshes to hunt and nest. Swallows (Family Hirundinidae), flycatchers (Family Tyrannidae), sparrows, finches (Family Fringillidae), juncos (*Junco* spp.), blackbirds (Family Icteridae), as well as many other songbirds and groundbirds also use coastal marshes, particularly freshwater ones, to feed (Mitsch and Gosselink 2000). Dabbling ducks use coastal marshes in the mid-Atlantic region in fall and winter to forage during migrations. Migrant shorebirds, wading birds, and seabirds also use marshes in spring and summer for breeding (Erwin 1996). Migrating birds, such as the long-billed marsh wren (*Telmatodytes palustris*), use high marsh areas above high tide as breeding grounds and feed extensively on the abundant food supplies available in summer and fall in preparation for seasonal migrations (Magwire 1976b; Gadallah and Jefferies 1995). It is partly this diversity that makes birds so useful in monitoring marsh habitats.

The density and species richness of bird populations in coastal marshes is dependent upon an adequate supply of water (Capen and Low 1980), the interspersion of vegetation and open water (Weller and Spatcher 1965), and a diversity of vertical structure brought about by a diversity of vegetation types (Craig and Beal 1992). Up to 90% of all bird species of eastern North America have been observed in coastal marshes of the Gulf of Mexico (Lowery and Newman 1954) and upwards of 280 species use freshwater marshes at some point in their lifecycle (Odum et al. 1984). Dabbling ducks and migratory geese[44] seek out tidal marshes during migrations to feed on the abundant seeds of annual grasses and sedges and upon the rhizomes of perennial marsh plants (Stewart 1962). Waterfowl often use emergent vegetation for cover and nesting and move to adjacent habitats to forage (Prince et al. 1992). Water level fluctuations, characteristic of coastal communities caused either by tides, storms, seiches, or lake level fluctuation, can, however, have serious impacts on waterfowl nesting in marsh habitats either through direct mortality caused by high winds (DuBowy 1996) or drowning of nests during high water periods (Figure 20 - Prince et al. 1992). Waterfowl may prefer the use of diked or isolated inland wetlands for nesting but still use coastal habitats for feeding purposes. In fact, bird diversity may actually be higher in impounded marshes compared to natural marshes. Several bird species, however, such as willets (*Catoptrophorus semipalmatus*), sharptailed sparrow (*Ammodramus caudacutus*), and seaside sparrow (*A. maritimus*) are considered marsh specialists and cannot use impounded habitats. These and other marsh specialists are solely dependent upon salt marshes open to tidal fluctuations for survival (Brawley et al. 1998).

Unlike other groups of animals, waterfowl have been known to graze heavily on marsh vegetation. While many ducks consume only the aboveground portion of marsh plants[45] (Adam 1990), others such as snow geese (*Anser caerulescens*) feed on rhizomes of young grasses and sedges, uprooting large amounts of vegetation in the process (Silby 1981). In some east coast marshes, large flocks of snow geese have been responsible for 'eatouts' in areas up to several square kilometers (Lynch et al. 1947; Smith and Odum 1981). Since the major reproductive mechanism for many marsh plants, such as cordgrass, is through vegetative reproduction of the rhizome, this heavy grazing can severely impact marsh plant communities,

[43]http://endangered.fws.gov/wildlife.html#Species

[44]Resident Canadian geese (*Branta canadensis*) may become a nuisance in marshes by eating newly planted or germinating plants and may need to be controlled.

[45]A notable exception to this generalization is duck potato (*Sagittaria* spp.). Ducks often eat the tubers and rhizomes of this genus.

Figure 20. Although this black bird nest in a Great Lakes marsh is build higher up in vegetation, it is still vulnerable to large changes in water level caused by seiches. Photo by David H. Merkey, NOAA Great Lakes Environmental Research Lab.

efforts to restore them, and the other organisms that depend on coastal marshes.

Measuring and Monitoring Methods

Birds can be one of the easiest types of animals to monitor since they can be measured directly (i.e., counting individuals by sight, sound, or mark and recapture) or through surrogate measures such as the number of nests (Levine and Willard 1990). Aerial surveys and direct counts have been used to estimate bird density and inventory migrant shorebirds (Erwin et al. 1991) and monitor wintering populations (Morrison and Ross 1989). Photographic, video, and sound recording equipment can also be used to build a permanent record of bird usage of an area. Video cameras and aerial photography can also be used to provide estimates of birds as well as a visual record of marsh structural characteristics (Dolbeer et al. 1997). Since many species of birds use marshes solely as foraging areas the amount of time individuals are observed in a marsh can also be used as an indicator of the quality of the habitat and amount of food available.

In 1994, Bird Studies Canada teamed up with Environment Canada and began the Marsh Monitoring Program (MMP). The program has since expanded into the United States and covers areas throughout the Great Lakes basin. The program uses volunteers to assess the health of coastal and inland marshes by monitoring bird and calling amphibian[46] populations and compiles the data together to develop basin-wide trends. The program has tracked the loss of species diversity at the regional scale and has been used to help identify areas where restoration opportunities exist. The protocols used in the MMP could also be used to monitor the progress of restoration projects over time to determine whether or not a restored marsh is providing habitat for marsh dependent birds. The protocols used in the MMP for monitoring birds in coastal marshes can be found on-line at http://www.bsc-eoc.org/mmpbirds.html.

Reptiles and Amphibians

Freshwater reptiles tend to be generalists, not adapted to specific types of freshwater marshes but able to tolerate conditions in a variety of settings (Odum et al. 1984).

[46]Calling amphibians such as frogs are those whose vocalizations can easily be heard. Non-calling amphibians such as salamanders are harder to sample.

Although they are generalists, their presence, absence, or abundance is often noteworthy for restoration monitoring, particularly in the case of endangered species. Amphibians have the added monitoring-related benefit of having a highly permeable skin through which they breathe and transfer water. They are, therefore, likely to be more sensitive to disturbance and contamination than reptiles or other wildlife and useful in restoration or ecological monitoring activities involving contaminated conditions (Weeber and Vallianatos 2000).

Reptiles and amphibians also form an important link in marsh food webs, typically feeding on plants or invertebrates and in turn being fed upon by one another, wading birds, mammals, and fish. Reptiles and especially amphibians are, however, rather rare in salt- compared to freshwater marshes (Gosselink et al. 1979; Zedler 1982), although the diamondback terrapin (*Malaclemys terrapin*) does frequent salt and freshwater tidal marshes along the Atlantic coast to forage for small crabs, snails, ribbed mussels, clams, and fish (Hurd et al. 1979; Montague et al. 1981). Due to the warmer climate, southern portions of the country have greater numbers of reptiles species than northern areas subject to severe winters and sub-freezing temperatures. About 100 reptile species are commonly found in freshwater marshes of the southeast including:

- Water snakes (*Nerodia*)
- Cottonmouths (*Agkistrodon piscivorus*)
- American alligators (*Alligator mississippiensis*), and
- River turtles such as the:
  - Painted turtle (*Chrysemys picta*)
  - River cooter (*Pseudemys concinna*)
  - Florida cooter (*Pseudemys floridana*) (Odum et al. 1984)

Great Lakes coastal marshes also support a variety of snakes and turtles. Herdendorf (1992) compiled a list of 28 species of amphibians and 27 species of reptiles that inhabit the Lake Erie region including the common snapping turtle (*Chelydra serpentina*).

The common snapping turtle has one of the largest distributions of any turtle in North America, from Canada to the Gulf of Mexico, east of the Rocky Mountains (Dillon 1998). Despite this wide range, individual turtles rarely, if ever, leave their home marsh (Froese 1974; Brown et al. 1994). The eggs of adult snappers have also been shown to reflect the amount and type of contaminants that a particular turtle has been exposed to throughout the year (Pagano et al. 1999). Thus, where populations of snapping turtles are abundant enough to support sampling, analysis of turtle eggs can be used to build a long term record of changing levels of contamination in coastal marshes (SOLEC 2003).

Due to seasonal and daily activity cycles, amphibians and reptiles may present a logistical complication to monitoring efforts. Most hibernate in the winter, sometimes at a distance from the marsh they typically use in the summer (Cagle 1942; Cagle 1950; Gibbons 1970; Ernst 1971; Ernst 1976). Daily activity cycles are dependent upon air and water temperature (Cagle 1942; Ernst 1971; Ernst 1976) with some species having both minimum and maximum temperatures required for activity. This highlights the need for monitoring efforts to be repeated over time to ensure that an accurate representation of any change in population or species diversity is captured over time.

When setting project goals and selecting monitoring characteristics for marsh restoration projects it should be noted that reptiles and amphibians typically have a much smaller migratory range than birds or even mammals. If direct seeding of the animals is not a part of a restoration activity and there are no other marshes in the area from which these animals can colonize a restored area, then populations of these animals may take many years to become established if at all.

Sampling

The Marsh Monitoring Program (MMP) has been monitoring bird and calling amphibian populations of coastal and inland marshes in the upper Midwest since 1994 (see section on monitoring birds above). As the ecological monitoring protocols the MMP has developed for birds can be modified for restoration monitoring purposes, so too could the protocols for amphibians. The MMP's simple protocols can be found on-line at http://www.bsc-eoc.org/mmpfrogs.html. Results of ecological monitoring done through the MMP, more detailed descriptions of sampling protocols, and contact information can also be found at http://www.bsc-eoc.org/mmpreport2002.html.

Mammals

Freshwater marshes have higher numbers and diversity of mammals than salt marshes (Seliskar and Gallagher 1983; Gosselink 1984). This is due in part to the lack of freshwater for drinking in salt marsh habitats (Seliskar and Gallagher 1983) with only precipitation, dew, and food juices to provide small mammals with enough freshwater (Magwire 1976a). While some species of mammals that commonly use coastal marshes are also found in upland habitats, such as raccoons (*Procyon lotor*) and white tailed deer (*Odocoileus virginianus*), others are completely dependent on freshwater marsh habitats for food, shelter, and nesting areas. River otters (*Lutra canadensis*), marsh rabbits (*Sylvilagus palustris*), marsh rice rats (*Oryzomys palustris),* mink (*Mustela vison*), nutria, and muskrats (*Ondatra zibenthicus*) may spend their entire lives in marshes (Gosselink 1984; Odum et al. 1984; Mitsch and Gosselink 2000). For additional information on specific species and their use of coastal marshes readers are referred to Odum et al. (1984) who compiled a list of 45 mammal species common to freshwater tidal marshes along the east coast and to Herdendorf (1992) who lists 20 mammal species common to Great Lakes coastal marshes.

Nutria

Herbivores such as nutria and muskrats tend to be much more important (and potentially detrimental) to the structure of plant communities and associated marsh morphology than are predators or other herbivores such as deer and rabbits (Odum et al. 1984). Nutria, an invasive species now common throughout wetlands of the southeastern United States, and muskrats prefer the roots and rhizomes of marsh plants to eating just the leaves (Figure 21). These are the

Figure 21. A nutria in a marsh in southern Louisiana. Photo courtesy of the Louisiana Department of Wildlife and Fisheries.

plant parts that hold marsh substrates in place. When these animals forage for and remove them, sediments can then be easily resuspended and may be washed away by storms or tidal action (Lynch et al. 1947). The aggressive foraging of nutria in particular has been known to severely impact marsh vegetation to such an extent that it may not be able to regenerate naturally (Ford and Grace 1998).

Muskrats

Similar to nutria, when muskrat populations get too high they can 'eat out' marsh vegetation making it harder for the vegetation to re-establish (Weller 1981). When muskrat populations are small, however, their foraging activity is actually beneficial to the overall habitat function of the marsh. By opening gaps in the vegetation, increasing the interspersion of vegetation to open water, and increasing the topographic diversity of the marsh substrate, muskrats increase the diversity of the overall marsh habitat (Weller 1981). The topographic diversity created by muskrat feeding stations creates additional structural diversity to the marsh substrate. This topographic diversity coupled with the control of dominant species and increase in light availability can lead to a greater variety of plant species colonizing a marsh and an increase in plant species diversity. In addition, some types of wildlife can benefit as well. Wading birds can use the open spaces created by muskrats for foraging and waterfowl can use muskrat feeding stations as nesting spots, safe from raccoon predation (Weller 1994).

Restoration efforts in the presence of high herbivore populations may require precautions such as the use of protective tubes around seedlings or fenced enclosures to limit herbivory (Llewellyn and Shaffer 1993; Myers et al. 1995), a technique often used to exclude or reduce impacts of geese. Planted areas should also be monitored regularly to assess the damage caused by herbivores so corrective actions may be taken before too much damage has occurred.

PHYSICAL

Sedimentation

The functional characteristics of sedimentation and methods to monitor sedimentation rates were covered previously with the discussion of sediment as a structural characteristic.

Reduces Erosion Potential and Wave energy

Coastal marshes protect adjacent upland areas from the erosive energy of waves and coastal storms (Möller et al. 2002). Marshes reduce the height and erosive power of waves through a combination of shallow depths causing shoaling and breaking of waves and from frictional losses due to high stem densities (Brampton 1992). Marshes are, in fact, able to reduce wave energy to the extent that little if any erosive energy remains at the landward limit of the wave. This protects shorelines from erosion and allows for the significant reduction in the cost and extent of coastal defenses in areas with healthy marshes (Wayne 1976; Knutson et al. 1982; Leggett and Dixon 1994; King and Lester 1995; Möller et al. 2002). In one study a swath of marsh only 6 meters wide in front of a coastal dike reduced wave energies enough that the dike necessary to protect inland areas from flooding and erosion could be halved in size (6 m tall instead of 12) at a significant reduction in construction and upkeep costs (King and Lester 1995). Several factors influence the ability of marshes to attenuate wave energy. These include meteorological conditions, tidal currents, spatial and seasonal changes in vegetation community, and the viscosity of the substrate (Möller et al. 2002).

Sampling

Sampling methods suitable for monitoring the wave energy affecting coastal marshes was covered in the discussion of waves as a structural characteristic earlier in this chapter.

Temporary Flood and Storm Water Storage

Marshes are transitional areas between permanent open water and uplands and are well adapted to changes in water level. The combination of basin geomorphology, topography, high vegetation stem densities, and interspersion of vegetation with open water contributes to water moving slowly through the marsh as sheet flow. Depending on the cycle of inundation and drydown, marsh sediments can also hold significant amounts of floodwaters. The slowing of water through sheet flow and holding water in the soil temporarily stores flood and storm water, thus helping to reduce flooding in downstream areas. Areas that are prone to flooding could be maintained as marsh so they continue to perform this function, preventing costly insurance payments for flood damage to buildings and agricultural fields in other areas. The function of floodwater storage can be measured by obtaining data on water level fluctuation over short (i.e., hourly) time intervals.

Sampling

Methods suitable for measuring the flood and stormwater storage functions of coastal marshes are covered in the section on the structural characteristic of Tides/Hydroperiod.

CHEMICAL

Coastal marshes perform a variety of chemical functions that help protect estuarine water quality. Marshes retain or transform nutrients, toxic chemicals, and metals (Khan and Brush 1994; Mitsch and Wang 2000; Krieger 2003). They also provide areas for sedimentation to occur, helping to preserve water clarity (Krieger 2003). Many of these functions are dependent upon sedimentation rates and water velocity (Heath 1992 and literature cited therein) but other factors such as the relative age of the marsh are also important (Leendertse et al. 1996; Tyler et al. 2003).

Modifies Water Quality and Supports Nutrient Cycling

Water quality, as measured by nutrient content, temperature, salinity, and the presence of toxic chemicals, has direct effects on primary productivity and species composition of coastal marshes (Weller 1995; Wilcox 1995; Stewart et al. 2000; Lougheed et al. 2001). Coastal marshes in turn modify the quality of water that passes through them (Klopatek 1978; Simpson et al. 1978; Stern et al. 1991; Khan and Brush 1994; Krieger 2003). The ability of individual marshes to retain or transform nutrients and pollutants depends on a variety of factors including:

- Hydrology (residence time and water depth)
- Sediment grain size
- Percent organic matter in the sediment
- Resident microbial community, and
- Age of the marsh (Heath 1992 and literature cited therein)

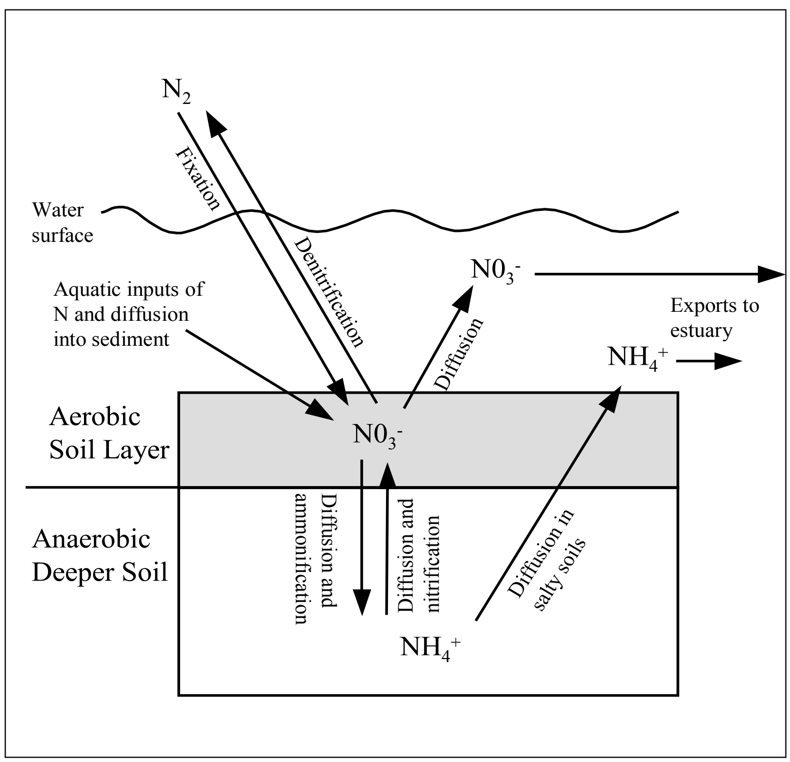
In a comparison of inland marshes with coastal marshes Heath (1992) found that inland marshes (particularly depressional marshes) are generally better at serving as nutrient sinks (Richardson 1989). This is primarily due to longer retention time of water. As water stays in a marsh soluble and reactive forms of N and P are taken up by plants, bound to sediments and organic matter, or converted into inactive forms before being released to receiving bodies of water or dissipated into the atmosphere (Heath 1992 and literature cited therein). Coastal marshes, on the other hand, typically have much shorter retention times and different hydrodynamics than inland wetlands (Heath 1992). They therefore are not as good at permanently retaining nutrients as inland marshes but often have higher productivity rates due to the constant inflow of new nutrients. Although they do not typically act as long-term sinks for nutrients, coastal wetlands are good transformers of nutrients (Simpson et al. 1978; Whigham et al. 1989), particularly of nitrogen (Teal 1986).

Supports nitrogen cycling

Nitrogen enters coastal marshes through a variety of means and forms. Elemental nitrogen (N_2) from the atmosphere can be fixed by cyanobacteria[47] into forms usable by plants. The amount that this process contributes to marsh nutrient pools varies by season (Whitney et al. 1981) but is generally believed to be a very small part (< 10%) of the total nitrogen inputs to coastal marshes (Wickstrom 1988). The vast majority of nitrogen available to marsh plants comes from a combination of nitrate (NO_3^-) and ammonium (NH_4^+) in the groundwater, in river flows, and from the associated estuary (Bedford 1992; Page et al. 1995; Staver and Brinsfield 1996; Brock 2001). Nitrate is more abundant in oxygenated surface waters and shallow groundwater while ammonium concentrations tend to be higher in oxygen-poor sources such as deeper groundwater, particularly when there is also dissolved carbon present to act as an energy source for bacteria that convert nitrate into ammonium. Organic nitrogen can also enter marshes through surface water inputs but is not readily available for uptake by plants.

Once nitrate enters marsh soils, it is quickly taken up by plants for growth or denitrified by bacteria in the sediment (Barko et al. 1986; Wickstrom 1988). A very simplified diagram of the nitrogen cycle in marsh soils is provided in Figure 22. As plants and animals die and decompose in the anaerobic marsh soils, ammonium is produced (Buchanan and Gibbons 1974). Available ammonium is then assimilated by microbes or released to the surrounding pore water (Hardy and Holsten 1973). In freshwater marshes the ammonium released into the pore water is bound to oxygenated sediments where it is eventually used by other groups of bacteria and converted back into nitrate (Watson et al. 1981). Once converted to nitrate, it is once again available to

Figure 22. Simplified version of the nitrogen cycling function of marshes. Nitrogen (nitrate) enters aerobic marsh sediments where it diffuses into anaerobic sediments and is changed to ammonium by bacteria. Ammonium then diffuses back up to aerobic sediments to repeat the process or, under salty conditions ammonium will diffuse through to the water column for export out to the estuary. A variety of additional cycles involving algal and vascular plant uptake of the different forms of nitrogen vof organic nitrogen to inorganic forms (NO_3^- and NH_4^+) could also be illustrated to add further complexity to the diagram. Graphic by David H. Merkey, NOAA/Great Lakes Environmental Research Laboratory.



[47]Blue-green algae.

plants or converted to elemental nitrogen (N_2) by yet another group of bacteria and released to the atmosphere (Jeter and Ingraham 1981).

In the sediments of salt and brackish marshes ammonium and nitrate are not retained in the sediment for eventual use by bacteria. Due to the influence of salts, sulfide, and other chemicals present in seawater, many of the nutrient cycling functions of freshwater marshes are significantly different than those of salt and brackish marshes (Heath 1992). Salts in the soil prevent ammonia from binding to sediment surfaces (Gardner et al. 1991; Seitzinger et al. 1991). These chemicals instead move from the soil to the water column where they may be transported out of the marsh (Seitzinger 1988). Through this mechanism, nitrate is transformed into ammonium as it passes through the marsh.

Supports phosphorus cycling

The cycling of phosphorus is much less complex than that of nitrogen. Phosphorus enters marshes bound to sediments entering the marsh with surface water. As sediments settle out and are buried by additional sediments, they may eventually become anaerobic. As sediments turn anaerobic, phosphate (PO_4^-) becomes soluble and is available for plants to use (Mortimer 1941; Mortimer 1942). As discussed in the structural section above, this process is magnified by the presence of sulfate (King et al. 1982; Roden and Edmonds 1997). In phosphorus-limited freshwater marshes, the high concentration of algae and vascular plants in marshes absorbs most of the available phosphorus so that little makes it out of the marsh where it may impact downstream or estuarine water quality. Most of the available phosphorus is retained within the marsh (Klarer 1988). Marshes that accumulate mineral and organic sediments may also accumulate phosphorus (Khan and Brush 1994). Salt marshes where phosphate is not limiting, however, may actually be a source of phosphorus to the associated estuary (Reimold 1972).

Measuring and Monitoring Methods

Nutrient concentrations of marsh surface and sediment pore water can be monitored directly or indirectly. A common method is to simply go out to the marsh with a sample bottle and bring a sample back to a laboratory for analysis. Short-term increases in nutrient concentration such as those caused by storms may, however, be missed by infrequent manual sampling times. High plant productivity is one surrogate measure of marsh nutrient levels but many other factors also affect macrophyte productivity as well. Phytoplankton type and abundance and chlorophyll concentration can also be good measures of marsh nutrient levels as algae are able to quickly take advantage of high nutrient concentrations and reproduce (Gerloff and Skoog 1954). Many forms of algae are also capable of luxury uptake (Rhee 1973; Tilman and Kilham 1976; Mackerras and Smith 1986). This is the ability to take up excess amounts of phosphorus that the algal cells are not going to immediately use. Monitoring the nutrient concentration within algal cells can be a good indication of recent increases in nutrient concentrations that might be missed by only sampling marsh water.

One of the simplest methods to evaluate the chemistry of water is to measure concentration. The use of simple chemical concentrations of water entering and leaving a marsh with tidal cycles or seiches, however, is inadequate to infer nutrient cycling functions without knowledge of the volume of water being exchanged (Merrill and Cornwell 2000). For example, a high concentration in a small amount of water might represent a much lower total amount of a chemical than a smaller concentration in a large amount of water. That said, calculation of a complete water budget for a marsh can be quite complicated as groundwater exchanges and the influences of storms are difficult to assess (Reed 1989; Orson et al. 1990; Staver and Brinsfield 1996; Murray and Spencer 1997). Intensive, long-term, automated sampling may be required to develop realistic estimates of nutrient cycling and other chemical functions in coastal marshes (Merrill and Cornwell 2000).

Retains Heavy Metals and Other Toxics

Heavy metals and other toxics can have serious detrimental effects on human and wildlife populations. Coastal marshes can protect surface water quality by accumulating and retaining metals dissolved in the water column or attached to sediments (Simpson et al. 1983; Orson et al. 1992). Tidal high marshes with high sediment organic content and high sedimentation rates have greater accumulation and retention of metals than low marshes (Khan and Brush 1994). In areas with high sedimentation rates where accumulated organic material is continually buried, marshes may be important long-term sinks for metals such as lead (Pb), nickel (Ni), copper (Cu), cadmium (Cd), and chromium (Cr), baring any major disturbance (Simpson et al. 1983; Whigham et al. 1989; Orson et al. 1992 and literature cited therein). Sediments of Great Lakes marshes that are rich in silts and clays can retain metals as well (Glooschenko et al. 1981). When present in large quantities, however, metals and toxics can have severe negative impacts on plants and wildlife (de la Cruz 1978) and can potentially work their way up the food chain to impact humans (Wiegert and Pomeroy 1981; Anderson et al. 1998).

The ability of a marsh to act as a sink for nutrients and metals is partly dependent upon the proportion of high marsh to low marsh, as high marshes have higher rates of sedimentation and accumulation of organic matter (Khan and Brush 1994). Due to longer periods of inundation, low marsh soils are more efficient at accumulating nutrients and metals per unit of organic carbon. The amount of sediment and organic matter deposition in high marshes, however, is so much larger compared to low marshes that considerably more nutrients and metals are retained there (Khan and Brush 1994).

Sampling

Monitoring for heavy metals or other toxic compounds such as pcbs and ppbs requires special equipment and may be rather expensive for most restoration efforts. In areas with suspected contamination, however, monitoring of these compounds may be necessary. As with all other chemical characteristics, practitioners should consult the American Public Health Association's *Standard Methods for the Examination of Water & Wastewater* for analytical methods.

PARAMETERS FOR MONITORING STRUCTURAL/FUNCTIONAL CHARACTERISTICS

The matrices of structural and functional characteristics and parameters for restoration monitoring presented below were developed through extensive review of restoration and ecological monitoring-related literature. Additional input was received from recognized experts in the field of coastal marsh ecology. These lists are not exhaustive and are merely intended as a starting point to help restoration practitioners develop monitoring plans for coastal marshes. Additional parameters not in this list, such as those related to human dimensions, may also be appropriate for restoration monitoring efforts. Parameters with closed circle (●) are those that, at the minimum, should be considered in monitoring restoration progress. Parameters with an open circle (❍) may also be monitored depending on specific restoration goals. Information on why these parameters are important for monitoring and how they relate to structural and functional characteristics as well as to one another is found throughout the previous text. Additional information on the ecology of coastal marshes, restoration case studies, and sampling strategies and techniques can be found in Appedix I: *Annotated Bibliography of Coastal Marshes* and Appendix II: *Review of Technical Methods Manuals*.

Parameters to Monitor the Structural Characteristics of Marshes

	Structural Characteristics								
	Biological	**Physical**		**Hydrological**				**Chemical**	
Parameters to Monitor	Habitat created by plants	Sediment grain size	Topography / Bathymetry	Tides / Hydroperiod	Water sources	Current velocity	Wave energy	Nutrient concentration	pH, salinity, toxics, redox, DO[48]
Geographical									
Acreage of habitat types	●								
Biological									
Plants									
Species, composition, and %cover of:									
Herbaceous vascular	●								
Canopy aerial extent and structure	❍								
Interspersion of habitat types	●		●						
Plant height	❍								
Stem density	❍								
Seedling survival	❍								
Hydrological									
Physical									
Shear force at sediment surface						❍	❍		
Sheet flow						❍			
Upstream land use					❍				
Water level fluctuation over time				●	●				
Chemical									
Groundwater indicator chemicals[49]					❍				
Nitrogen and phosphorus								❍	
pH									❍
Salinity (in tidal areas)				●	●				●
Toxics									❍
Soil/Sediment									
Physical									
Basin elevations			●						
Geomorphology (slope, basin cross section)			●	●					
Organic content		●							
Percent sand, silt, and clay		❍							
Sedimentation rate and quality			❍						
Chemical									
Pore water nitrogen and phosphorus								❍	
Pore water salinity (in tidal areas)									❍
Redox potential									❍

[48]Dissolved oxygen.
[49]Calcium and magnesium.

Parameters to Monitor the Functional Characteristics of Marshes

Parameters to Monitor	Biological: Contributes primary production	Supports biomass production	Provides breeding grounds	Provides nursery areas	Provides feeding grounds	Provides refuge from predation	Supports high biodiversity	Supports a complex trophic structure	Provides substrate for attachment	Physical: Affects transport of suspended/dissolved material	Alters turbidity	Reduces erosion potential	Reduces wave energy	Provides temporary floodwater storage	Chemical: Supports nutrient cycling	Modifies chemical water quality
Geographical																
Acreage of habitat	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●
Biological																
Plants																
Species, composition, and % cover of:																
Herbaceous vascular	●	●	●	●	●	●	●	●	●	●	●	●	●		●	●
Invasives			❍	❍	❍	❍	❍	❍								
Interspersion of habitat types		❍	❍	❍	❍	❍	❍	❍		❍	❍	❍	❍	❍		
Plant health (herbivory damage, disease[50])					❍											
Plant height	❍	❍														
Plant weight (above and/or below ground parts)	❍	❍			❍											
Seedling survival[49]												❍				
Stem density				❍		❍		❍	❍	❍	❍	❍	❍			
Animals																
Species, composition, and abundance of:																
Amphibians		❍	❍	❍	❍	❍	❍	❍								
Birds		❍	❍	❍	❍	❍	❍	❍								
Fish		❍	❍	❍	❍	❍	❍	❍								
Invasives		❍		❍	❍	❍	❍									

[50] If the whole community is destroyed by disease or lack of seedling survival, all vegetation-related functions will be impaired.

Parameters to Monitor the Functional Characteristics of Marshes (cont.)

Parameters to Monitor	Biological: Contributes primary production	Supports biomass production	Provides breeding grounds	Provides nursery areas	Provides feeding grounds	Provides refuge from predation	Supports high biodiversity	Supports a complex trophic structure	Provides substrate for attachment	Physical: Affects transport of suspended/dissolved material	Alters turbidity	Reduces erosion potential	Reduces wave energy	Provides temporary floodwater storage	Chemical: Supports nutrient cycling	Modifies chemical water quality
Biological (cont.)																
Animals																
Species, composition, and abundance of:																
Invertebrates		❍	❍	❍	❍	❍	❍	❍								
Mammals		❍	❍	❍	❍	❍	❍	❍								
Reptiles		❍	❍	❍	❍	❍	❍	❍								
Hydrological																
Physical																
Fetch										❍	❍	❍	❍			
PAR	❍	❍								❍	❍					
Seiche disc depth	❍	❍								❍	❍					
Shear force at sediment surface										❍	❍	❍	❍			
Sheet flow										❍	❍	❍		❍	❍	❍
Trash											❍					
Upstream land use	❍	❍								❍	❍					❍
Water level fluctuation over time			●	●	●	●				●	●	●		●	●	
Chemical																
Groundwater indicator chemicals																❍
Nitrogen and phosphorus	❍	❍									❍				❍	❍
pH																❍
Salinity (in tidal areas)							❍									❍
Toxics			❍	❍	❍											❍

Parameters to Monitor the Functionalv Characteristics of Marshes (cont.)

Parameters to Monitor	Biological: Contributes primary production	Biological: Supports biomass production	Biological: Provides breeding grounds	Biological: Provides nursery areas	Biological: Provides feeding grounds	Biological: Provides refuge from predation	Biological: Supports high biodiversity	Biological: Supports a complex trophic structure	Biological: Provides substrate for attachment	Physical: Affects transport of suspended/dissolved material	Physical: Alters turbidity	Physical: Reduces erosion potential	Physical: Reduces wave energy	Physical: Provides temporary floodwater storage	Chemical: Supports nutrient cycling	Chemical: Modifies chemical water quality
Soil/Sediment																
Physical																
Basin elevations			❍	❍	❍	❍	❍		❍	❍				❍		
Geomorphology (slope, basin cross section)			●	●	●	●	●		●	●	●	●		●		●
Sediment grain size (OM[51]/sand/silt/clay/gravel/cobble)		❍							❍	❍	❍	❍	❍		❍	❍
Sedimentation rate and quality							❍			❍	❍	❍				
Chemical																
Organic content in sediment		❍			❍		❍	❍		❍	❍				❍	❍
Pore water nitrogen and phosphorus		❍													❍	❍
Pore water salinity (in tidal areas)							❍									
Redox potential								❍							❍	❍

[51] Organic matter.

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Zedler, J. B., T. Winfeld and D. Mauriello. 1978. Primary productivity in a So. California estuary, pp. 649-662. In Coastal Zone '78. Symposium of Technical, Environmental, Socioeconomic and Regulatory Aspects of Coastal Zone Management. American Society of Civil Engineers, New York.

Zimmerman, R. J. and T. J. Minello. 1984. Densities of *Penaeus aztecus*, *Penaeus setiferus*, and other natant macrofauna in a Texas salt marsh. *Estuaries* 7:421-433.

Zimmerman, R. J., T. J. Minello and L. P. Rozas. 2000. Salt marsh linkages to productivity of penaeid shrimps and blue crabs in the northern Gulf of Mexico, pp. 293-314. In Weinstein, M. P. and D. A. Kreeger (eds.), Concepts and Controversy in Tidal Marsh Ecology. Kluwer Academic Press, Dordrecht, The Netherlands.

APPENDIX I: COASTAL MARSHES ANNOTATED BIBLIOGRAPHY

This annotated bibliography contains summaries of restoration case studies and basic ecological literature. It is designed to provide restoration practitioners with examples of previous restoration projects as well as overviews of papers from the ecological literature that offer more detail than that covered in the associated chapter. Entries are presented from both peer reviewed and grey literature. They were selected through extensive literature and Internet searches as well as input from reviewers. They are not, however, a complete listing of all of the available literature. Entries are arranged alphabetically by author. Wherever possible, web addresses or other contact information has been included in the reference to assist readers in more easily obtaining the original resource. Summaries preceded by the terms '*Author Abstract*' or '*Publisher Introduction*' or similar descriptors were taken directly from their original source. Summaries without such descriptors were written by the authors of the associated chapter. Additional references concerning tidal marsh restoration can be found at http://www.neers.org/main/library/wetbiblio.htm.

Allen, H. H., E. J. Clairain, R. J. Diaz, A. W. Ford, L. F. Junt and B. R. Wells. 1978. Habitat development field investigations-Bolivar Peninsula marsh and upland habitat development site. Galveston: Summary Report. 73. City: United States Army Corps of Engineers Waterways Experiment Station, Vicksburg, MS. Technical Report D-78-15.

This study was conducted to establish salt marsh and upland vegetation on a 2-yr old dredged material deposition site on the Galveston Bays side of Bolivar Peninsula, Texas. Small bulldozers and a rubber tire front-end loader were used for grading and transporting sand. Intertidal planting were in 3 elevation tiers. Various techniques were used for seasonal plantings (e.g., fertilizers and application methods). These techniques are described in this report. Monthly samplings recorded changes in plant height, density, number of stems, number of stressed plants, number of stable plants, the percent foliage cover, vegetative reproduction, number of plants with flowers, seed heads and new growth, and above and below-ground biomass. Before and after the marsh was constructed, fish and aquatic species were sampled. Results showed no significant changes in fish diversity or abundance. In marsh benthos protected by the dike, polychaetes and oligochaetes increased in some species. Bird and mammal usage of the marsh area also increased. Researchers concluded that the salt marsh could be created on dredged material, and could function like a natural marsh.

Allen, H. H. and J. W. Webb, Jr. 1993. Bioengineering methods to establish salt marsh on dredged material. In Laska, S. and A. Puffer (eds.), Coastal Zone 93 in New Orleans, Louisiana, American Society of Civil Engineering, New Orleans, LA.

A low-cost wave stilling device and five transplanting treatments was used to develop a *Spartina alterniflora* marsh along a shoreline in Bolivar Peninsula in the Galveston Bay area, which was exposed to moderate to high wave action. Researchers used two breakwaters, a modified floating tire design (FTB) and a fixed tire design. Transplanting treatments included: single stem, multi-stem clumps, multi-stem clumps wrapped in burlap, multi-stem clumps on 0.5-m intervals in a burlap roll with substrate between, and single stems planted in erosion control fiber mat openings and secured in the substrate. Four test plots of each planting treatment were prepared outside the breakwaters.

Techniques for planting and measuring cover are provided in this publication. Results showed that within two and a half years, there was about 25% cover in three mat plots, two multi-stem plots, and one burlap wrapped multi-stem plot. After four years about 50% of the vegetation cover vanished. *Spartina,* however, dominated at the end of five years.

Barrett, N. E. and W. A. Niering. 1993. Tidal marsh restoration: trends in vegetation change using a geographical information system (GIS). *Restoration Ecology* 1:18-28.

Author Abstract. Adequately evaluating the success of coastal tidal marsh restoration has lagged behind the actual practice of restoring tidally restricted salt marshes. A *Spartina* dominated valley marsh at Barn Island Wildlife Management Area, Stonington, Connecticut, was tidally restricted in 1946 and consequently converted mostly to *Typha angustifolia*. With the re-introduction of tidal flooding in 1978, much of the marsh has reverted to *Spartina alterniflora* . Using a geographical information system (GIS), this study measures restoration success by the extent of geographical similarity between the vegetation of the restored marsh and the pre-impounded marsh. Based on geographical comparisons among different hydrologic states, pre-impounded (1946), impounded (1976), and restored (1988) tidal marsh restoration is a convergent process. Although salt marsh species currently dominate the restored system, the magnitude of actual agreement between the pre-impounded vegetation and that of the restored marsh is only moderate.

Bontje, M. P. 1988. The application of science and engineering to restore a salt marsh, pp. 16-23. In Webb, F. J. Jr. (ed.), Proceedings of the 15th Annual Conference on Wetlands Restoration and Creation, Hillsborough Community College, Tampa, FL.

This report briefly describes the creation of the *Spartina* marsh and compared the use of a 63-acre man-made *S. alterniflora* marsh by birds, mammals and fish, to a 113-acre *Phragmites communis* (reed) marsh. The *Spartina* marsh was established by removing *Phragmites* using glyphosate, excavating and grading the area by digging wide, gently sloping canals. Excavated material was mounded to form berms for shrubs and trees. Once the surface was at a suitable slope and elevation (0.15 -0.45 ft below MHW), *S. alterniflora* was sow into the substrate and established itself within the first growing season. Birds, mammals, fish and water were sampled for 11 months. Bird counts were made monthly by walking or boating through the study site. Mammals were trapped with bait for 24-hrs each month and their tracks and burrows recorded. Fish were collected bimonthly using seine nets. Results showed significantly greater diversity and abundance of birds in *Spartina* marsh compared to *Phragmites* marsh. Muskrat burrows were more densely populated in *Spartina* marsh than the *Phragmites* marsh. Benthos was also significantly greater and more diverse in the *Spartina* marsh compared to *Phragmites* marsh. In adjacent rivers and creeks, fish diversity was low due to poor water quality.

Bontje, M. P. 1991. A successful salt marsh restoration in the New Jersey meadowlands, pp. 5-16. In Webb, F. J., Jr., (ed.), Proceedings of the 18th Annual Conference on Wetlands Restoration and Creation, Hillsborough Community College, Tampa, FL.

This article addresses a salt marsh restoration and creation project conducted in Lyndhurst, NJ. In an old dredged material deposition site, *Phragmites australis* had invaded the site. Researchers eliminated the reed (*P. australis*), decreased the elevation of the site to match regular marsh levels, improved drainage across the site, and planted and established *Spartina alterniflora.* Techniques used included the use of glyphosate to eradicate *Phragmites*, by means of two aerial sprayings and one hand spraying of recruits. The ground was cultivated using backhoes and dump trucks. There were 9 acres of salt marsh, 2 acres of tidal channels and 3 acres of upland berms established. The salt marsh drained about 80% at low tide and during high tide, dike and a central ridge submerged. *Spartina alterniflora* was planted in peat pots on 3-feet centers. Results showed no significant plant mortality and successful growth.

Brawley, A. H., R. S. Warren and R. A. Askins. 1998. Bird use of restoration and reference marshes within the Barn Island Wildlife Management Area, Stonington, Connecticut, USA. *Environmental Management* 22:625-633.

Author Abstract. Tidal marshes have been actively restored in Connecticut for nearly 20 years, but evaluations of these projects are typically based solely on observations of vegetation change. A formerly impounded valley marsh at the Barn Island Wildlife Management Area is a notable exception; previous research at this site has also included assessments of primary productivity, macroinvertebrates, and use by fishes. To determine the effects of marsh restoration on higher trophic levels, we monitored bird use at five sites within the Barn Island complex, including both restoration and reference marshes. Use by summer bird populations within fixed plots was monitored over two years at all sites. Our principal focus was Impoundment One, a previously impounded valley marsh reopened to full tidal exchange in 1982. This restoration site supported a greater abundance of wetland birds than our other sites, indicating that it is at least equivalent to reference marshes within the same system for this ecological function. Moreover, the species richness of birds and their frequency of occurrence at Impoundment One was greater than at 11 other estuarine marshes in southeastern Connecticut surveyed in a related investigation. A second marsh, under restoration for approximately ten years, appears to be developing in a similar fashion. These results complement previous studies on vegetation, macroinvertebrates, and fish use in this system to show that, over time, the reintroduction of tidal flooding can effectively restore important ecological functions to previously impounded tidal marshes.

Brown, S. C. and D. P. Batzer. 2001. Birds, plants, and macroinvertebrates as indicators of restoration success in New York marshes, pp. 237-248. In Rader, R. B., D. P Batzer, and S. A. Wissinger (eds.) Bioassessment and Management of North American Freshwater Wetlands. John Wiley and Sons, New York.

Author Abstract. Ongoing losses of wetlands have resulted in dramatically increased efforts at restoration of wetlands, often in an attempt to increase habitat for wildlife. Assessment of the success of these restoration efforts must often be done with severely limited resources and time. We examined the use of birds, plants, and macroinvertebrates as indicators of the success of wetland restoration in shallow marshes in northern New York. Analysis of the taxonomic richness of macroinvertebrates and species richness of plants and birds indicated that restored and natural reference sites were not significantly different. However, in terms of community composition, birds, plants, and macroinvertebrates each has significant differences between restored and natural wetlands. Richness measures for the different groups did not correlate with each other, so each group must be analyzed separately. Plants were the most sensitive measure, and bird sampling required the least effort. Macroinvertebrates should be analyzed when one of the goals of the restoration project is to restore macroinvertebrate diversity or overall food web structure. In these wetlands, no single group of organisms indicates overall success of restoration.

Broome, S. W., E. D. Seneca and W. W. Woodhouse, Jr. 1986. Long-term growth and development of transplants of the salt marsh grass *Spartina alterniflora. Estuaries* 9:63-74.

Author Abstract. The effect of transplant spacings (45, 60, and 90 cm) on establishment of *S. alterniflora* along an eroding shoreline in North Carolina was evaluated and annual biomass production of the planted marsh was compared to a natural marsh. The 45- and 60-cm spacings were more successful for establishment on marginal sites that were near the lower elevation limits of *S. alterniflora*. The 90-cm spacing was adequate where growing conditions were favorable. Measurements of aboveground growth indicated that there were no differences due to spacing by the end of the second growing season. Differences between spacing treatments in belowground dry weight persisted through three growing seasons. Annual aboveground and belowground standing crop of the transplanted marsh and a nearby natural marsh were compared over a ten-year period. During the early years of development, several characteristics of the transplanted vegetation differed from the natural marsh, but these differences diminished with time.

Broome, S. W., E. D. Seneca and W. W. Woodhouse, Jr. 1988. Tidal salt marsh restoration. *Aquatic Botany* 32:1-22.

This document presents techniques used to restore *S. alterniflora* salt marshes in the southeastern U.S. Transplanting is a common method used for restoring vegetation. Young plants were available from nearby, healthy, natural donor marshes, or from nursery stocks. Researchers stated that planting was best done early in the growing season (April-June) and growth monitored and evaluated every two months. Additional information on techniques for restoration and monitoring are described in this paper. Based on results, the site must be at a suitable elevation between MSL and MHW, and have a gentle slope less than 10%. While salt marshes occurred in a variety of substrates, sandy substrates were not considered the most suitable for grass growth because they are relatively nutrient poor. Authors stated that restoration work and replanting be done whenever monitoring reveals any deficiency. In addition documentation should be made of successes and failures in a restoration project with some rationale of why failures occurred in order to prevent future failures.

Broome, S. W. 1989. Creation and restoration of tidal wetlands of the Southeastern United States, pp. 37-72. In Kusler, J. A. and M. E. Kentula (eds.), Wetland Creation and Restoration: the Status of the Science. Island Press, Washington, D.C.

Presented are tidal salt marsh restoration efforts, marsh functions, and evaluations of the project success. The dominant plant species *Spartina alterniflora* is commonly used in salt marsh restoration efforts. The common method used in *Spartina* restoration is transplanting. The project success will depend on careful planning. Restoration practitioners should make observations, measure and prepare notes of the elevation at the study site, water circulation in and out the area, salinity levels, sunlight, whether it is protected from wave action, pests activities and anthropogenic impacts. Monitoring is needed to track trends in success and failures of a project as well as the technique used. Monitoring techniques of plant species used in this study include: aerial dry weight, below ground dry weight, number of stems, number of flowering stems, height of the plant, and basal area (area occupied by stems at ground level). Further information regarding monitoring and restoration techniques is described in this paper.

Chabreck, R. H. 1989. Creation, restoration and enhancement of marshes of the Northcentral Gulf Coast, pp. 125-142. In Kusler, J. A. and M. E. Kentula (eds.), Wetland Creation and Restoration: the Status of the Science. Island Press, Washington, D.C.

This paper provides information on creating and/or restoring coastal marshes. Factors that are to be considered during the restoration planning process include: location, topography, hydrology, substrate type, salinity, and wind and wave climates are all important factors to be considered in the planning process. Monitoring allows practitioners to determine whether the project is on track as planned and if the level of success accomplished. Site characteristics, dredged material placement, protective measures, plant establishment and growth, and wildlife use are monitored. See article for additional measures that are monitored. Plant establishment is an important factor in marsh creation and restoration because plant abundance and diversity indicate marsh success. Sampling marsh characteristics at the sites is also significant because it provides quantative data needed for research or data analysis of sites. Information collected for data analysis includes number of stems, mean height, number flowering, aboveground biomass and belowground biomass.

Craft, C. 2000. Co-development of wetland soils and benthic invertebrate communities following salt marsh creation. *Wetlands Ecology and Management* 8:197-207.

Author Abstract. The development of wetland soil characteristics and benthic invertebrate communities were evaluated in created *Spartina alterniflora* salt marshes in North Carolina ranging in age from 1 to 25 years old. A combination of measurements from different-age created marshes as well as periodic measurements over time on two marshes were used to (1) document rates of wetland pedogenesis, especially soil organic matter, and, (2) explore relationships between soil and benthic invertebrate community development. Soil macro-organic matter (MOM, the living and dead root and rhizome mat), organic C and N increased and bulk density decreased during the 25 years following marsh establishment. The most dramatic changes in bulk density, MOM, C and N occurred within the upper 10 cm of the soil with lesser changes below this depth. Created marshes were sinks for organic C (90–140 $g \cdot m^{-2} \cdot yr^{-1}$) and N (7–11 $g \cdot m^{-2} \cdot yr^{-1}$) but not for P (0–1 $g \cdot m^{-2} \cdot yr^{-1}$). The density of benthic invertebrates (>250 μm) and subsurface-deposit feeding oligochaetes also increased over time on created salt marshes. Invertebrate and oligochaete density were strongly related to MOM content ($r^2 = 0.83–0.87$) and soil organic C ($r^2 = 0.52–0.82$) and N ($r^2 = 0.62–0.84$). These findings suggest that, in created salt marshes, development of the benthic invertebrate community is tied to marsh soil formation, especially accumulation of organic matter as MOM and soil. Field studies that manipulate the quantity and quality of soil organic matter are needed to elucidate the relationship between salt marsh pedogenesis and benthic invertebrate community development.

Dawe, N. K., G. E. Bradfield, W. S. Boyd, D. E. C. Trethewey and A. N. Zolbrod. 2000. Marsh creation in a northern Pacific estuary: Is thirteen years of monitoring vegetation dynamics enough? *Conservation Ecology* 4:12. http://www.consecol.org/vol4/iss2/art12

Author Abstract. Vegetation changes were monitored over a 13-yr period (1982-1994) in the Campbell River estuary following the development of marshes on four intertidal islands. The marshes were created to mitigate the loss of a natural estuarine marsh resulting from the construction of a dry land log-sorting facility. Plant species coverage was measured along 23 permanent transects in planted and unplanted blocks on the constructed islands, and in naturally occurring low-marsh and mid-to-high marsh reference communities on nearby Nunn's Island. Five dominant species, *Carex lyngbyei, Juncus balticus, Potentilla pacifica, Deschampsia caespitosa*, and *Eleocharis palustris* established successfully and increased in cover in both planted and unplanted areas. The planted, unplanted, and Nunn's Island low-marsh sites had similar total plant cover and species richness by the 13th year. Principal components analysis of the transects through time indicated successful establishment of mid-to-low marsh communities on the constructed islands by the fourth year. Vegetation fluctuations on the constructed islands were greater than in the mid-to-high and low-marsh reference communities on Nunn's Island. Results showed that substrate elevation and island configuration were major influences on the successful establishment and subsequent dynamics of created marsh communities. Aboveground biomass estimates of marshes on the created islands attained those of the reference marshes on Nunn's Island between years six and thirteen. However, *Carex lyngbyei* biomass on the created islands had not reached that of the reference marshes by year 13. Despite the establishment of what appeared to be a productive marsh, with species composition and cover similar to those of the reference marshes on Nunn's Island, vegetation on the created islands was still undergoing changes that, in some cases, were cause for concern. On three of the islands, large areas devoid of vegetation formed between years six and thirteen probably a result of water ponding. Adaptive management has allowed us to modify the island configuration through the creation of channels to drain these sites in an attempt to reverse the vegetation dieback. These changes, occurring even after thirteen years, further underscore the need for caution when considering the trading of existing natural, healthy, productive wetlands for the promise of created marshes that may or may not prove to be equal to the natural systems. Where marsh creation is warranted, we recommend that management of created marshes be adaptive and flexible, including a long-term monitoring program that should continue at least until the annual variation in vegetation of the created marsh is similar to that of natural, nearby systems.

Edwards, K. R. and C. E. Proffitt. 2003. Comparison of wetland structural characteristics between created and natural salt marshes in southwest Louisiana, USA. *Wetlands* 23:344-356.

The use of dredge material is a well-known technique for creating or restoring salt marshes that is expected to become more common along the Gulf of Mexico coast in the future. However, the effectiveness of this restoration method is still questioned. Wetland structural characteristics were compared between four created and three natural salt marshes in southwest Louisiana, USA. The created marshes, formed by the pumping of dredge material into formerly open water areas, represent a chronosequence, ranging in age from 3 to 19 years. Vegetation and soil structural factors were compared to determine whether the created marshes become more similar over time to the natural salt marshes. Vegetation surveys were conducted in 1997, 2000, and 2002 using the line-intercept technique. Site elevations were measured in 2000. Organic matter (OM) was measured in 1996 and 2002, while bulk density and soil particle-size distribution were determined in 2002 only. The natural marshes were dominated by *Spartina alterniflora*, as were the oldest created marshes; these marshes had the lowest mean site elevations (< 30 cm NGVD). The six-year-old created marsh (formed in 1996) was higher in elevation (> 35 cm NGVD) and became dominated by high marsh (*S. patens, Distichlis spicata*) and shrub (*Baccharis halimifolia,* *Iva frutescens*) species. The higher elevation marsh seems to be following a different plant successional trajectory than the other marshes, indicating a relationship between marsh elevation and species composition. The soils in both the created and natural marshes contain high levels of clays (30-65 %), with sand comprising < 1 % of the soil distribution. OM was significantly greater and bulk density significantly lower in two of the natural marshes when compared to the created marshes. The oldest created marsh had significantly greater OM than the younger created marshes, but it may still take several decades before equivalency is reached with the natural marshes. Vegetation structural characteristics in the created marshes take only a few years to become similar to those in the natural marshes, just so long as the marshes are formed at a proper elevation. This agrees with other studies from North Carolina and Texas. However, it will take several decades for the soil characteristics to reach equivalency with the natural marshes, if they ever will.

Erwin, K. L., C. M. Smith, W. R. Cox and R. P. Rutter. 1994. Successful construction of a freshwater herbaceous marsh in south Florida, USA, pp. 493-508. In Mitsch, W. J. (ed.) Global Wetlands: Old World and New. Elsevier, Amsterdam.

In 1987, permits were issued for the construction of a correctional facility on a 113 ha site in south Florida. The area contained a mix of pine flatwoods, isolated herbaceous marshes, mesic oak hammocks, and high wet prairies impacted by clearing and cattle grazing. Local hydrology had been altered on-site by a series of berms and ditches and by off-site agricultural pumping. Due to the loss of wetlands during construction, the Army Corps of Engineers (ACE) required on-site, in-kind, one-to-one mitigation. Pre- and post-construction monitoring was required by the ACE permits on both existing and constructed wetlands. Pre-construction monitoring was concluded in October 1987; post-construction monitoring was done in November 1988, September 1989, and September 1990. Measurements included: rainfall, water levels, vegetation, aquatic macroinvertebrates, fish, and wildlife usage.

Rainfall data were obtained from a local county airport located ~12 km from the study site. Water levels were only taken at times of vegetation or macroinvertebrate sampling. Vegetation sampling was done using transects through each major vegetation zone. Species richness and percent cover were measured visually in permanent quadrats located within the major vegetation zones along each transect. Macroinvertebrates were used to assess the wetland's biologic integrity. Macroinvertebrates and fish were reported qualitatively using a D-frame dip net (1-mm mesh size) swept through vegetation and open water within the vegetation sampling station. Use of the wetlands by wildlife was also reported qualitatively; by visual or audible sightings, animal tracks, droppings, nests, burrows, feathers, hair, bones, and reptile skins noted during site visits.

Constructed wetlands met permit success criteria for percent vegetative cover and lack of invasive species after 28 months. Use of the constructed wetlands by macroinvertebrates, fish, and other wildlife was comparable to that at reference sites. Qualitative data are cost effective and often used by regulatory agencies; however, directly equating wetland structure and hydroperiod with wildlife values, percent vegetation cover, and species richness is not well documented in the literature. In response to this lack of information, this wetland has since undergone more rigorous, quantitative sampling of the macroinvertebrate and fish communities to improve performance criteria and determine biological integrity.

Faber, P. M. 1991. The Muzzi marsh, Corte Madera, California: long term observations of a restored marsh in San Francisco Bay, pp. 424-438. In Bolton, H.S. (ed.), Coastal Wetlands. American Society of Engineers, New York.

This article addresses observations made of drainage channel formation, sedimentation, and re-vegetation of the 53-ha portion of the Muzzi Marsh at Corte Madera, California, San Francisco Bay. The Muzzi Marsh was a 81-ha natural coastal marsh that was diked in 1959. The marsh dried out afterward, killing all marsh vegetation. In 1976, an additional 28 ha were diked to retain dredged material, but another 53-ha was opened for tidal circulation by breaching the dikes in two areas. *Salicornia virginica* and *Spartina foliosa* rapidly developed from water born seeds produced by the plants growing on the bayside of the dikes and in the 27-ha natural marsh just to the north of the Muzzi marsh. Data indicated that there was constant competition between *S. virginica* and *S. foliosa* along the MHW elevation. Competition was influenced by yearly rainfall. Results showed that in wetter years *S. foliosa* was more dominant at higher elevations, but during drier years *S. virginica* dominated the lower elevations.

Flynn, K. M., I. A. Mendelssohn and B. J. Wilsey. 1999. The effect of water level management on the soils and vegetation of two coastal Louisiana marshes. *Wetlands Ecology and Management* 7:193-218.

Author Abstract. Wetland degradation and loss is the result of a combination of natural causes and anthropogenic activities and is a serious problem in coastal Louisiana, where approximately 80% of the total US coastal wetland loss since the 1930's has occurred. One method currently used to address this wetland loss problem is structural marsh management, which is the use of levees and water control structures to control hydroperiod. The effects of structural marsh management on two managed marshes in Southern Louisiana (Unit 4 of the Rockefeller Wildlife Refuge and the Fina LaTerre Mitigation Bank) were evaluated by comparing the soils and the dominant emergent marsh vegetation (*Spartina patens*) of the two managed marshes with those of two nearby unmanaged marshes. Soil redox potential, water depth, interstitial water sulfide concentration, salinity, NH4-N and elemental concentrations of Na, K, Ca, Mg, P, Fe and Zn were measured four times during 1989 which was a drawdown year. Net and total CO_2 exchange rate, primary productivity, leaf area, stem density, and live, dead and total aboveground biomass were also measured. The managed marsh at Rockefeller had lower water levels, significantly less reduced surface and 15 cm deep soils and significantly lower interstitial sulfide concentrations and salinity levels. Na, K, Mg and Ca concentrations reflected the same pattern as salinity. Live aboveground biomass, primary productivity and leaf area were 3–4 times greater in the managed marsh. This indicates that marsh management improved soil conditions and provided an environment favorable to more vigorous plant growth. The management scheme at Fina LaTerre was also successful at maintaining lower water levels than in the adjacent unmanaged area. However, surface soils were more reduced and interstitial salinity higher, on average, in the managed marsh indicating generally poorer water circulation. Primary productivity was 50% less and stem density, leaf area, net CO_2 and total CO_2 exchange rates were significantly lower in the managed marsh, compared to the nearby reference marsh. Conditions in the managed marsh indicate that the management scheme was not successful at improving soil conditions when compared to those in the adjacent unmanaged marsh. This study indicates that structural marsh management is not the universal answer to problems faced by Louisiana's coastal wetlands, but may be of value in specific situations.

Fowler, B. K., G. R. Hardaway, G. R. Thomas, C. L. Hill, J. E. Frye and N. A.Ibison. 1985. Vegetation growth patterns in planted marshes of the vegetative erosion control project, pp. 110-120. In Webb, F. J., Jr. (ed.), Proceedings of the 12th Annual Conference on Wetlands Restoration and Creation, Hillsborough Community College, Tampa, FL.

The Vegetative Erosion Control Project studied the success of twenty-four marsh plantings in the Chesapeake Bay system in Virginia. Sites selected were under diverse conditions. Seven sites had low wave energy (average fetch exposure < 1.8km), ten sites had medium wave energy (average fetch exposure from 1.8 to 9.2 km), and seven sites had high wave energy (average fetch exposure > 9.2 km). *S. alterniflora* was planted on 0.5-m centers from MHW to below MSL. *S. patens* were planted above *S. alterniflora*, at a few sites. Practitoners placed about 30-ml of Osmocote fertilizer which has a slow release formula in each hole just before planting. Techniques used are discussed in detail in this paper. Based on results, marshes on low energy shorelines were more productive than those on high-energy shorelines; *S. alterniflora* was more productive in the higher intertidal zone than the lower intertidal zone; and stem densities were greater in marsh areas exposed to greater sunlight and located on the leeward side of the marsh. Additional information on techniques used and recommendations to improve successful establishment of fringe marshes are described in this paper.

Garbisch, E. W., Jr. and L. B. Coleman. 1978. Tidal freshwater marsh establishment in Upper Chesapeake Bay: *Pontedaria cordata* and *Pentandra virginica*, pp. 285-298. In Good, R. E., D. F. Whigham, R. L. Simpson and C. G. Jackson, Jr. (eds.), Freshwater wetlands: ecological processes and management potential. Academic Press, San Diego, CA.

Author Abstract. The effects of tidal elevation, substrate type, and fertilization on the establishment of *Peltandra virginica* and *Pontederia cordata* by seedling and transplanting seedling stock has been determined at a freshwater location in the Upper Chesapeake Bay, Maryland.

Germination percentages ranged from 93% to 5% for *Peltandra virginica* and from 20% to 5% for *Pontedaria cordata* with the higher percentages occurring at the high tidal elevations. The percentages of seedlings that survived the study period averaged ~30% for both species, but the surviving seedlings developed poorly. The establishment of either *Peltandra virginica* or *Pontedaria cordata* by seedling is not considered feasible in unsheltered tidal areas.

No transplanted 1.5-month-old seedlings of *Peltandra virginica* survived at the intermediate and low elevations because of wave stress, debris deposition, and animal depredation. Those surviving at the high elevations did not flower or develop much beyond their stage at the time of planting. Because of the low productivity of 1st year *Peltandra virginica* seedlings, their satisfactory establishment in unprotected tidal environments is not promising. Planting 1st year bulbs or 2nd year seedling stock may yield better results.

The survival of the 3-month-old seedling transplants of *Pontedaria cordata* was relatively high at all elevations and in all substrate types. Both the number of flowering stems and the aboveground standing crop values were significantly greater at the lower tidal elevations. Fertilization effected significant increase in productivity, particularly in sand at the high tidal elevation and peat at the low tidal elevation. Seedling transplants of *P. cordata* became satisfactorily established at all tidal elevations. It is estimated that a tidal *P. cordata* marsh exhibiting a 1st-year aboveground standing crop of 1 x 10^3 to 4 x 10^3 kg/ha ca be establishing in the Chesapeake Bay region by planting single seedling transplants on 1- to 0.5-m centers, respectively.

Gulf of Maine Council Habitat Restoration Subcommittee. 2004. Gulf of Maine habitat restoration strategy: Restoring coastal habitat in the Gulf of Maine region, 25 pp., Gulf of Maine Council on the Marine Environment. www.gulfofmaine.org

The Gulf of Maine Restoration Strategy states that habitat restoration is necessary to support aquatic resources in the Gulf of Maine to meet both biological and socioeconomic needs. While restoration projects have already occurred in each of the States or Provinces that share the Gulf of Maine, no formal statement of shared goals or a unified strategy to meet them has been presented. This document lays the groundwork for this by:

- Stating the purpose and scope of regional habitat restoration in the Gulf of Maine
- Identifying habitat types, impacts, and restoration needs, and
- Developing recommendations for enhancing habitat restoration

This report identifies resources of regional significance and promotes habitat restoration that is needed to support the viability of these resources. The strategy presented focuses on four categories of habitats:

(1) Riverine
(2) Intertidal
(3) Subtidal, including nearshore and offshore waters, and
(4) Beaches, sand dunes, and islands

Recommendations provided for the continued success with habitat restoration efforts in the Gulf of Maine include:

- Restore the four coastal marine habitat types identified in this document using a regional strategy to prioritize projects
- Improve our ability to identify habitat restoration sites, focus regional efforts, understand regional trends, and develop effective long-range planning
- Increase development and management capacity in all jurisdictions in the region to make restoration more efficient and effective
- Enhance outreach efforts to federal, state, local governments and the private sector to create a common understanding of the social, economic, and environmental benefits of habitat restoration
- Complete and maintain a database of restoration projects in the region to evaluate progress and ensure accordance with the US National Estuary Restoration Inventory (NERI)
- Refine existing salt marsh monitoring protocols and develop monitoring protocols for other habitats identified in this document

Johnson, G. E., H. L. Diefenderfer, T. J. Berquam, B. D. Ebberts, C. Tortorici and J. D. Wilcox. 2004. Plan for research, monitoring, and evaluation of salmon in the Columbia River Estuary, 133 pp., Pacific Northwest National Laboratory, Richland, WA.

Author Overview. The purpose of this *plan* for research, monitoring, and evaluation (RME) in the Columbia River estuary is to provide a strategic framework to conduct an estuary RME *program*. A formal, integrated RME program does not currently exist; however, it was called for in Action 161 of the Reasonable and Prudent Alternative in the Opinion. Specifically, the estuary RME plan contained herein 1) establishes RME goals and objectives for salmon-related activities in the estuary; 2) develops performance indicators and monitored attributes that are responsive to the objectives; 3) identifies methods to obtain and analyze data on the monitored attributes; and 4) uses project and program level assessments to make recommendations as part of a phased action plan for estuary RME.

Knutson, P. L., J. C. Ford, M. R. Inkeep and J. Oyler. 1981. National survey of planted salt marshes (vegetative stabilization and wave stress). *Wetlands* 1:129-157.

A technique used for evaluating a coastal site's potential for vegetative stabilization based on the site's shoreline characteristics that relate to wave-climate severity was investigated. There were 104 salt marsh plantings in twelve coastal states that were evaluated for this study. The marshes studied were exposed to wind waves, located in brackish and saltwater environments and planted with *S. alterniflora* or *S. foliosa* at least one year prior to the survey. Based on correlation analyses, sediment grain size in the swash zone, longest or average fetch, and shore configuration were good indicators of whether a site is suitable for vegetative stabilization. See publication for additional information on methods used for surveying marsh plants. Results showed an 80% success rate in establishing a fringe marsh when sediment grain size was 0.4mm or less, and an 80% failure when increased. Authors recommended that the site should be at least 6m of intertidal width and be planted over 60% of this area; this should cause sufficient wave dampening to prevent erosion during most of the year. A site evaluation form called the Vegetative Stabilization Site Evaluation Form, was developed to predict the success of *Spartina* planting to control erosion based on observations made.

Kraus, D. B. and M. L. Kraus. 1986. The establishment of a fiddler crab colony on a manmade *Spartina* mitigation marsh, and its effect on invertebrate colonization, pp. 343-348. In Kusler, J. A., M. L. Quammen and G. Brooks (eds.), National Wetland Symposium: Mitigation of Impacts and Losses in Berne, New York. Association of State Wetland Managers, Berne, NY.

A study was conducted to establish fiddler crab populations in a manmade *S. alterniflora* marsh at the Mills Creek mitigation site, and to compare macrobenthos in the manmade marsh to a natural marsh area on Sawmill Creek which. Crabs were collected from the creek and transported to the test sites, with one crab deposited per artificial burrow. Censuses were done of the number of burrows, types of burrows, and crabs observed in the two sites. Benthic macro fauna were sampled at each colony, two control sites, and in a *Phragmites* marsh using a bulb corer to a depth of 10 cm. Details of techniques used in this study can be seen in the article. Results demonstrated that many of the crabs remained in each test site forming two colonies. However, at the end of the study, the fiddler crabs occupied about 42% to 43% of the burrows in the developed marsh. Benthic macroinvertebrates were significantly greater in the developing marsh and natural marsh than the crab colonies or in the *Phragmites* marsh.

LaSalle, M. W., M. C. Landin and J. G. Sims. 1991. Evaluation of the flora and fauna of a *Spartina alterniflora* marsh established on dredged material in Winyah Bay, South Carolina. *Wetlands* 11:191-208.

Author abstract. Approximately 35 hectares of *Spartina alterniflora* marsh has, over a 14-year period, developed naturally on unconfined dredged material placed within the intertidal zone of Winyah Bay, South Carolina. The above- and below-ground vegetative structure, benthic macrofauna, and resident fish and shellfish assemblages of two varying-aged zones (4 and 8 years) of this marsh were evaluated and compared in September 1988. Samples were collected at 10 randomly selected sites along 50-m transect in each marsh. Aboveground vegetative and were assessed from 0.25 m^2. Belowground biomass and sediments were sampled by coring at these sites. Large (1 to 2 cm) macrobenthos were collected only in the 4-year old marsh with Breder traps and block nets. Vegetative structure (stem height, density, percent cover, and biomass) in both zones was within the range reported for natural sites, with a trend toward greater below-ground development with age. The macrofaunal assemblages of both zones were similar in both species composition and numbers of species (17-21 species), with oligochaetes and polychaetes dominating both assemblages. Overall density of macrofauna in the eight-year-old-zone (19,943 individuals per m^2) was significantly greater than that in the four-year-old zone (4,628 individuals per m^2).

Levine, D. A. and D. E. Willard. 1990. Regional analysis of fringe wetlands in the Midwest: creation and restoration, pp. 299-321. In Kusler, J. A. and M. E. Kentula (eds.), Wetland Creation and Restoration: the Status of the Science. Island Press, Washington, D. C.

Levin and Willard provide a brief overview of the history of fringe wetland restoration and creation throughout the Midwest (fringe wetlands are defined as Great Lakes coastal marshes and marshes along inland lakes and reservoirs). They also discuss many of the important ecological characteristics that make up these systems as well as the functions these systems provide such as shoreline protection, fish and wildlife habitat, and water quality protection. They offer recommendations on which site-level characteristics need to be monitored before and restoration/mitigation construction can take place as well as methods for planning successful restoration projects. They recommend that the following steps be included in any restoration/mitigation plan or permit application:

- Justification of location
- Description of site characteristics prior to restoration/mitigation including water level fluctuations, soil type, and elevation
- Clear statement of project goals
- Development of detailed construction plans
- List of target species (to be planted) consistent with project goals
- Long-term management plan
- Complete monitoring plan

Levin and Willard also provide several specific examples of planting techniques, long-term management, monitoring, and mid-course corrections (i.e. adaptive management).

Levin, L. A., D. Talley, T. Talley, A. Larson, A. Jones, G. Thayer, C. Currin and C. Lund. 1997. Restoration of *Spartina* marsh function: an infaunal perspective. In Macdonald, K. B. and F. Weinmann (eds.), Wetland and Riparian Restoration: Taking a Broader View, Proceedings of a Conference, Society for Ecological Restoration International Conference, Seattle, WA.

This study was conducted to investigate factors influencing recovery of restored systems, rates of recovery, and causes for difference in composition between natural marshes and created marshes using sediment dwelling infauna. Researchers examined sediment dwelling fauna functions in salt marshes at two sites in North Carolina and California. Details of techniques used are described in this publication. In North Carolina, organic matter treatments were used at each study site. Results showed reduction in macrofaunal densities and species richness in created marshes compared to natural marshes. Oligochaetes dominated natural marshes and surface deposit feeders dominated created marshes. At the California site, planktrophic organisms were dominant in created marshes compared to natural marshes; and their densities and species richness were greater in the created marsh than natural marsh. Authors concluded that organic treatments should be used to increase *Spartina* growth and support sediment fauna.

Levin, L. A. and T. S. Talley. 2000. Influences of vegetation and abiotic environmental factors on salt marsh invertebrates, pp. 661-707. In Weinstein, M. P. and D. A. Kreeger (eds.), Concepts and Controversy in Tidal Marsh Ecology. Kluwer Academic Publishers, Dordrecht, The Netherlands.

Author Abstract. Sediment-dwelling fauna are a ubiquitous component of salt marshes yet we have limited understanding of their roles in marsh functioning and of the environmental conditions that control their distributions and abundances. This paper examines the influence of vegetation (presence, type, density, and biomass) and other environmental variables (marsh age, sediment and porewater properties, elevation, flow, oxygen, and biogenic structures) on salt marsh macrofauna and meiofauna. We review studies from a variety of geographical locations and include new information from systems with adjacent and natural and restored sites in southern California. The influence of environmental factors on faunal assemblages varies with marsh systems, factor intensity or concentration, taxon studied, and with other interacting factors present. We hypothesize a hierarchy of environmental variables in which abiotic properties such as marsh age, elevation and salinity act over large space and time scales, and are most likely to influence the presence or absence of species. Sediment properties (organic matter and particle size) and vegetation presence or type act on intermediate scales affecting macrofaunal abundance and composition. Plant biomass, culms and biogenic structures generated by fauna are patchy and act on small scales, often interacting with flow, to affect distribution and abundance patterns. Resolution of these processes in salt marshes should improve our understanding of controls on invertebrate communities and will ultimately aid in conservation and restoration of salt marsh habitat.

Llewellyn, D. W. and G. P. Shaffer. 1993. Marsh restoration in the presence of intense herbivory: the role of *Justicia lanceolata* (Chapm.) Small. *Wetlands* 13:176-184.

Author Abstract. Research in southern Louisiana over the last decade indicates that large expanses of mudflats are being maintained in an unvegetated state primarily by the rodent nutria (*Myocastor coypus*). At present, there is a dearth of work on managing wetlands in the presence of intense herbivory. The present study was undertaken to elucidate the potential in wetlands restoration of *Justicia lanceolata*, a wetland plant that is resistant to herbivory by nutria. Results from a previous study indicate that *J. lanceolata* is effective at trapping sediments. Furthermore, once it is established and islet elevations are built up, *J. lanceolata* is readily outcompeted by other species of wetland vegetation.

Results from this study indicate that *J. lanceolata* has several other properties that render it amenable for use in marsh restoration in the southeastern region of the USA: (1) thousands of propagules can be obtained from a single *J. lanceolata* islet without mortality to the adult plants; (2) it is resistant to herbivory, perhaps to the extent of being an herbivore repellant; (3) it is resilient with respect to saline storm surges, particularly if followed by a freshwater flushing event; (4) it is well-adapted to flooded conditions.

Lougheed, V. L. and P. Chow-Fraser. 2002. Development and use of a zooplankton index of wetland quality in the Laurentian Great Lakes basin. *Ecological Applications* 12:474-486.

Author Abstract. Recent interest in biological monitoring as an ecosystem assessment tool has stimulated the development of a number of biotic indices designed to aid in the evaluation of ecosystem integrity however, zooplankton have rarely been included in biomonitoring schemes. We developed a wetland zooplankton index (WZI) based on water quality and zooplankton associations with aquatic vegetation (emergent, submergent, and floating-leaf) that could be used to assess wetland quality, in particular in marshes of the Laurentian Great Lakes basin. Seventy coastal and inland marshes were sampled during 1995-2000 these ranged from pristine, macrophyte-dominated systems, to highly degraded systems containing only a fringe of emergent vegetation. The index was developed based on the results of a partial canonical correspondence analysis (PCCA), which indicated that plant-associated taxa such as chydorid and macrothricid cladocerans were common in high-quality wetlands while more open-water, pollution-tolerant taxa (e.g., *Brachionus, Moina*) dominated degraded wetlands. The WZI was found to be more useful than indices of diversity H', species richness) and measures of community structure (mean cladoceran size, total abundance) for indicating wetland quality. Furthermore, an independent test of the WZI in a coastal wetland of the Great Lakes, Cootes Paradise Marsh, correctly detected moderate improvements in water quality following carp exclusion. Since wetlands used in this study covered a wide environmental and geographic range, the index should be broadly applicable to wetlands in the Laurentian Great Lakes basin, while further research is required to confirm its suitability in other regions and other vegetated habitats.

Meyer, D. L., M. S. Fonseca, D. R., Colby, W. J., Kenworthy and G. W. Thayer. 1993. An examination of created marsh and seagrass utilization by living marine resources, pp. 1858-1863. Coastal Zone 93', Vol. 2. In Magoon, O., W. S. Wilson, H. Converseand L. T. Robin (eds.), Proceedings of the 8th Symposium on Coastal and Ocean Management. ASCE, New York.

The authors evaluated fish, shrimp, and crab utilization of planted and natural *Spartina alterniflora* marshes. *S. alterniflora* was planted in 1987 at three dredged material sites in North Carolina with access to channels. The planting method used is described in this publication. Within four years, the marsh developed into a productive vegetative stand habitat. Heterogeneity was added by placing oyster cultch along specific areas of the marsh shoreline. Fishery utilization of the created marshes and nearby natural marsh was examined from 1987 to 1989 using block and fyke nets. Fish density data were done in two years after transplanting. Based on results, average shrimp density was significantly larger in the natural reference marsh than in the planted marshes. Mean crab densities were significantly higher in the natural marsh than in the created marshes. The effect of depositing oyster cultch along the marsh shoreline was examined three months after the cultch placement. The sampling techniques used to collect fauna and perform analysis are described in this article. Oysters, xanthid crabs, amphipods, and other reef organisms occupied the cultch. Overall animal diversity increased in the marsh.

Meyer, D. L., J. M. Johnson and J. W. Gill. 2001. Comparison of nekton use of *Phragmites australis* and *Spartina alterniflora* marshes in the Chesapeake Bay, USA. *Marine Ecology Progress Series* 209:71-83.

Throughout the eastern USA many *Spartina alterniflora* salt-marsh systems are being altered through the invasion of *Phragmites australis*. As a result, substantial declines in the areal distribution of *S. alterniflora*-dominated habitat have occurred in contrast to increases in *P. australis* dominated habitat. While information is scarce on nekton use of *P. australis* marsh, increases in the areal distribution of this species have concerned resource managers. Managers typically view the shift of *S. alterniflora* to *P. australis* marsh as a shift from a biologically diverse and productive marsh to one less biologically diverse and productive. We examined nekton use of *P. australis* marsh relative to *S. alterniflora* marsh with similar geographic location and physical conditions. We found no significant differences ($p > 0.05$) in the utilization of *P. australis* and *S. alterniflora* marsh by nekton in terms of abundance or biomass. Further, no significant difference ($p > 0.05$) in the total number of nekton species was evident between *P. australis* and *S. alterniflora* marsh. We postulate that under similar environmental and physical conditions these marsh types are equivalent in terms of nekton use. It may be necessary to reevaluate current wetland management practices which involve the elimination of *P. australis* in favor of *S. alterniflora* marsh in order to increase nekton use.

Minello, T. J. and J. W. Webb, Jr. 1997. Use of natural and created *Spartina alterniflora* salt marshes by fishery species and other aquatic fauna in Galveston Bay, Texas, USA. *Marine Ecology Progress Series* 151:165-179.

Author Abstract. We compared densities of nekton and infauna among 5 natural and 10 created (3 to 15 yr in age) salt marshes in the Galveston Bay system of Texas to test whether these marshes were functionally equivalent. Techniques used to evaluate fauna abundance and diversity are described in detail in this publication. Decapod crustaceans dominated the nekton on the marsh surface during both the spring and the fall. Densities of daggerblade grass shrimp (*Palaemonetes pugio)*, the most abundant decapod, were not significantly different among marshes, but the size of these shrimp in created marshes was significantly smaller than in natural marshes. Densities of the marsh grass shrimp (*Palaemonetes vulgaris)* and of three commercially-important crustaceans white shrimp (*Penaeus setiferus)*, brown shrimp (*Penaeus aztecus)*, and blue crab (*Callinectes sapidus*) were significantly lower in created marshes than in natural marshes. Gulf menhaden (*Brevoortia patronus)* were the most abundant fish collected, mainly on nonvegetated bottom adjacent to marsh habitats. Fish densities within vegetation (predominantly gobies and pinfish *Lagodon rhomboides*) were significantly lower in created marshes than in natural marshes. Natural and created marshes, however, did not differ in species richness of nekton. Sediment macro-organic matter and density and species richness of macroinfauna (mainly polychaete worms) were all significantly lower in created marshes than natural marshes. There was a positive relationship in created marshes between marsh age and sediment macro-organic matter, but marsh age was not related to nekton densities. Natural marshes were similar in having low elevations and flooding durations between 74 and 80% of the year; while created marshes were flooded from 43 to 91% of the time. In contrast to marsh age, tidal flooding was often related to nekton densities in marsh habitats. We conclude that marsh elevation and tidal flooding are key characteristics affecting use by nekton and should be considered in marsh construction projects.

Minello, T. J. and J. W. Webb, Jr. 1993. The development of fishery habitat value in created salt marshes, pp. 1864-1865. Coastal Zone '93, Vol. 2. In Magoon, O., W. S. Wilson, H. Converse and L. T. Tobin

(eds.), Proceedings of the 8th Symposium on Coastal and Ocean Management. ASCE, New York.

The Coastal Ocean Program project in Galveston Bay, Texas compared ten created *S. alterniflora* marshes with five natural marshes. The created marshes consisted of transplants on dredged material and aged from three to fifteen years at the time of sampling. A drop enclosure was used to estimate densities of juvenile fishery species within the marsh vegetation. The predominated species were grass shrimp, commercial penaeid, blue crabs, pinfish, and gobies. Results showed that above ground plant biomass was equal or higher in most created marshes than natural marshes while below ground biomass and sediment organic content was lower in created marshes. Also, created marshes supported lower numbers of natant macrofauna, particularly juvenile brown shrimp, white shrimp, and blue crabs. A caging study was also perfomed in the marshes in which the preliminary results indicated that juvenile brown shrimp growth rates were comparable in created and natural marshes, however, survival in cages was significantly lower in created marshes than natural marshes.

Minello, T. J. and R. J. Zimmerman. 1992. Utilization of natural and transplanted Texas salt marshes by fish and decapod crustaceans. *Marine Ecology Progress Series* 90: 273-285.

Author Abstract. Habitat utilization by fish and decapod crustaceans was compared among three transplanted and three natural *Spartina alterniflora* marshes on the Texas (USA) coast during spring 1986. Created marshes had been transplanted on dredged material and were approximately 2 to 5 yr old at the time of sampling. Quantitative drop enclosures (2.6m^2 area) were used to collect juvenile fishes and crustaceans on the marsh surface. Aboveground density and biomass of macrophytes were also measured within these enclosures, and sediment cores were collected to examine sediment macro-organic matter (MOM) and benthic infaunal densities. Transplanted marshes had significantly lower densities of decapod crustacea (primarily daggerblade grass shrimp *Palaemonetes pugio* and juvenile brown shrimp *Penaeus aztecus*) compared with natural marshes. This reduced utilization may have been a response to low densities of benthic food organisms, and densities of decapods were positively correlated with densities of prey in sediment cores. In contrast to the utilization pattern of decapods, densities of fish (dominated by the darter goby *Gobionellus boleosoma* and pinfish *Lagodon rhomboides*) were similar between natural and transplanted marshes. These small fish may rely on salt marshes more for protective cover than for enhanced food resources, and aboveground structure in the transplanted marshes may have adequately provided this function.

Mitsch, W. J. and R. F. Wilson. 1996. Improving the success of wetland creation and restoration with know-how, time, and self-design. *Ecological Applications* 6:77-83.

Author Abstract. The creation and restoration of new wetlands for mitigation of lost wetland habitat is a newly developing science/technology that is still seeking to define and achieve success of these wetlands. Fundamental requirements for achieving success of wetland creation and restoration projects are: understanding wetland function; giving the system time; and allowing for the self-designing capacity of nature. Mitigation projects involving freshwater marshes should require enough time, closer to 15-20 yr than 5 yr, to judge the success or lack thereof. Restoration and creation of forested wetlands, coastal wetlands, or peatlands may require even more time. Ecosystem-level research and ecosystem modeling development may provide guidance on when created and restored wetlands can be expected to comply with criteria that measure their success. Full-scale experimentation is now beginning to increase our understanding of wetland function at the larger spatial scales and longer time scales than those of most ecological experiments. Predictive ecological modeling may enable ecologists to estimate how long it will take the mitigation wetland to achieve steady state.

Mitsch, W. J. 2000. Self-design applied to coastal restoration, pp. 554-564. In Weinstein, M. P. and D. A. Kreeger (eds.), Concepts and Controversy in Tidal Marsh Ecology. Kluwer Academic Publishers, Dordrecht, The Netherlands.

Author Introduction. Ecological engineering as the practice and self-design as the theoretical concept may offer the framework in which coastal restoration can take place on a large scale around the world. This paper introduces the concept of ecological engineering, contrasting it with the more familiar term ecosystem restoration. It then focuses on several attempts at large-scale coastal restoration projects that have been undertaken in the USA, describing the scale at which the projects are being developed and the general approaches that are being used. Finally, the paper points out practices that pass the self-design litmus test and those that do not.

Montalto, F. A. and T. S. Steenhuis. 2004. The link between hydrology and restoration of tidal marshes in the New York/New Jersey estuary. *Wetlands* 24:414-425.

Author Abstract. The objectives of this paper are to summarize existing knowledge on the hydrologic characteristics of tidal marshes in the New York/New Jersey (NY/NJ) Estuary, to document the extensive linkages between hydrology and tidal marsh function, to underline their importance in designing restoration projects, and to identify research needs in this area. Hydrologic processes are responsible for the evolution, inter- and intra- marsh variability, and functional value of tidal marshes. Hydrology also controls the movement of materials and organisms between estuaries, wetlands, uplands, and the atmosphere. The importance of hydrology to tidal marsh function is widely recognized by the scientific community. Hydrologic research in tidal wetlands of the NY/NJ Estuary, however, is lacking. Anthropogenic development activities have resulted in drastic losses of tidal wetland value, and restoration is now finally a priority in many of the region's natural resource management plans. The success of tidal marsh restoration efforts depends on how appropriately hydrologic factors and their interdependencies are recognized and incorporated into design; yet, little guidance about how best to restore tidal marsh hydrology is available. There is a need to document better the hydrologic characteristics of existing and historical tidal wetlands, to improve hydrologic modeling capabilities, and to accompany other ecological investigations in tidal marshes with hydrologic documentation.

Morgan, P. A. and F. T. Short. 2002. Using functional trajectories to track constructed salt marsh development in the Great Bay estuary, Maine New Hampshire, U.S.A. *Restoration Ecology* 10:461-473.

Author Abstract. A growing number of studies have assessed the functional equivalency of restored and natural salt marshes. Several of these have explored the use of functional trajectories to track the increase in restored marsh function over time; however, these studies have disagreed as to the usefulness of such models in long-term predictions of restored marsh development. We compared indicators of four marsh functions (primary production, soil organic matter accumulation, sediment trapping, and maintenance of plant communities) in 6 restored and 11 reference (matched to restored marshes using principal components analysis) salt marshes in the Great Bay Estuary. The restored marshes were all constructed and planted on imported substrate and ranged in age from 1 to 14 years. We used marsh age in a space-for-time substitution to track constructed salt marsh development and explore the use of trajectories. A high degree of variability was observed among natural salt marsh sites, displaying the importance of carefully chosen reference sites. As expected, mean values for constructed site (n = 6) and reference site (n = 11) functions were significantly different. Using constructed marsh age as the independent variable and functional indicator values as dependent variables, nonlinear regression analyses produced several ecologically meaningful trajectories ($r^2 > 0.9$), demonstrating that the use of different-aged marshes can be a viable approach to developing functional trajectories. The trajectories illustrated that although indicators of some functions (primary production, sediment deposition, and plant species richness) may reach natural site values relatively quickly (<10 years), others (soil organic matter content) will take longer.

Moy, L. D. and L. A. Levin. 1991. Are *Spartina* marshes a replaceable resource? A functional approach to evaluation of marsh creation efforts. *Estuaries* 14:1-16.

This study was conducted to compare the functioning of a man-made *Spartina* salt marsh (between ages one to three years) with two adjacent natural marshes. Researchers performed quantifiable measurements on sediment properties, infaunal community composition, and *F. heteroclitus* marsh utilization. Results showed that sediment organic content of the man- made marsh was significantly lower than the natural marshes. *Fundulus* abundance in the man made marsh was significantly lower than in natural marshes indicating that fewer fish were supported by the habitat. *Spartina* stem densities in the man made marsh were significantly lower than the natural marshes. As a result protection or spawning habitat for the fundulids was not suitable. Further details for techniques used are described in this paper. Researchers concluded that the man made marsh ecological functioning was not equivalent to the natural marshes after three years. Authors stated that mitigation could be enhanced by increasing tidal flushing to allow marine organisms additional access to the salt marsh, as well as adding *Spartina* to increase sediment organic-matter content and porosity.

Newling, C. J., M. C. Landin and S. D. Parris. 1983. Long-term monitoring of the Apalachicola Bay wetland habitat development site, pp. 164-186. In Webb, F. J., Jr. (ed.), Proceedings of the 10th Annual Conference on Wetland Restoration and Creation, Hillsborough Community College, Tampa, FL.

Man made cordgrass marshes that occurred in the Apalachicola Bay in an area of dredged material deposition were studied. *Spartina alterniflora* was planted in the intertidal zone, and *Spartina patens* was planted in the supratidal zone. Techniques used included the use of quadrats. Results showed within two growing seasons, all *S. alterniflora* plots began with plants on 1-m centers or less and eventually acheived 100% coverage (using $0.5m^2$). Plants located on larger centers were washed out, or were barely surviving. Similar coverage was found for S. *patens* using $0.25m^2$ quadrats. Within the second year, *Distichillis spicata* dominated in areas between the two cordgrasses. Techniques used are described in this paper.

Six years after the planting, *Scirpus robustus* grew as rapidly as *S. alterniflora* along the landward margin; *S. patens* coverage reduced because of invasive dune type vegetation; vegetation diversity in the dunes and marshes increased to 97 species of plants; plant assemblage was diverse in both manmade and natural marsh sites; and wading birds fed more frequently on vegetation and benthic organisms in the created island.

Poach, M. E. and S. P. Faulkner. 1998. Soil phosphorus characteristics of created and natural wetlands in the Atchafalaya Delta, Lousisiana. *Estuarine, Coastal and Shelf Science* 46:195-203.

Author Abstract. Quantitative comparisons of created and natural wetlands are typically confounded by differences in wetland age, with created wetlands generally younger than their natural counterparts. Observed differences may be attributed to either age differences or to the inability to create wetland functions. The objective of this study was to determine if created dredge-material wetlands and comparably aged wetlands formed by natural deposition in the Atchafalaya Delta have similar sediment phosphorus compositions. Sediment cores were collected on five occasions from elevational strata (low, mid and high) in created and natural wetlands belonging to three age classes (<1-3 years old, 5-10 years old, and 15-20 years old). Sediment phosphorus fractions were determined by sequential chemical extraction. When compared to similarly aged natural wetland sediments: (1) old, created wetland sediments had similar mean phosphorus contents at mid and low elevations, but had lower mean contents at high elevations; and (2) intermediate aged, created wetland sediments had greater phosphorus contents on a per weight basis, but mean contents were lower on a per area basis. At all elevations, the young created wetland had lower phosphorus contents than all other wetlands. Results suggest that dredge sediment used to form the created wetlands in the Atchafalaya Delta is lower in phosphorus than the suspended sediment that forms the natural wetlands. Also, the created wetlands develop natural phosphorus characteristics through time due to sediment deposition during river flooding. In the Atchafalaya Delta, if created wetlands provide the natural flooding cycle, then they begin to develop natural phosphorus characteristics between 10 and 20 years after formation.

Potnoy, J. W. and A. E, Giblin 1996. Biogeochemical effects of seawater restoration to diked salt marshes. *Ecological Applications* 7:1054-1063.

A greenhouse microcosm experiments was conducted to examine biogeochemical effects of restoring seawater to historically diked Cape Cod salt marshes. The peat cores from seasonally flooded and drained diked marshes were water logged with seawater. The porewater chemistry was monitored for twenty-one months. Seawater added to low organic content increases acidic peat from the drained marsh, the pH of the porewater and, alkalinity, PO_4-P, and Fe (II). Increase in cation exchange caused a six-fold increase in dissolved Fe (II) and Al, and a sixty-fold increases in NH_4-N within six months of salination. Re-introducing seasonally flooded diked marshes causes an increase in porewater sulfides to increase affecting re-vegetation success. Restoration of either seasonally flooded or drained diked marshes may encourage large nutrient and Fe (II) releases resulting in primary production and lower oxygen in receiving waters. Some important points mentioned by the authors were that monitoring in diked marshes should occur over a minimum of three years; the common vegetative species in the marsh should be replanted or transplanted; salinity measurements should be taken; sediment testing should be performed; pH levels must be measured; evaluations of adjacent land use should occur; and that nutrient levels must be monitored to determine whether increase in N, SO_4, and PO_4 is due to natural responses or anthropogenic sources. Techniques used in this study are described in detail within the article.

Raposa, K. B. and C. T. Roman. 2003. Using gradients in tidal restriction to evaluate nekton community responses to salt marsh restoration. *Estuaries* 26:98-105.

Author Abstract. Few studies concerning tide-restricted and restoring salt marshes emphasize fishes and decapod crustaceans (nekton) despite their ecological significance. This study quantifies nekton utilization of three New England salt marshes under tide-restricted and restoring conditions (Hatches Harbor, Massachusetts; Sachuest Point and Galilee, Rhode Island). The degree of tidal restriction differed among marshes allowing for an examination of nekton utilization patterns along a gradient of tidal restriction and subsequent restoration. Based on sampling in shallow subtidal creeks and pools, nekton density and richness were significantly lower in the restricted marsh compared to the unrestricted marsh only at the most tide-restricted site (Sachuest Point). The dissimilarity in community composition between the unrestricted and restricted marsh sites increased with more pronounced tidal restriction. The increase in nekton density resulting from tidal restoration was positively related to the increase in tidal range. Species richness only increased with restoration at the most tide-restricted site; no significant change was observed at the other two sites. These patterns suggest that only severe tidal restrictions significantly reduce the habitat value of New England salt marshes for shallow subtidal nekton. This study suggests that the greatest responses by nekton, and the most dramatic shift towards a more natural nekton assemblage, will occur with restoration of severely restricted salt marshes.

Raposa, K. 2002. Early responses of fishes and crustaceans to restoration of a tidally restricted New England salt marsh. *Restoration Ecology* 10:665-676.

Author Abstract. Nekton (fishes and decapod crustaceans) is an abundant and productive faunal component of salt marshes, yet nekton responses to tidal manipulations of New England salt marshes remain unclear. This study examined nekton use of a tidally restricted salt marsh in Narragansett, Rhode Island relative to an unrestricted marsh during summer. In addition, a before-after-control-impact design was used to examine early responses of nekton to the reintroduction of natural tidal flushing. Species richness and densities of *Cyprinodon variegatus, Lucania parva, Menidia beryllina,* and *Palaemonetes pugio* were higher in the restricted marsh compared with the unrestricted marsh. The unrestricted marsh supported higher densities of *Menidia menidia* and *Fundulus majalis*. Mean lengths of *Carcinus maenas* and *P. pugio* were greater in the restricted marsh. Tidal restoration resulted in increased tidal flushing, salinity, and water depth in the restricted marsh. Densities of *Fundulus heteroclitus*, *F. majalis*, and *Callinectes sapidus* were higher after two years of restoration. Density of *L. parva* decreased after restoration, probably in response to a loss of macroalgal habitat. Species richness also decreased after 2 years, from 20.9 species when the marsh was restricted to 13.0 species. Total nekton density did not change with restoration, but shifts in community composition were evident. In this study restoration induced rapid changes in the composition, density, size, and distribution of nekton species, but additional monitoring is necessary to quantify longer-term effects of salt marsh restoration on nekton.

Roberts, T. H. 1991. Habitat value of manmade coastal marshes in Florida. Vicksburg, Mississippi, United States Army Corps of Engineers Waterways Experiment Station. Techinical Report. WRP-REP-2.

This study was conducted to determine the efficiency of marsh creation as mitigation for natural coastal marsh loss along Florida's Gulf and Atlantic coasts. There were four *Spartina* and two *Juncus* natural marshes that ranged in size from 0.20 to 3.2 ha. There were twenty-two manmade marshes between one to ten years in age, seven were one to two years old, six were two to three years old, and six were three to five years old. Researchers collected data on soil substrate texture, particle size and organic content. Vegetation was sampled using stratified random transects with the point-intercept method. Data collected on vegetation included species composition, percent cover, stem density, and height of *Spartina* plants. Below-ground biomass of *Spartina* was measured using 7-cm- diameter cores. Fish were collected using fyke, Breder traps, and a Wegener ring net. Birds were surveyed in each marsh on three consecutive days. Bird-calls were also identified and recorded. Mammals were trapped at each site using Sherman Box and Museum Special Snap traps, one each per station. Detailed methods of the techniques used are presented in the report. Results showed that in manmade marshes, there were no differences observed between the age groups. There was a significant variation in *S. alterniflora* cover with age in the manmade marshes. *S. alterniflora* cover was 80% on a one-year old site and 40% on a two-year old site. Most fish species in natural marshes were found in manmade marshes as well. Details of the results can be seen in the report.

Roman, C. T., K. B. Raposa, S. C. Adamowicz, M.-J. James-Pirri and J. G. Catena. 2002. Quantifying vegetation and nekton response to tidal restoration of a New England salt marsh. *Restoration Ecology* 10:450-460.

Author Abstract. Tidal flow to salt marshes throughout the northeastern United States is often restricted by roads, dikes, impoundments, and inadequately sized culverts or bridge openings, resulting in altered ecological structure and function. In this study we evaluated the response of vegetation and nekton (fishes and decapod crustaceans) to restoration of full tidal flow to a portion of the Sachuest Point salt marsh, Middletown, Rhode Island. A before, after, control, impact study design was used, including evaluations of the tide-restricted marsh, the same marsh after reintroduction of tidal flow (i.e., tide-restored marsh), and an unrestricted control marsh. Before tidal restoration vegetation of the 3.7-ha tide-restricted marsh was dominated by *Phragmites australis* and was significantly different from the adjacent 6.3-ha *Spartina*-dominated unrestricted control marsh (analysis of similarities randomization test, $p< 0.001$). After one growing season vegetation of the tide-restored marsh had changed from its pre-restoration condition (analysis of similarities randomization test, $p< 0.005$). Although not similar to the unrestricted control marsh, *Spartina patens* and *S. alterniflora* abundance increased and abundance and height of *Phragmites* significantly declined, suggesting a convergence toward typical New England salt marsh vegetation. Before restoration shallow water habitat (creeks and pools) of the unrestricted control marsh supported a greater density of nekton compared with the tide-restricted marsh (analysis of variance, $p< 0.001$), but after one season of restored tidal flow nekton density was equivalent. A similar trend was documented for nekton species richness. Nekton density and species richness from marsh surface samples were similar between the tide-restored marsh and unrestricted control marsh. *Fundulus heteroclitus* and *Palaemonetes pugio* were the numerically dominant fish and decapod species in all sampled habitats. This study provides an example of a quantitative approach for assessing the response of vegetation and nekton to tidal restoration.

Sacco, J., E. D. Seneca and T. R. Wentworth. 1994. Infaunal community development of artificially established salt marshes in North Carolina. *Estuaries* 17:489-500.

Author Abstract. In recent years, artificial establishment of *Spartina alterniflora* marshes has become a common method for mitigating impacts to salt marsh systems. The vegetative component of artificially established salt marshes has been examined in several studies, but relatively little is known about the other aspects of these systems. This study was undertaken to investigate the infaunal community of artificially established salt marshes as a follow up to Researcher Sacco's Ph. D thesis in 1989. Infauna was sampled from pairs of artificially established (AE) salt marshes and nearby natural marshes at six sites along the North Carolina coast. The AE marshes ranged in age from 1 yr to 17 yr. Total infaunal density, density of dominant taxa, and community trophic structure (proportions of subsurface-deposit feeders, surface-deposit and suspension feeders, and carnivores) were compared between the two types of marsh to assess infaunal community development in AE marshes. Overall, the two marsh types had similar component organisms and proportions of trophic groups, but total density and densities within trophic groupings were lower in the AE marshes. Soil organic matter content of the natural marshes was nearly twice that of the AE marshes, and is a possible cause for the higher infaunal densities observed in the natural marshes. Using the same three criteria, comparisons of the natural and AE marshes at each of the six locations revealed varying degrees of similarity. Similarity of each AE marsh to its natural marsh control appeared to be influenced by differences in environmental factors between locations more than by AE marsh age. Functional infaunal habitat convergence of an AE marsh with a natural marsh somewhere within its biogeographical region is probable, but success in duplicating the infaunal community of a particular natural marsh is contingent upon the deveopmental age of the natural marsh and the presence and interaction of site specific factors.

Seabloom, E. W., K. A. Moloney and A. G. van der Valk. 2001. Constraints on the establishment of plants along a fluctuating water-depth gradient. *Ecology* 82:2216-2232.

Author Abstract. We used simulation modeling to investigate the relative importance of current environmental conditions and factors affecting establishment of different plant species on the formation of vegetative zonation patterns. We compared the results from a series of six models that incorporated increasing amounts of information about key factors affecting species' ability to adjust to water-level fluctuations. We assessed model accuracy using aerial photographs taken of a 10-yr field experiment, in which 10 wetlands were flooded to 1 m above normal water level for 2 yr, drawn down for 1 or 2 yr, and reflooded for 5 yr to three different water levels (normal, 10.3 m, 10.6 m). We compared each model's ability to predict relative areal cover of five dominant emergent species and to recreate the spatial structure of the landscape as measured by mean area of monospecific stands of vegetation and the degree to which the species were intermixed.

The simplest model predicted post-treatment species distributions using logistic regressions based on initial species distributions along the water-depth gradient in the experimental wetlands. Subsequent models were based on germination, rhizomatous dispersal, and mortality functions implemented in each cell of a spatial grid. We tested the effect on model accuracy of incrementally adding data on five factors that can alter the composition and distribution of vegetative zones following a shift in environmental conditions: (1) spatial relationships between areas of suitable habitat (landscape geometry), (2) initial spatial distribution of adults, (3) the presence of ruderal species in the seed bank, (4) the distribution of seed densities in the seed bank, and (5) differential seedling survivorship.

Because replicated, long-term data are generally not available, the evaluation of these models represents the first experimental test, of which we are aware, of the ability of a cellular-automaton-type model to predict changes in plant species' distributions.

Establishment constraints, such as recruitment from the seed bank, were most important during low-water periods and immediately following a change in water depth. Subsequent to a drop in water level, the most detailed models made the most accurate predictions. The accuracy of all the models converged in 1–2 years after an increase in water level, indicating that current environmental conditions became more important under stable conditions than the effects of historical recruitment events.

Simenstad, C. A. and R. M. Thom. 1996. Functional equivalency trajectories of the restored Gog-Le-Hi-Te estuarine wetland. *Ecological Applications* 6:38-56.

Author Abstract. Assessing performance of restored and created wetlands for compensatory mitigation and restoration poses a mismatch between long-term processes and the short-term expediency of management decisions. If they were predictable, patterns in the temporal development of important wetland processes could reduce long-term uncertainty of the outcome of restoration projects. To test our ability to predict long-term trends and patterns in the development of a restored wetland based on the first 7 yr of its development, we analyzed 16 ecosystem functional attributes of the Gog-Le-Hi-Te Wetland, in the Puyallup River estuary, Puget Sound, Washington, USA. This estuarine wetland system was restored to tidal inundation in 1986. Only a few of the 16 ecosystem attributes analyzed showed functional trajectories toward equivalency with natural wetlands, and many were inconclusive or suggested disfunction relative to reference wetlands. Natural variability among reference sites also inhibited our ability to interpret an expected asymptote in developmental trajectories. The ability of wetland managers to assess compensatory-mitigation success over short-term (e.g., regulatory) timeframes depends upon the selection of wetland attributes that can predict long-term trends in the development of the restored/created system. However, we are hampered by a basic lack of long-term data sets describing the patterns, trends, and variability in natural wetland responses to disturbance, as well as natural variability in wetland attributes in presumably mature wetland communities. Ultimately, it may be necessary to supplant our descriptive means of assessing functional equivalency with simple, controlled manipulative experiments or assays, standardized across restoration/mitigation and reference sites.

Sinicrope, T. L., P. G. Hine, R. S. Warren and W. A. Niering. 1990. Restoration of an impounded salt marsh in New England. *Estuaries* 13:25-30.

Author Abstract. The restoration of a 20 ha tidal marsh, impounded for 32 yr, in Stonington, Connecticut was studied to document vegetation change 10 yr after the reintroduction of tidal flushing. These data were then compared to a 1976 survey of the same marsh when it was in its freshest state and dominated by *Typha angustifolia.* Aerial photography examined vegetation by comparing data from a study of the area by Hebard in 1976, with data obtained in 1986. Transects were then evaluated in 1987 and 1988 to determine current coverage by species using the same line intercept method. Currently, *T. angustifolia* remains vigorous only along the upland borders and in the upper reaches of the valley marsh. Live coverage of *T. angustifolia* has declined from 74% to 16% and surviving stands are mostly stunted and depauperate. Other brackish species have also been adversely effected, except for *Phragmites* *australis* which has increased. In contrast, the salt marsh species *Spartina alterniflora* has dramatically expanded, from < 1% to 45% cover over the last decade. Locally, high marsh species have also become established, covering another 20% of the marsh.

Steyer, G. D., C. E. Sasser, J. M. Visser, E. M. Swenson, J. A. Nyman and R. C. Raynie. 2003. A proposed coast-wide reference monitoring system for evaluating wetland restoration trajectories in Louisiana. *Environmental Monitoring and Assessment* 81:107-117.

Author Abstract. Wetland restoration efforts conducted in Louisiana under the Breaux Act require monitoring the effectiveness of individual projects, as well as monitoring the cumulative effects of all projects in restoring, creating, enhancing, and protecting the coastal landscape. The effectiveness of the traditional paired-reference monitoring approach has been limited due to difficulty in finding comparable reference sites. A multiple reference approach is proposed that uses aspects of hydrogeomorphic functional assessments and probabilistic sampling. This approach includes a suite of sites that encompass the range of ecological condition for each stratum, with projects placed on a continuum of conditions found for that stratum. Trajectories in reference sites through time are then compared with project trajectories through time. Issues regarding selection of indicators and strata, and determination of sample size will be discussed. The approach proposed could serve as a model for evaluating wetland ecosystems.

Thom, R. M. 1997. System-development matrix for adaptive management of coastal ecosystem restoration projects. *Ecological Engineering* 8:219-232.

Author Abstract. Ecological performance of coastal habitat and ecosystem restoration projects is not yet predictable with great certainty. The simple method developed in this paper applies the principles of adaptive management to coastal ecosystem restoration to improve the ability to assess performance and make informed decisions on how to improve performance. The method uses a system-development matrix to assist in identifying the state of the system for which restorative actions were applied. The matrix defines development in terms of structure and function, but can accommodate other performance and development characteristics. Monitoring of the system provides input on the state of the system. Phrases in the matrix provide plausible explanations for the condition of the system and point toward possible actions to be taken. The matrix is applied using examples from community development on dredged material, a seagrass system and tidal marsh system. It is recommended that the matrix be developed by all interested parties during the planning phase. This group can then utilize the matrix for managing the project.

Thom, R. M. 2000. Adaptive management of coastal ecosystem restoration projects. *Ecological Engineering* 15:365-372.

Author Abstract. There is a clear need to apply better and more effective management schemes to coastal ecosystem restoration projects. It is very common for aquatic ecosystem restoration projects not to meet their goals. Poor performance has led to a high degree of uncertainty about the potential success of any restoration effort. Under adaptive management, the knowledge gained through monitoring of the project and social policies is translated into restoration policy and program redesign. Planners and managers can utilize the information from the monitoring programs in an effective way to assure that project goals are met or that informed and objective decisions are made to address both ecological and societal needs. The three main ingredients of an effective adaptive management plan in a restoration project are: (1) a clear goal statement, (2) a conceptual model, and (3) a decision framework. The goal drives the design of the project and helps guide the development of performance criteria. The goal statement and performance criteria provide the means by which the system can be judged. With the conceptual model, the knowledge base from the field of ecological science plays an active and critical role in designing the project to meet the goal. A system-development matrix provides a simple decision framework to view the alternative states for the system during development, incorporate knowledge gained through the monitoring program, and formulate a decision on actions to take if the system is not meeting its goal.

Timmermans, S. T. A. 2001. The Marsh Monitoring Program: 1995 - 2000, Monitoring Great Lakes wetlands and their bird and amphibian inhabitants, 83 pp. Bird Studies Canada, Port Rowan, Ontario, Canada. http://www.bsc-eoc.org/mmpreport2002.html

Partial Executive Summary. Many birds and amphibians frequent and rely heavily on marshes to support their annual life cycle. With continual degradation and loss of marsh habitat, there has long been a recognized need to monitor populations of avian and amphibian species that rely on these sensitive wetland environments. In 1995, a bi-national Great Lakes basinwide effort was launched in a multi-partner effort to establish the Marsh Monitoring Program, a program whose primary goal is to monitor populations of marshbirds and calling amphibians across wetlands in this globally unique and water-rich region. Since 1995, through a unique partnership between Bird Studies Canada, United States Environmental Protection Agency, Environment Canada, Great Lakes United, the Great Lakes Protection Fund, and hundreds of citizen scientists, the Marsh Monitoring Program has succeeded in capturing important and meaningful population and wetland habitat information from hundreds of wetlands throughout the Great Lakes basin.

In 2000, the Marsh Monitoring Program released its first five-year report summarizing information it has gained during its first five years of operation. During this time (and including 2000), the Great Lakes have undergone a dramatic period of water level fluctuation, with the last three years (1997-2000) having undergone relatively dramatic rates of water level decreases. This report provides updated information about numerous avian and amphibian species-specific population trends and how some relate to changes in annual Great Lakes water level changes, at both lake-specific and basin-wide levels. Relations between trends of several avian and amphibian species and trends in lake level changes elucidate how long-term hydrologic dynamics of the Great Lakes may influence bird and amphibian populations occupying and breeding in marshes throughout the basin.

Trends in many species' annual indices, as measured by MMP surveyors, in many instances have been closely related (positively or negatively) to changes in mean annual water levels of Great Lakes. Unique patterns of water level change in Lake Ontario offered an opportunity to assess how species trend responses differed from those of other Great Lakes not under significant anthropogenic operating regimes. Results herein provide an impetus to continue studying these relations and demonstrate a need for additional research to complement and increase our understanding of marshes, their avian and amphibian occupants, and sources of marsh ecosystem health and integrity. The success of the Marsh Monitoring Program demonstrates the value in multi-partner ventures and the need to continue building and strengthening the current partnership that supports this invaluable wetland conservation initiative.

Turner, R. E. and B. Streever. 2002. Bay bottom terracing. Approaches to coastal wetland restoration, pp. 63-76. SPB Academic Publishing, The Hague, The Netherlands.

A project was conducted to create marshes on terraces to support fish and invertebrate species and promote submerged aquatic vegetation in areas protected by terraces. The Schleswick-Holstein method was used to create marshes which involved the use of groins made from stakes and the brushwood to act as breakwaters that protected frequently inundated areas from tidal action. This method was further modified with the construction of Sabine Terracing Project in Calcasieu Lake, LA, in 1990. The Sabine Terracing Project encouraged construction and removal of bay bottom sediment to create terraces. Marsh grass species *S. alterniflora* was planted in these areas. The technique for this method is described in Chapter 6 of this publication. The project was then monitored by the Louisiana Department of Natural Resources since 1990. *S. alterniflora* plugs and sprigs was planted on the terraces and monitored. In ten months, data showed that more than 95% of plugs and over 80% of sprigs survived. After a year, plugs were distibuted over an area with an average width of 1.07m. Within two-years of planting, vegetation was widely distributed over terraces.

Wainright, S. C., M. P. Weinstein, K. W. Able and C. A. Currin. 2000. Relative importance of benthic microalgae, phytoplankton and the detritus of smooth cordgrass *Spartina alterniflora* and the common reed *Phragmites australis* to brackish-marsh food webs. *Marine Ecology Progress Series* 200:77-91.

Author Abstract. We conducted a study to determine the trophic pathways leading to juvenile fish in 2 mesohaline tidal marshes bordering Delaware Bay. The relative roles of the major primary producers in supplying energy, ultimately, to the mummichog *Fundulus heteroclitus* were assessed by measuring the stable isotopic compositions of juveniles (21 to 56 mm total length, TL; most of which were young-of-the-year) and those of macrophyte vegetation, phytoplankton, and benthic microalgae at each site. We collected samples of primary producers and *F. heteroclitus*, the dominant fish species in this and other marshes along the east coast of the USA, in June and August 1997, at 2 study sites (upstream and downstream) within Mad Horse Creek (a *Spartina alterniflora*-dominated site) and Alloway Creek (a *Phragmites australis*-dominated site), for a total of 4 study sites. Our results indicate that *F. heteroclitus* production is based on a mixture of primary producers, but the mixture depends on the relative abundance of macrophytes. In *S. alterniflora*-dominated marshes, C and S isotope ratios indicate that *F. heteroclitus* production is supported by *S. alterniflora* production (ca 39%, presumably via detritus), while in *P. australis*-dominated marshes, secondary production is based upon *P. australis* (73%). To our knowledge, this finding provides the first evidence that *P. australis* may contribute to aquatic food webs in tidal marshes. Benthic microalgae also contribute to the food chain that leads to *F. heteroclitus* in both marsh types, while phytoplankton may be of lesser importance. Benthic microalgal biomass was lower in the *P. australis*-dominated system, consistent with a greater effect of shading in *P. australis*- versus *S. alterniflora*-based creek systems. Based on the difference in nitrogen isotope values between *F. heteroclitus* and the primary producers, the trophic level of *F. heteroclitus* appears to be similar in the 2 marsh types, despite the differing vegetation types. In summary, the relative roles of the primary producers in supplying energy to *F. heteroclitus* varies locally and, in particular, with respect to the type of marsh macrophyte vegetation.

Warren, R. S., P. E. Fell, R. Rozsa, A. H. Brawley, A. C. Orsted, E. T. Olson, V. Swamy and W. A. Niering. 2002. Salt marsh restoration in Connecticut: 20 years of science and management. *Restoration Ecology* 10:497-513.

Author Abstract. In 1980 the State of Connecticut began a tidal marsh restoration program targeting systems degraded by tidal restrictions and impoundments. Such marshes become dominated by common reed grass (*Phragmites australis*) and cattail (*Typha angustifolia* and *T. latifolia*), with little ecological connection to Long Island Sound. The management and scientific hypothesis was that returning tidal action, reconnecting marshes to Long Island Sound, would set these systems on a recovery trajectory. Specific restoration targets (i.e., pre-disturbance conditions or particular reference marshes) were considered unrealistic. However, it was expected that with time restored tides would return ecological functions and attributes characteristic of fully functioning tidal salt marshes. Here we report results of this program at nine separate sites within six marsh systems along 110 km of Long Island Sound shoreline, with restoration times of 5 to 21 years. Biotic parameters assessed include vegetation, macroinvertebrates, and use by fish and birds. Abiotic factors studied were soil salinity, elevation and tidal flooding, and soil water table depth. Sites fell into two categories of vegetation recovery: slow, ca. 0.5%, or fast, more than 5% of total area per year. Although total cover and frequency of salt marsh angiosperms was positively related to soil salinity, and reed grass stand parameters negatively so, fast versus slow recovery rates could not be attributed to salinity. Instead, rates appear to reflect differences in tidal flooding. Rapid recovery was characterized by lower elevations, greater hydroperiods, and higher soil water tables. Recovery of other biotic attributes and functions does not necessarily parallel those for vegetation. At the longest studied system (rapid vegetation recovery) the high marsh snail *Melampus bidentatus* took two decades to reach densities comparable with a nearby reference marsh, whereas the amphipod *Orchestia grillus* was well established on a slow-recovery marsh, reed grass dominated after 9 years. Typical fish species assemblages were found in restoration site creeks and ditches within 5 years. Gut contents of fish in ditches and on the high marsh suggest that use of restored marsh as foraging areas may require up to 15 years to reach equivalence with reference sites. Bird species that specialize in salt marshes require appropriate vegetation; on the oldest restoration site, breeding populations comparable with reference marshland had become established after 15 years. Use of restoration sites by birds considered marsh generalists was initially high and was still nearly twice that of reference areas even after 20 years. Herons, egrets, and migratory shorebirds used restoration areas extensively. These results support our prediction that returning tides will set degraded marshes on trajectories that can bring essentially full restoration of ecological functions. This can occur within two decades, although reduced tidal action can delay restoration of some functions. With this success, Connecticut's Department of Environmental Protection established a dedicated Wetland Restoration Unit. As of 1999 tides have been restored at 57 separate sites along the Connecticut coast.

Webb, J. W., Jr. and C. J. Newling. 1985. Comparison of natural and man-made salt marshes in Galveston Bay complex, Texas. *Wetlands* 4:75-86.

Vegetation of a manmade *S. alterniflora* marsh planted in 1976 on Bolivar Peninsula, Texas, was compared to three natural marshes in the Galveston Bay complex in 1978 and 1979. Methods used included 0.5m^2 quadrats that were randomly placed along elevational transects. From quadrats, researches were able to obtain above-ground biomass analysis on live stem density, dead stem density, stem height, percent cover, and species composition. Below-ground biomass was collected in the same quadrats using about 8-10 cm diameter corers; core depths were 25 and 30 cm. Techniques used are described in detail in this publication. Data collected showed that *S. alterniflora* dominated below the mean high water mark. In the manmade marsh, *S. alterniflora* was significantly greater in 1978 than in natural marshes. At lower elevations below ground biomass was significantly lower in manmade marshes than natural marshes. However, within one-year, below-ground biomass increased in manmade marshes. Authors concluded that above-ground biomass in a two to three year old created salt marsh can be comparable to those in nearby natural marshes.

Weinstein, M. P., J. H. Balletto, J. M. Teal and D. F. Ludwig. 1997. Success criteria and adaptive management for a large-scale wetland restoration project. *Wetlands Ecology and Management* 4:111-127.

Author Abstract. We are using a 20+ year photographic history of relatively undisturbed and formerly diked sites to predict the restoration trajectories and equilibrium size of a 4,050 ha salt marsh on Delaware Bay, New Jersey (USA). The project was initiated to offset the loss of finfishes from once-through cooling at a local power plant. We used a simple food chain model to estimate the required restoration size. This model assumed that annual macrophyte detritus production and benthic algal production resulted in production of finfishes, including certain species of local interest. Because the marsh surface and intertidal drainage system are used by many finfishes and are the focal points for exchange of detrital materials, the restoration planning focused on both vegetational and hydrogeomorphological parameters. Recolonization by *Spartina* spp. and other desirable taxa will be promoted by returning a natural hydroperiod and drainage configuration to two types of degraded salt marsh: diked salt hay (*Spartina patens*) farms and brackish marsh dominated by *Phragmites australis*. The criteria for success of the project address two questions: What is the "bound of expectation" for restoration success, and how long will it take to get there? Measurements to be made are macrophyte production, vegetation composition, benthic algal production, and drainage features including stream order, drainage density, channel length, bifurcation ratios and sinuosity. A method for combining these individual parameters into a single success index is also presented. Finally, we developed adaptive management thresholds and corrective measures to guide the restoration process.

Weller, M. W. 1978. Management of freshwater marshes for wildlife, pp. 267-298. In Good, R. E., D. F. Whigham, R. L. Simpson and C. G. Jackson, Jr. (eds.), Freshwater Wetlands: Ecological Processes and Management Potential. Academic Press, San Diego, CA.

Author Abstract. Although commonly practiced on wildlife management areas, marsh management is poorly founded in theory and as a predictive science. Major objectives have been to preserve marshes in a natural state and to maintain their productivity. System or community-oriented management techniques are encouraged as most likely to meet diverse public needs, whereas species-specific management is more difficult, costly and limited in application.

The structure of a marsh is a product of basin shape, water regimes, cover, water interspersion, and plant species diversity. Resultant vegetative patterns strongly influence species composition and size of bird populations. Food resources influence mammals as well as birds. Species richness (i.e., number of species) may be the simplest index to habitat quality, although various diversity indices need further evaluation.

Marshes are in constant change, and wildlife species have evolved adaptations of wide tolerance or mobility. Throughout the Midwest, water levels and muskrats (*Ondatra zibethicus*) induce most vegetative change, and pattern of vegetation, muskrat and avian responses are predictable in a general way. This short-term successional pattern in marshes forms a usable management strategy. Various ramifications are discussed that may enhance or perpetuate the most beneficial stages.

Artificial management practices are discouraged as costly and of short-term value whereas systems based on natural successional patterns produce the most ecologically and economically sound results. Public pressures for single-purpose management often increase as management potential increases, but such problems can often be avoided by advance planning and public relations.

Marsh management projects for wildlife have rarely been adequately evaluated because of cost, manpower, and inadequate experimental study areas. Some high priority, management oriented research goals are suggested.

Wilcox, D. A. and T. H. Whillans. 1999. Techniques for restoration of disturbed coastal wetlands of the Great Lakes. *Wetlands* 19:835-857.

Author Abstract. A long history of human-induced degradation of Great Lakes wetlands has made restoration a necessity, but the practice of wetland restoration is relatively new, especially in large lake systems. Therefore, we compiled tested methods and developed additional potential methods based on scientific understanding of Great Lakes wetland ecosystems to provide an overview of approaches for restoration. We addressed this challenge by focusing on four general fields of science: hydrology, sedimentology, chemistry, and biology. Hydrologic remediation methods include restoring hydrologic connections between diked and hydrologically altered wetlands and the lakes, restoring water tables lowered by ditching, and restoring natural variation in lake levels of regulated lakes Superior and Ontario. Sedimentological remediation methods include management of sediment input from uplands, removal or proper management of dams on tributary rivers, and restoration of protective barrier beaches and sand spits. Chemical remediation methods include reducing or eliminating inputs of contaminants from point and non-point sources, natural sediment remediation by biodegradation and chemical degradation, and active sediment remediation by removal or by in situ treatment. Biological remediation methods include control of non-target organisms, enhancing populations of target organisms, and enhancing habitat for target organisms. Some of these methods were used in three major restoration projects (Metzger Marsh on Lake Erie and Cootes Paradise and Oshawa Second Marsh on Lake Ontario), which are described as case studies to show practical applications of wetland restoration in the Great Lakes. Successful restoration techniques that do not require continued manipulation must be founded in the basic tenets of ecology and should mimic natural processes. Success is demonstrated by the sustainability, productivity, nutrient-retention ability, invasibility, and biotic interactions within a restored wetland.

Wilcox, D. A., J. E. Meeker, P. L. Hudson, B. J. Armitage, M. G. Black and D. G. Uzarski. 2002. Hydrologic variability and the application of Index of Biotic Integrity metrics to wetlands: a Great Lakes evaluation. *Wetlands* 22:558-615.

Author Abstract. Interest by land-management and regulatory agencies in using biological indicators to detect wetland degradation, coupled with ongoing use of this approach to assess water quality in streams, led to the desire to develop and evaluate an Index of Biotic Integrity (IBI) for wetlands that could be used to categorize the level of degradation. We undertook this challenge with data from coastal wetlands of the Great Lakes, which have been degraded by a variety of human disturbances. We studied six barrier beach wetlands in western Lake Superior, six drowned-river-mouth wetlands along the eastern shore of Lake Michigan, and six open shoreline wetlands in Saginaw Bay of Lake Huron. Plant, fish, and invertebrate communities were sampled in each wetland. The resulting data were assessed in various forms against gradients of human disturbance to identify potential metrics that could be used in IBI development. Our results suggested that the metrics proposed as potential components of an IBI for barrier beach wetlands of Lake Superior held promise. The metrics for Lake Michigan drowned-river-mouth wetlands were inconsistent in identifying gradients of disturbance; those for Lake Huron open embayment wetlands were yet more inconsistent. Despite the potential displayed by the Lake Superior results within the year sampled, we concluded that an IBI for use in Great Lakes wetlands would not be valid unless separate scoring ranges were derived for each of several sequences of water-level histories. Variability in lake levels from year to year can produce variability in data and affect the reproducibility of data collected, primarily due to extreme changes in plant communities and the faunal habitat they provide. Substantially different results could be obtained in the same wetland in different years as a result of the response to lake level change, with no change in the level of human disturbance. Additional problems included limited numbers of comparable sites, potential lack of undisturbed reference sites, and variable effects of different disturbance types. We also evaluated our conclusions with respect to hydrologic variability and other major natural disturbances affecting wetlands in other regions. We concluded that after segregation of wetland types by geographic, geomorphic, and hydrologic features, a functional IBI may be possible for wetlands with relatively stable hydrology. However, an IBI for wetlands with unpredictable yet recurring influences of climate-induced, long-term high water periods, droughts, or drought-related fires or weather-related catastrophic floods or high winds (hurricanes) would also require differing scales of measurement for years that differ in the length of time since the last major natural disturbance. A site-specific, detailed ecological analysis of biological indicators may indeed be of value in determining the quality or status of wetlands, but we recommend that IBI scores not be used unless the scoring ranges are calibrated for the specific hydrologic history pre-dating any sampling year.

Williams, G. D. and J. B. Zedler. 1999. Fish Assemblage Composition in Constructed and Natural Tidal Marshes of San Diego Bay: Relative Influence of Channel Morphology and Restoration History. *Estuaries*: 22:702–716.

Author Abstract. This study evaluated the use by fish of restored tidal wetlands and identified links between fish species composition and habitat characteristics. We compared the attributes of natural and constructed channel habitats in Sweetwater Marsh National Wildlife Refuge, San Diego Bay, California, by using fish monitoring data to explore the relationships between channel environmental characteristics and fish species composition. Fishes were sampled annually for 8 yr (1989–1996) at eight sampling sites, four in constructed marshes and four in natural marshes, using beach seines and blocking nets. We also measured channel habitat characteristics, including channel hydrology (stream order), width and maximum depth, bank slope, water quality (DO, temperature, salinity), and sediment composition. Fish

colonization was rapid in constructed channels, and there was no obvious relationship between channel age and species richness or density. Total richness and total density did not differ significantly between constructed and natural channels, although California killifish (*Fundulus parvipinnis*) were found in significantly higher densities in constructed channels. Multivariate analyses showed fish assemblage composition was related to channel habitat characteristics, suggesting a channel's physical properties were more important in determining fish use than its restoration status. This relationship highlights the importance of designing restoration projects with natural hydrologic features and choosing proper assessment criteria in order to avoid misleading interpretations of constructed channel success. We recommend that future projects be designed to mimic natural marsh hydrogeomorphology and diversity more closely, the assessment process utilize better estimates of fish habitat function (e.g., individual and community-based species trends, residence time, feeding, growth) and reference site choice, and experimental research be further incorporated into the restoration process.

Yozzo, D. J. and D. E. Smith. 1998. Composition and abundance of resident marsh-surface nekton: comparison between tidal freshwater and salt marshes in Virginia, USA. *Hydrobiologia* 362:9-19.

Author Abstract. Previous research on intertidal nekton communities has identified important determinants of community structure and distribution; however, few studies have compared nekton utilization of disparate marsh habitats. In this study, abundance and distribution patterns of resident nekton were compared between tidal freshwater marsh and salt marsh surfaces varying in flooding depth and duration. Nekton were collected in pit traps installed along elevational transects at four marshes in coastal Virginia (two freshwater, two saline) from April through November 1992–1993. The dominant fish collected at all sites was the mummichog (*Fundulus heteroclitus)*. The daggerblade grass shrimp (*Palaemonetes pugio)* was the dominant nekton species collected at salt marsh sites, and was seasonally abundant on tidal freshwater marshes. A positive correlation between flooding depth and nekton abundance was observed on salt marshes; an opposite pattern was observed on tidal freshwater marshes. Tidal flooding regime influences the abundance of resident nekton, however, the effect may be confounded by other environmental variables, including variation in surface topography and seasonal presence or absence of submerged aquatic vegetation (SAV) in adjacent subtidal areas. In mid-Atlantic tidal freshwater wetlands, SAV provides a predation refuge and forage site for early life stages of marsh-dependent nekton, and several species utilize this environment extensively. Salt marshes in this region generally lack dense SAV in adjacent subtidal creeks. Consequently, between-site differences in species and size-specific marsh surface utilization by resident nekton were observed. Larvae and juveniles represented 79% and 59% of total fish collected at tidal freshwater and salt marsh sites, respectively. The resident nekton communities of tidal freshwater and salt marsh surfaces are characterized by a few ubiquitous species with broad environmental tolerances.

Yozzo, D. J. and R. J. Diaz. 1999. Tidal freshwater wetlands: invertebrate diversity, ecology, and functional significance, pp. 889-918. In Batzer, D. P., R. B. Rader and S. A. Wissinger (eds.), Invertebrates in Freshwater Wetlands of North America: Ecology and Management. John Wiley and Sons, Inc., New York.

Author Abstract. Tidal freshwater wetlands are vegetated intertidal habitats characterized by measurable tidal fluctuation and, on occasion, measurable salinity (usually <0.5 practical salinity units). They are unique endpoint habitats created by a combination of terrestrial-riverine and oceanic-estuarine influences. Vascular floral composition is species-rich, among the highest of any wetland type. In contrast, the invertebrate faunal composition of tidal freshwater wetlands is species-poor relative to nontidal rivers, lakes, or estuaries. Tidal freshwater wetlands are characterized by high primary and secondary production and provide critical nursery habitat for many freshwater and estuarine fishery species. Major habitat types found in tidal freshwater wetlands include submerged and floating aquatic macrophyte beds, intertidal emergent marshes, unvegetated intertidal mudflats, and tidal creeks. Macroinvertebrate communities of tidal freshwater wetlands are dominated by annelids (Tubificidae, Naididae, Enchytraidae) and insect larvae (Chironomidae). Meiofaunal communities are dominated by nematodes, microcrustaceans (Ostracoda, Copepoda), naidid oligochaetes, and tardigrades. Despite the potential ecological importance in tidal freshwater wetland invertebrate communities, we know relatively little about how they function in comparison to those of nontidal freshwater and/or estuarine wetlands and how they may respond to both natural and man-induced disturbance.

Zedler, J. B. 2001. Handbook for Restoring Tidal Wetlands. CRC Press, Boca Raton, FL.

This handbook provides a collection of case studies and principle guidelines to guide tidal restoration management. In this handbook Zedler describes the conceptual planning for coastal wetlands restoration, strategies for management of hydrology and soils, the restoration of vegetation and assemblages of fishes and invertebrates, and the process of evaluating, monitoring, and sustaining restored wetlands. Zedler also highlights parameters that should be monitored and techniques that can be used during restoration. Such parameters that are addressed include: hydrology and topography, water quality, soils, substrate qualities, nutrient dynamics, elevation, species abundance and diversity (vegetation, invertebrates and fishes). Techniques that used to monitor certain parameters include: Global Positioning Systems (GPS) and Geographic Information Systems (GIS). Additional information on parameters monitored and techniques used are described in this handbook.

Zedler, J. B. 1996. Tidal Wetland Restoration: A Scientific Perspective and Southern California Focus, 129 pp. California Sea Grant College System, University of California, La Jolla, California. Report No. T-038.

Structural attributes are measured during monitoring as surrogates for functional processes. This is mainly due to the fact that basic ecosystem functioning is still being discovered, and monitoring structural criteria is cheaper than extensive functional assessments. Each monitoring program should have performance criteria that are tailored to that site. With respect to southern California tidal salt marshes, frequency of monitoring is as follows: water quality is biweekly or monthly; vegetation in September; salinity of marsh soil in April and September; fishes and invertebrates on a quarterly basis; and special interest species during reproductive periods.

Three indicators of ecosystem functioning were selected as simple criteria. These included ability to support biodiversity, canopy architecture, and other indicators. Monitoring should be designed to track populations of sensitive and endangered species in order to support biodiversity. Canopy architecture needs to be monitored such that the vegetation can support endangered birds. Other indicators such as water quality can be used to assess potential support of fishes and invertebrates. Once these indicators have been selected, they must be reviewed and accepted by scientific peers. Agencies that manage endangered species must then test the cause-effect relationship between the indicator and the ecosystem function it represents.

Zedler, J. B. 1995. Salt marsh restoration: lessons from California. In Cairns, J. Jr. (ed.) Rehabilitating Damaged Ecosystems, 2nd edition, CRC Press, Incorporated. Boca Raton, FL.

In order to evaluate success, goals and objectives need to be established before performing restoration efforts. Such goals should include the need for regional coordination, and maintaining native species communities that are uncommon in the region as well as maintaining natural variation in communities instead of increasing diversity. Additional goals for hydrological planning are discussed further in this publication.

Experimentation is the most efficient way to refine the science of salt marsh restoration. Practitioners must understand and learn from failures and successes through controlled, replicated field experiments, performed in conjunction with restoration will be extremely valuable. Restoration success should be assessed for two reasons. The first is the need for resource agencies to keep track of how much regional wetland is being restored. The second is to determine whether mitigation has met contractual requirements. Two general criteria of success are whether the restoration project has met the present objectives and what the restoration provided in comparison to the region's needs. Assessment must be performed over the long-term, from at least one to five years up to beyond twenty years. Detailed and frequent sampling is required to detect changes due to restoration as opposed to natural variation.

Zhang, M., S. L. Ustin and E. W. Sanderson. 1996. Monitoring Pacific coast salt marshes using remote sensing. *Ecological Applications* 7:1039-1053.

A study was conducted using field sampling and remote sensing approaches to understand salt marsh ecosystem functions and species distribution. This paper discusses the implications for salt marsh monitoring using remote sensing. Three sites were selected for study along the Petaluma River near the entrance into San Pablo Bay, California. The standing biomass was assessed by field sampling and estimated canopy reflectance. During this study, a positive relationship was found between salinity and biomass up to a threshold of 42kg, after which the biomass declined with increasing salinity for *Salicornia*. No strong relationships were found between the biomass and nitrate nitrogen.

The soil's ammonium nitrogen however had a positive relation to biomass. The soil's redox and salinity increased with elevation and distance from the shoreline, while the soil's moisture and H_2S decreased. Vegetation Index (VI) and Atmospherically Resistant Vegetation Index (ARVI) were measured by handheld field spectrometers and used for estimating green biomass for high cover of *Salicornia*. Soil Adjusted Vegetation Index (SAVI) and Soil Adjusted and Atmospherically Resistant Vegetation Index (SARVI) were used to estimate *Spartina* while the Global Environment Monitoring Index (GEMI) was used to give the best results for *Scirpus*. The relationships between the vegetation indices and biomass were established from the field spectra. The VI estimated spatial patterns of biomass across the salt marsh from Landsat satellite Thematic Mapper ™. The TM displayed spatial patterns equivalent to species zones and biomass abundance. The author indicates that a narrow band reflectance features measured with a handheld spectrometer can be used to predict canopy plant water content. Interpolated estimates of water content from field measured canopy reflectance shown relations to variation in salinity and soil moisture. The Airborne Advance Visible Infrared Imaging Spectrometer data was used to estimate plant water content, displayed similar spatial patterns at the site. The results indicate that biomass production and canopy water content can be determined from remotely sensed spectral measures. The differences in species-specific characteristics may be used for monitoring the species distribution and abundance from airborne or satellite images. Further details of techniques used in this study can be located in the article.

Zheng, L., R. J. Stevenson and C. Craft. 2004. Changes in benthic algal attributes during salt marsh restoration. *Wetlands* 24:309-323.

Author Abstract. To assess attributes of algal assemblages as indicators of salt marsh restoration, we chose eight pairs of salt marshes in North Carolina, USA, each pair with one restored marsh (from 1 to 28 years old) and a nearby existing salt marsh. Algae on both *Spartina alterniflora* and sediments (sediment algae) were collected in each marsh during spring and summer 1998 for assaying algal biomass (dry mass (DM), ash free dry mass (AFDM), chl *a* content, algal biovolume), algal species composition and diversity, and gross primary production. An attribute restoration ratio was calculated by dividing attribute values from each restored marsh by values from a paired reference marsh. Controlling for regional variation in reference marshes substantially increased precision in relations between attributes and the increase in age of restored marshes. The organic matter restoration ratio of sediments increased with age of restored marshes in both spring and summer. The algal biomass restoration ratios of epiphytes, calculated with algal biovolume and chl *a,* increased with restored marsh age in summer but not during spring. Biomass of sediment algae was not related to marsh age. The species diversity of sediment algae in summer showed an asymptotic relationship with sediment nutrient concentration. The similarity of diatom species composition between paired restored and reference sites increased with age of restored marshes during spring and summer. Primary production by epiphytic and sediment algae in summer showed site-specific changes and did not change consistently with marsh age. Algal biomass, algal diversity, and diatom species composition during summer were positively correlated with sediment nitrogen and phosphorus concentration. We concluded that other structural and functional development of restored wetlands, especially nutrient storage in sediments, regulates algal species composition and algal biomass accumulation, which can be used to evaluate salt marsh restoration.

APPENDIX II: COASTAL MARSHES
REVIEW OF TECHNICAL METHODS MANUALS

This Review of Technical Methods Manuals includes a variety of sampling manuals, Quality Assurance/Quality Control (QA/QC) documents, standardized protocols, or other technical resources that may provide practitioners with the level of detail needed when developing a monitoring plan for a coastal restoration project. Examples from both peer reviewed and grey literature are presented. Entries were selected through extensive literature and Internet searches as well as input from reviewers. As with the Annotated Bibliographys, these entries are not, however, a complete list. Entries are arranged alphabetically by author. Wherever possible, web addresses or other contact information are included in the reference to assist readers in more easily obtaining the original resource. Summaries preceded by the terms '*Author Abstract*' or '*Publisher Introduction*' or similar descriptors were taken directly from their original source. Summaries without such descriptors were written by the authors of the associated chapters.

Adamus, P. R., L. T. Stockwell, E. J. Clairain, Jr., M. E. Morrow, L. P. Rozas and R. D. Smith. 1991. Wetland evaluation technique. United States Army Corps of Engineers, Waterways Experiment Station. Technical report WRP-DE-2.

The Wetland Evaluation Technique (WET) provides information on predictors of wetland functions. The manual is divided into two volumes. Information presented in volume one includes: conceptual fundamentals for WET, wetland functions in relation to their processes and interactions with other functions, a review of technical literature on each function, the predictors used for determining the probability ratings for wetland functions, and discussion of the concept of wetland social significance as it is used in WET. Volume two of the manual outlines steps required to put into practice the WET method, discusses its application and limitations in detail, and provides documentation for a computer program designed to assist data analysis in WET. Detailed information on methods and procedures described here can be obtained from the manual.

Adamus, P. and K. Brandt. 2003. Impacts on quality of inland wetlands of the United States: a survey of indicators, techniques, and applications of community level biomonitoring data. U.S. Environmental Protection Agency. http://www.epa.gov/owow/wetlands/wqual/introweb.html

This on-line resource is based on the now out of print Report #EPA/600/3-90/073 prepared for the U.S. EPA Wetland Research Program. It is currently being updated. Although it is intended for inland wetlands, many of the resources cited and information provided is applicable to coastal freshwater wetlands. The report describes in detail many of the interactions and possible effects of eutrophication, organic loading, contaminant toxicity, acidification, salinization, sedimentation, turbidity/shade, vegetation removal, thermal alteration, dehydration, inundation, and fragmentation of habitat on wetland biological communities. The effect of these stressors on microbes, algae, vascular plants, invertebrates, fish, amphibians, reptiles, birds, mammals, and selected biological processes is presented wherever information is available. Extensive lists of literature cited could be used to supplement presented information if desired.

This resource was originally designed for use in developing biological criteria for use in wetland assessment, protection, and management as well as to help identify degraded sites for potential restoration. The information presented can also be used to develop parameters to monitor the progress of restoration efforts, before and after implementation. By linking many of the structural components that help make up wetland habitats with functional components (in this case biota) the information presented can be used to help restoration practitioners select the appropriate structural and functional parameters to monitor as they relate to project goals.

American Public Health Association. 1999. Standard Methods for Examination of Water & Wastewater. 20 ed. American Public Health Association, Washington, D.C.

Standard Methods for Examination of Water and Wastewater is an essential resource for any laboratory performing analyses on water samples for chemical or biological components. Procedures for the sampling of zooplankton, phytoplankton, periphyton, macrophytes, benthic macroinvertebrates, and fish are also included as well as general identification keys to these organisms. Each procedure is explained in step-by-step detail with information on the strengths and weaknesses of various measurement methods. To a general practitioner, this resource would be useful to explain the chemical and biological components they are sampling, what the analysis entails, and the meaning of the final value obtained from each analysis. Various editions should be available at most any laboratory, or scientific or university library.

American Society of Mammalogists. 1998. Guidelines for the capture, handling, and care of mammals, 47 pp. American Society of Mammalogists. http://www.unh.edu/osr/compliance/98acucguidelines.PDF

Partial Author Introduction. The objective of the Society's 1987 guidelines for acceptable field methods in mammalogy was to identify field methods in mammalogy that would meet standards of the American Society of Mammalogists. The guidelines were formulated with consideration for both the welfare of subject animals and the research needs of field investigators for whom guidelines for laboratory animal care generally do not apply. These published guidelines have served ASM members and non-members well during the past decade; however, the passage of time has seen advances in technology (e.g., passive integrated transponders - PIT tags - for marking animals) that need to be addressed. In addition, the past decade has produced increased recognition of the potential risks to field investigators from handling live and dead mammals, as well as heightened concern within and outside the scientific community regarding the humane treatment of mammals collected and used in scientific research.

Baker, J. M. and W. J. Wolff. 1987. Biological Surveys of Estuaries and Coasts. 449 pp. Cambridge University Press, Cambridge, England.

Baker and Wolff have compiled an indispensable resource for anyone planning a coastal monitoring effort. Various authors have contributed chapters detailing the planning and sampling of salt marsh, soft bottom, and rock bottom habitats. While one chapter focuses on remote sensing techniques, the bulk of the book is devoted to field survey equipment and techniques to sample a variety of biological components including: bacteria, fungi, plankton, fish, birds, and plants. A chapter listing identification manuals for each type of organism likely to be encountered in sampling coastal habitats is also provided. Each type of sampling gear and method is briefly described with readers directed to the original sources for more detail as needed.

Batzer, D. P., A. S. Shurtleff and R. B. Rader. 2001. Sampling invertebrates in wetlands, pp. 339-354. In Rader, R. B., D. P Batzer and S. A. Wissinger (eds.) Bioassessment and Management of North American Freshwater Wetlands. John Wiley and Sons, New York.

Author Abstract. Difficulties in sampling have long hindered research on wetland macroinvertebrates. With the increasing interest in using macroinvertebrate populations to monitor the environmental health of wetlands, sampling of these organisms has become an important research focus. For this chapter we summarized sorting and subsampling procedures and queried many of the prominent researchers who study freshwater wetland macroinvertebrates about their preferences in samplers. For each device we provide a synopsis of their comments, both pro and con, and provide direction on how to use each sampler. Based on the results of this survey as well as published studies that contrast sampler efficacies, we conclude that the sweep net should probably become the sampler of choice for most bioassessment efforts that use wetland macroinvertebrates. We also recommend that most programs sort in the laboratory using either a selective or random technique (depending on the level of taxonomic expertise) and a fixed count of 100 to 300 individuals.

Carlisle, B. K., A. M. Donovan, A. L. Hicks, V. S. Kooken, J. P. Smith and A. R. Wilbur. 2002. A Volunteer's Handbook for Monitoring New England Salt Marshes, 164 pp. Massachusett's Office of Coastal Zone Management, Boston, MA.

This manual was designed to help volunteer groups collect and record data on salt marsh health in a consistent approach. Protocols discussed in this manual are a collaboration of information by the authors, other wetland scientists in the Northeast and federal and state agencies. Authors focused on bioassessment techniques, used to measure wetland health by examining resident plants, animals, and their habitat. In 1995 the authors began to develop scientific monitoring protocols in a series of pilot projects that allowed them to test, evaluate, and revise the sampling and analysis techniques for different biological, physical, and chemical parameters of the wetland condition. The manual highlights methods and parameters used when monitoring salinity, tidal hydrology, invertebrates, plants, fish and birds in salt marshes. Examples of methods used to monitor a few of the parameters previously mentioned include: sound surveys for monitoring birds; sampling fish using bag seines and then identifying the species; and sampling invertebrates using a ponar grab and then identifying taxa. The manual also discusses cost estimates and the time expected to be applied when monitoring each parameter. Additional information on methods used for monitoring salt marsh conditions are described in this document.

Cook Inlet Keeper. 1998. Volunteer training manual: citizens environmental monitoring program. U.S. Environmental Protection Agency. Homer, AK. http://www.inletkeeper.org/training.htm

This manual provides Cook Inlet Keeper volunteers with information needed to monitor water quality in the Cook Inlet watershed. It also provides guidelines for monitoring procedures that are currently included in the Keeper's Citizens' Environmental Monitoring Program (CEMP). Outlined in this document are safety and access issues; a monitoring overview that discusses water quality test methods, test parameters and a proposed sampling schedule; monitoring procedures including: a field procedure checklist, field observations, steps for collecting the samples, detailed testing procedures, sample custody guidelines, and instructions for completing data sheets; equipment care and waste disposal; data management and reporting; and quality control. Additional information for methods and procedures used can be obtained from this manual.

Davies, J., J. Baxter, M. Bradley, D. Connor, J. Khan, E. Murray, W. Sanderson, C. Turnbull and M. Vincent. 2001. Marine Monitoring Handbook. UK Marine Science Project, and Scottish Association of Marine Science. Joint Nature Conservation Committee, English Nature, Scottish Natural Heritage, Environment and Heritage Services. http://www.jncc.gov.uk/marine/mmh/Contents.htm

The UK Marine Science Project developed this handbook to provide guidelines for recording, monitoring and reporting characteristics and conditions of marine habitats. However, based on location and other environmental conditions, methodologies will have to be modified to suit the structural characteristics of the habitat. This manual addresses the fundamentals and procedures for monitoring different parameters in marine habitats, management tools, and benefits and costs for developing a monitoring project. Topics presented in this document include establishing marine monitoring programs highlighting what needs to be measured and methods to use; provides guidance when developing a monitoring program; selecting proper monitoring techniques to attain precision and accuracy; and procedural guidelines for monitoring a specific marine habitat. Detailed information on the tools needed for monitoring marine habitats are described within the marine monitoring handbook.

Dobson, J. E., E. A. Bright, R. L. Ferguson, D. W. Field, L. L. Wood, K. D. Haddad, H. Iredale III, J. R. Jensen, V. V. Klemas, R. J. Orth, and J. P. Thomas. 1995. NOAA Coastal Change Analysis Program (C-CAP): Guidance for Regional Implementation, 92 pp. NOAA Technical Report NMFS 123.

The coastal change analysis program (C-CAP) is part of the Estuarine Habitat Program of NOAA's Coastal Ocean Program. C-CAP inventories benthic habitats, wetland habitats, and adjacent uplands to learn more about the linkages between coastal and upland habitats, as well as impacts on living marine resources. Through remote sensing technology, C-CAP monitors changes in the habitats on a 1-5 year cycle. Satellite imagery, aerial photography, and field data are meshed in a geographic information for spatial analysis. Ongoing C-CAP research will continue to develop remote sensing techniques to measure biomass, productivity, and functional status of wetlands and other coastal habitats. Land-cover maps will be produced on both local and regional scales for distribution. This technique provides a better understanding of how the wetlands and organisms living there interact and which influence this whole ecosystem. This allows for a better restoration design to be created. Details for techniques used for monitoring vegetation cover and habitat change are described in this paper.

Erwin, R. M., C. J. Conway and S. W. Hadden. 2002. Species occurrence of marsh birds at Cape Cod National Seashore, Massachusetts. *Northeastern Naturalist* 9:1-12.

Author Abstract. We initiated an inventory and a field test of a protocol that could be used for monitoring marsh birds at the Cape Cod National Seashore in eastern Massachusetts during 1999 and 2000, as part of a more comprehensive national effort. Using cassette tapes during call broadcast surveys, we visited a total of 78 survey points at freshwater, brackish, and salt marsh sites three times on the ground or in canoes during the breeding season (May-June), fall migration (September to November), and twice during winter (December-January). Observer bias on our marsh bird surveys appeared negligible. Although both auditory and visual detection of most species was low (mean < 0.3 birds per replicate-survey point), we confirmed the presence of seven marsh species, including American Bittern (*Botaurus lentiginosus*), Least Bittern (*Ixobrychus exilis*), American Coot (*Fulica americana*), King Rail (*Rallus elegans*), Pied-billed Grebe (*Podilymbus podiceps*), Sora (*Porzana carolina*), and Virginia Rail (*Rallus limicola*). We suspected breeding of Least Bitterns and Soras at Great Pond in Provincetown, and for Virginia Rails at Hatches Harbor, Provincetown. The most frequently detected species were Soras, Pied-billed Grebes, and Virginia Rails. We recommend using call broadcast surveys for these cryptic species to enhance their probabilities of detection.

Firehock, K., J. V. Middleton, K. D. Starinchak, C. Williams and L. Geoff. 1998. Handbook for Wetlands Conservation and Sustainability. 2nd ed. Izaak Walton League of America. http://www.iwla.org/sos/handbook/

This 288-page handbook explains wetland ecology, functions, and values. It provides tips for organizing your community to monitor, conserve, and restore local wetlands. It also includes monitoring instructions, wetland project ideas, regulatory avenues for wetland protection, case studies, and an extensive resource section. Some sections of the book are available free on-line at the link above.

Gertz, S. M. 1984. Biostatistical aspects of macrophyton sampling, pp. 28-35. ASTM Special Technical Publication 1984. ASTM, Philadelphia.

Author Abstract. Problems of sampling macrophytes are related to the types of communities under consideration and the goals of a particular study. The communities may range from completely submersed beds of large algae, mosses, pteridophytes, or angiosperms to rooted plants with floating leaves or floating plants with emergent leaves to wetland areas. The goals of a study may be community description or impact analysis. Because of this community goal diversity a quantitative investigation often requires a rigorous statistical design to determine the best sampling design. Of the various sampling designs available there are two general techniques; plot or quadrat methods and plotless methods. Plot or quadrat methods are area methods of sampling communities where the plot may be rectangular, square, or circular, and all individuals in the plot are sampled. Plotless methods usually involve a more random approach of sampling; for example, a compass line is laid out through the community and samples are taken according to some fixed rule. It is the purpose of this paper to review these various sampling methodologies and to evaluate their efficacy, in a statistical sense, in view of the goals of a specific study.

Hayes, D. F., T. J. Olin, J. C. Fischenich and M. R. Palermo. 2000. Wetlands engineering handbook. 14 pp. ERDC/EL TR-WRP-RE-21, U. S. Army Engineer Research and Development Center, Vicksburg, MS. http://www.wes.army.mil/el/wetlands/pdfs/wrpre21/wrpre21.pdf

The *Wetlands Engineering Handbook* presents methods for monitoring and evaluating success of wetland restoration/creation efforts. Authors emphasize that local expertise and databases for particular wetland types must be used together with the guide to ensure monitoring plans for a specific project are effectively developed. Chapter 8 of this report provides a guide for developing evaluation criteria and monitoring projects for wetland restoration and creation. Also presented is guidance for monitoring and success evaluation on basic monitoring concepts, assessing wetland hydrology, evaluating soils and vegetation, and fauna usage. The authors also outline an approach to determining project goals and evaluation criteria, basic considerations related to monitoring, detailed information on how to assess wetland structure and function regarding hydrology, soils, vegetation, and fauna (e.g. macroinvertebrates, birds and fish). Additional information needed on assessment, monitoring and evaluating success are described within this report.

Holst, L., R. Rozsa, L. Benoit, S. Jacobson and C. Rilling. 2003. Long Island Sound habitat restoration initiative: technical support for coastal habitat restoration. EPA Long Island Sound Office, Stamford, CT. http://www.longislandsoundstudy.net/habitat/

Partial Introduction. This document contains a series of reports produced through the Habitat Restoration Work Group of the Long Island Sound Study (LISS). It is designed to provide basic technical information about the subject habitat and its restoration for persons interested in planning and pursuing a restoration project. Topics covered include ecological descriptions of the plant and animal communities associated with the habitat, the natural history and effects of human influence on the habitat, and the state of the science in restoring the habitat. Included at the end of each section is a list of the literature cited. The reader is strongly urged to investigate these source materials further to achieve a fuller understanding of the ecology and issues related to the subject habitat. The reader is also encouraged to contact the state and federal agency representatives of the Habitat Restoration Work Group for technical advice.

The habitats covered to date include: tidal wetlands, freshwater wetlands, submerged aquatic vegetation, coastal grasslands, coastal barriers, beaches, and dunes.

Matthews, G. A., and T. J. Minnello. 1994. Technology and success in restoration, creation, and enhancement of *Spartina alterniflora* marshes in the United States. Vol. 2 Inventory and human resources directory. NOAA Coastal Ocean Program Office, Decision Analysis Series No.2. NOAA Coastal Ocean Office, Silver Spring, Maryland. Executive Summary available at: http://www.cop.noaa.gov/pubs/das/das2.html

Author Abstract. This document describes a project that was conducted to provide resource managers, habitat researchers, coastal planners and the general public with an assessment of the technology and success in restoration, enhancement, and creation of salt marshes in the United States. The objective was to be accomplished through the development of three products: 1) an annotated bibliography of the pertinent literature, 2) an inventory of restored, enhanced, or created *Spartina alterniflora* marshes, and 3) a directory of people working in salt marsh creation and restoration. This executive summary describes these products and provides an overall assessment of our understanding regarding restoration, enhancement, and creation of salt marsh habitats. In particular, we have stressed *Spartina alterniflora* marshes and habitat functions related to the support of fishes, crustaceans, and other aquatic life.

McCauley, V. J. E. 1975. Two new quantitative samplers for aquatic phytomacrofauna. *Hydrobiologia* 47:81-89.

Author Abstract. A description and drawings are given for 2 new samplers for quantitative studies on invertebrates associated with aquatic macrophytes. One was designed for sampling rushes and bullrushes, and the other for submerged and/or floating vegetation.

McCobb, T. D. and P. K. Weiskel. 2002. Long-term hydrologic monitoring protocol for coastal ecosystems, 93 pp. Protocol, USGS

Patuxent Wildlife Research Center, Coastal Research Field Station, University of Rhode Island, Narragnasett, RI. http://science.nature.nps.gov/im/monitor/protocols/caco_hydrologic.pdf

Author Abstract. Long-term monitoring of hydrologic change using a standard data-collection protocol is essential for the effective management of terrestrial, aquatic, and estuarine ecosystems in the coastal park environment. This study develops a consistent protocol for monitoring changes in ground-water levels, pond levels, and stream discharge using methods and techniques established by the U.S. Geological Survey for use in the Long-term Coastal Monitoring Program at the Cape Cod National Seashore. The protocol establishes a hydrologic sampling network in the four ground-water-flow cells in the Seashore area, and provides justification for the measurement methods selected and for the spatial and temporal sampling frequency. Data collected during the first year of monitoring are included in this report; common hydrologic analyses such as hydrographs for ground-water and pond levels, and rating curves between stream stage and discharge for streamflow, are presented for selected sites. Long-term hydrologic monitoring at the Seashore will aid in interpretation of the findings of other monitoring programs. Developing and initiating long-term hydrologic monitoring programs will provide a better understanding of effects of natural and human-induced change at both the local and global scales on coastal water resources in park units.

Merritt, R. W. and K. W. Cummins, (eds.). 1996. An Introduction to the Aquatic Insects of North America. Third edition ed. Kendall/Hunt Publishing Company, Dubuque, IA, USA.

While the bulk of this book is on identification of aquatic insects of North America, Merritt and Cummins include several chapters useful in project planning as well. Various experts in the field of aquatic insect collection and identification have submitted chapters on: the general morphology of aquatic insects, designing studies, collection equipment and techniques, aquatic insect respiration, habitat and life history, and the ecology and distribution of aquatic insects. The rest of the manual is devoted to identification keys for each family of aquatic insect found in North America with many detailed and useful pictures of identifying characteristics.

Since this book is continental in scope, it is suggested that practitioners first look for identification keys prepared for their local or regional waterways. This will reduce much confusion in the identification process by eliminating species that are not found locally. Any local aquatics expert or science librarian should be able to locate these materials. If local materials are not available, then Merritt and Cummins will be useful, however, be sure to check the distribution of species identified whenever possible as a way to check accuracy.

Molano-Flores, B. 2002. Critical trends assessment program: monitoring protocols, 39 pp. Illinois Natural History Survey, Office of the Chief Technical Report 2002-2, Champaign, IL. http://ctap.inhs.uiuc.edu/mp/pdf/mp.htm

The Critical Trends Assessment Program (CTAP) monitors the conditions of forests, grasslands, wetlands and streams throughout Illinois. CTAP also assesses current and future trends in ecological conditions for state, regional and site-specific basis. The CTAP document presents standardized monitoring protocols for the habitat types previously mentioned. Wetland habitat criteria as well as wetland sampling protocols are discussed in this document. Highlighted in this section are methods used to monitor ecological changes occurring in wetlands. These methods include establishing study plots, GPS data, general site characteristics, slope and aspects, ground cover and woody vegetation measurements, big plot and collection of voucher specimens. Each method used and parameters measured provide data on the structural and functional characteristic of the habitat as well as the habitat's overall condition.

Murphy, B. R. and D. W. Willis, (eds.). 1996. Fisheries Techniques: Second edition. American Fisheries Society, Bethesda, MD.

Murphy and Willis have edited the industry standard for fisheries sampling techniques. A variety of experts in the field have written chapters that cover all aspects of how to sample and measure fish. Topics include: planning for sampling, data management and statistical techniques, safety, habitat measurements, care and handling of samples, passive and active capture techniques, collection and identification of eggs and larvae, sampling with toxics, invertebrates, tagging and marking, acoustic assessment, field examination and measurements, age and growth rate determination, diet, underwater observation, creel sampling, commercial surveys, and socioeconomic measurements.

Muscha, M. J., K. D. Zimmer, M. G. Butler and M. A. Hanson. 2001. A comparison of horizontally and vertically deployed aquatic invertebrate activity traps. *Wetlands* 21:301-307.

Author Abstract. Activity traps are commonly used to develop abundance indices of aquatic invertebrates and may be deployed with either the funnel parallel to the water surface (horizontal position) or facing down (vertical position). We compared the relative performance of these two positions in terms of numbers of invertebrates captured, species richness of samples, detection rates of specific taxa, and community-level characterizations. Estimates of zooplankton abundance were also compared to quantitative estimates obtained using a water-column sampler. We used a matched pairs design where 10 pairs of traps (one horizontal, one vertical) were deployed in each of 4 prairie wetlands on 5 dates in 1999. Vertical traps had higher detection rates and captured greater numbers of adult and larval Coleoptera, Hemiptera, Chaoboridae, hydracarina, cladocera, and Copepoda and also produced samples with greater species richness. Horizontal traps captured greater numbers of Amphipoda and Ostracoda and had higher detection rates for these taxa. Estimates of zooplankton abundance with vertical traps also correlated better with quantitative estimates and indicated greater differences between wetlands than horizontal traps. Both traps showed similar relationships among wetlands and changes through time at the community level, but vertical traps were more sensitive to temporal change. Our results indicate that vertical traps outperform horizontal traps and are preferable for obtaining indices of invertebrate abundance.

National Park Service Inventory and Monitoring. Guidance for designing an integrated monitoring program. http://science.nature.nps.gov/im/monitor/vsmTG.htm#Introduction

The goal of the National Park Service (NPS) program is to monitor the status and trend of the park's habitat structure and function as well as its condition. Monitoring tracks management and restoration efforts, detects early warning signs of threats to the habitat and provides fundamentals needed to understand and identify changes occurring in the habitat. NPS provides information on developing a scientifically sound monitoring program. Information needed to develop a monitoring plan include: the establishment of clearly stated project goals and objectives; creation of effective, realistic, specific, unambiguous, and measurable monitoring objectives; development of conceptual models of relevant ecosystems processes; selection and prioritization of indicators to be monitored; consideration of sampling designs; development of protocols; and management and analysis of data. Additional information on guidelines for developing monitoring protocols is described in this report.

Neckles, H. A., M. Dionne, D. M. Burdick, C. T. Roman, R. Buchsbaum and E. Hutchins. A monitoring protocol to assess tidal restoration of salt marshes on local and regional scales. Restoration Ecology 10:556-570.

Author Abstract. Assessing the response of salt marshes to tidal restoration relies on comparisons of ecosystem attributes between restored and reference marshes. Although this approach provides an objective basis for judging project success, inferences can be constrained if the high variability of natural marshes masks differences in sampled attributes between restored and reference sites. Furthermore, such assessments are usually focused on a small number of restoration projects in a local area, limiting the ability to address questions regarding the effectiveness of restoration within a broad region. We developed a hierarchical approach to evaluate the performance of tidal restorations at local and regional scales throughout the Gulf of Maine. The cornerstone of the approach is a standard protocol for monitoring restored and reference salt marshes throughout the region. The monitoring protocol was developed by consensus among nearly 50 restoration scientists and practitioners. The protocol is based on a suite of core structural measures that can be applied to any tidal restoration project. The protocol also includes: additional functional measures for application to specific projects. Consistent use of the standard protocol to monitor local projects will enable pooling information for regional assessments. Ultimately, it will be possible to establish a range of reference conditions characterizing natural tidal wetlands in the region and to compare performance curves between populations of restored and reference marshes for assessing regional restoration effectiveness.

Niedowski, N. L. 2000. New York state salt marsh restoration and monitoring guidelines, 141 pp. New York Department of State, Albany, N.Y. and the New York Department of Environmental Conservation, East Setauket, New York. http://www.csc.noaa.gov/lcr/rhodeisland/html/resource/nymarsh.pdf

This monitoring protocol is designed to assess the progress towards, success or failures of salt marsh restoration. The author discusses in this document parameters and methods to be used to monitor a salt marsh restoration project. Depending on restoration goals and details of the project, modifications of the suggested protocol may be needed. Guidelines followed when planning and locating restoration project transects, 1.0m^2 quadrats, and fixed-point photo stations are presented in the document. Monitoring parameters and activities should also be clearly expressed and documented.

The author suggested that monitoring be conducted at the restoration site and at an appropriate reference site. The reference site should consist of a minimum of three control transects and three quadrats, and located adjacent with or nearby the restoration project site. It should also be similar in morphology and vegetation. Techniques used when monitoring salt marsh restoration such as transects, quadrats, permanent fixed-photo stations, video monitoring, aerial infrared photography are discussed in detail within the document. The importance of pre-restoration monitoring activities and post-construction monitoring activities are described in the document with suggested timeline for each. Assessments performed for more than five years on vegetation development, benthic invertebrates, macrofauna and soil properties (salinity and organic matter) are described in the document. See document for additional information on guidelines and methods used.

Olin, T. J., J. C. Fischenich, M. R. Palermo and D. F. Hayes. 2000. Wetlands Engineering Handbook: Monitoring. U. S. Army Engineer Research and Development Center, Vicksburg, MS. Technical Report ERDC/EL TR-WRP-RE-21.

The wetlands engineering handbook presents methods for monitoring and evaluating success. Authors emphasize that local expertise and data bases for particular wetland types must be used together with the guide to ensure monitoring plans for a specific project are effectively developed. Chapter eight of this report provides a guide for developing evaluation criteria and monitoring projects for wetland restoration and creation. Also presented is guidance for monitoring and success evaluation on basic monitoring concepts, assessing wetland hydrology, evaluating soils and vegetation, and fauna usage. The authors also outline an approach to determining project goals and evaluation criteria, basic considerations related to monitoring, provide detailed information on how to assess wetland structure and function regarding hydrology, soils and vegetation, and fauna (e.g., macroinvertebrates, birds and fish). Additional information needed on assessment, monitoring and evaluating success are described within this report.

Ossinger, M. 1999. Success standards for wetland mitigation projects - a guideline, 31 pp. Washington State Department of Transportation, Environmental Affairs Office. http://pnw.sws.org/forum/success.PDF

This report offers guidance and examples on how to write specific success criteria for mitigation and restoration projects. Though it was designed to address mitigation projects in the Pacific Northwest, its information and approach make it useful throughout the United States. It outlines the steps necessary for planning the monitoring and management of a mitigation/restoration project. Guidance in writing the following program elements is provided: how to set project goals, how to select specific project objectives (i.e., what functions or values will the mitigation/restoration provide), how to select performance objectives (i.e., what structural characteristics need to be in place to provide desired functions), selection of success standards (measurable benchmarks used to determine success of performance objectives), monitoring method (how will the success standard be measured), contingency measure (what to do if the success standards are not met). Several examples are provided of each of these steps. These examples, while not all-inclusive, facilitate the application of this method to diverse areas and project types.

Ozesmi, S. L. and M. E. Bauer. 2002. Satellite remote sensing of wetlands. *Wetlands Ecology and Management* 10:381-402.

Author Abstract. To conserve and manage wetland resources, it is important to inventory and monitor wetlands and their adjacent uplands. Satellite remote sensing has several advantages for monitoring wetland resources, especially for large geographic areas. This review summarizes the literature on satellite remote sensing of wetlands, including what classification techniques were most successful in identifying wetlands and separating them from other land cover types. All types of wetlands have been studied with satellite remote sensing. Landsat MSS, Landsat TM, and SPOT are the major satellite systems that have been used to study wetlands; other systems are NOAA AVHRR, IRS-1B LISS-II and radar systems, including JERS-1, ERS-1 and RADARSAT. Early work with satellite imagery used visual interpretation for classification. The most commonly used computer classification method to map wetlands is unsupervised classification or clustering. Maximum likelihood is the most common supervised classification method. Wetland classification is difficult because of spectral confusion with other landcover classes and among different types of wetlands. However, multi-temporal data usually improves the classification of wetlands, as does ancillary data such as soil data, elevation or topography data. Classified satellite imagery and maps derived from aerial photography have been compared with the conclusion that they offer different but complimentary information. Change detection studies have taken advantage of the repeat coverage and archival data available with satellite remote sensing. Detailed wetland maps can be updated using satellite imagery. Given the spatial resolution of satellite remote sensing systems, fuzzy classification, subpixel classification, spectral mixture analysis, and mixtures estimation may provide more detailed information on wetlands. A layered, hybrid or rule-based approach may give better results than more traditional methods. The combination of radar and optical data provide the most promise for improving wetland classification.

Pacific Estuarine Research Laboratory. 1990. A manual for assessing restored and natural coastal wetlands with examples from Southern California. La Jolla, California. California Sea Grant Report -T-CSGCP-021. http://www.tijuanaestuary.com/nat_res.asp

This manual provides information for assessing the structure and functions of coastal wetlands. The main purpose of this document is to standardize methods of assessing restored, enhanced or constructed wetlands in order to maintain biodiversity. However, the function of this manual emphasizes use for salt marshes and tidal creeks. The document provides strategies for wetland construction, restoration and enhancement that include stating the rationale for functional assessment, objectives of assessment, criteria, and reference wetlands and reference data sets. Sampling methods and comparative data collected from natural wetlands include hydrologic functions, water quality, soil substrate quality and nutrient dynamics, vegetation composition and growth, and fauna presence and abundance. Additional information on methods used for coastal wetlands are described in this document.

Poppe, L. J., A. H. Eliason, J. J. Fredericks, R. R. Rendigs, D. Blackwood and C. F. Polloni. 2003. Grain-size analysis of marine sediments: methodology and data processing, 58 pp. In USGS East-coast Sediment Analysis: Procedures, Databases, and Georeferenced Displays. US Geological Survey Open-File Report 00-358. http://pubs.usgs.gov/of/of00-358/text/chapter1.htm

Partial Author Introduction. The purpose of this chapter is to describe some of the laboratory methods, equipment, computer hardware, and data-acquisition and data-processing software employed in the sedimentation laboratory at the Woods Hole Field Center of the Coastal and Marine Geology Program of the U.S. Geological Survey. The recommendations and laboratory procedures given below are detailed, but are by no means complete. Serious users are strongly encouraged to consult the original references and product manuals.

Purinton, T. A. and D. C. Mountain. 1997. Tidal crossing handbook: A volunteer guide to assessing tidal restrictions. Parker River Clean Water Association. http://www.parker-river.org/PRCWAbookstore/Publications/Guides/TidalHandbook/HB-Contents.htm

This online resource outlines methods for volunteers to monitor water level fluctuations in tidally-restricted areas. Methods are broken down into three phases. Phase I consists of locating crossings and performing a preliminary, visual assessment to determine which crossings are potentially restrictive and may require the collection of quantitative data. Phase II is based on an intensive, day-long monitoring effort to provide quantitative data on the impact on tidal range of the crossing. Phase III consists of analyzing the data obtained from Phase II and formulating recommendations for changes that can be made to improve tidal flow. Troubleshooting recommendations and sample data sheets are also included.

Raposa, K. B. and C. T. Roman. 2001. Monitoring nekton in shallow estuarine habitats, 39 pp. Protocol, Long-term Coastal Ecosystem Monitoring Program, Cape Cod National Seashore, Wellfleet, MA. http://science.nature.nps.gov/im/monitor/protocols/caco_nekton.pdf

Author Abstract. Long-term monitoring of estuarine nekton has many practical and ecological benefits but efforts are hampered by a lack of standardized sampling procedures. This study develops a protocol for monitoring nekton in shallow (<1 m) estuarine habitats for use in the Longterm Coastal Monitoring Program at Cape Cod National Seashore. Sampling in seagrass and salt marsh habitats is emphasized due to the susceptibility of each habitat to anthropogenic stress and to the abundant and rich nekton assemblages that each habitat supports. Extensive sampling with quantitative enclosure traps that estimate nekton density is suggested. These gears have a high capture efficiency in most habitats and are small enough (typically 1 m2) to permit sampling in specific microhabitats. Other aspects of nekton monitoring are discussed, including seasonal sampling considerations, sample allocation, station selection, sample size estimation, parameter selection, and associated environmental data sampling. Developing and initiating long-term nekton monitoring programs will help track natural and human-induced changes in estuarine nekton over time and advance our understanding of the interactions between nekton and the dynamic estuarine environment.

Rey, J. R., R. A. Crossman, T. R. Kain, F. E. Vose and M. S. Peterson. 1987. Sampling zooplankton in shallow marsh and estuarine habitats: gear description and field tests. *Estuaries* 10:61-67.

Author Abstract. Pump and net samplers for collecting zooplankton from very shallow marsh and estuarine habitats are described. Their use is illustrated with data obtained in salt marshes along the Indian River lagoon in east central Florida. In general, both pump and net samplers were found to be satisfactory for sampling zooplankton in these areas. Larger sample volumes were obtained with gear utilizing 202 μ mesh sizes than with gear using 63 μ mesh because the latter became clogged very quickly. Quantitative and qualitative similarity between samples collected with different gear was moderate to low. Comparison of the kinds and densities of taxa captured with the various gear indicate that a combination of techniques may be needed to ensure a proper description of the plankton communities of the area.

Ribic, C. A., T. R. Dixon and I. Vining. 1992. Marine debris survey manual, 92 pp. NOAA Technical Report NMFS 108, NOAA National Marine Fisheries Service, Seattle, Washington.

Author Introduction. Over the last several years, concern has increased about the amount of man-made materials lost or discarded at sea and the potential impacts to the environment. The scope of the problem depends on the amounts and types of debris. One problem in making a regional comparison is the lack of a standard methodology. The objective of this manual is to discuss designs and methodologies for assessment studies of marine debris.

This manual has been written for managers, researchers, and others who are just entering this area of study who seek guidance in designing marine debris surveys. Active researchers will be able to use this manual along with applicable references herein as a source for design improvement. To this end, the authors have synthesized their work and reviewed survey techniques that have been used in the past for assessing marine debris, such as sighting surveys, beach surveys, and trawl surveys, and have considered new methods (e.g., aerial photography). All techniques have been put into a general survey planning framework to assist in developing different marine debris surveys.

Richardson, C. J. and J. Vymazal. 2001. Sampling macrophytes in wetlands, pp. 297-336. In Rader, R. B., D. P Batzer and S. A. Wissinger (eds.), Bioassessment and Management of North American Freshwater Wetlands. John Wiley and Sons, New York.

Author Abstract. The use of macrophytes as biomonitors in wetland ecosystems are presented in terms of assessment of plant population and community responses to disturbance or anthropogenic inputs. The life forms of macrophytes are reviewed and the sampling procedures for estimating changes in population size as well as community structure are presented for herbaceous plants, shrubs, and trees. The methods and formulas for determining abundance and cover as well as frequency, density and dominance are given for plant biomass and productivity measurements. We also outline procedures for establishing macrophytes growth rates and nutrient status in wetland plants. Procedures for determining both above- and belowground biomass, nitrogen and phosphorous as well as ash-free dry matter are presented along with representative data for typical wetland species. In this chapter, we provide a comprehensive plan for sampling and monitoring of plant populations and communities in wetlands.

Roman, C. T., M. J. James-Pirri and J. F. Heltshe. 2001. Monitoring salt marsh vegetation. A protocol for the long-term coastal ecosystem monitoring program at Cape Cod National Seashore, 48 pp. Long-term Coastal Ecosystem Monitoring Program, Cape Cod National Seashore, Wellfleet, MA 02667. http://science.nature.nps.gov/im/monitor/protocols/caco_marshveg.pdf

Author Abstract. The protocol presented is a minimum for monitoring vegetation in salt marshes. Provided in this document are consistent methods for sampling programs in different geographical areas that allows comparisons to be made among datasets over time. The authors present methods used when monitoring salt marshes. Permanent plots using point intercept methods are suggested for sampling vegetation community composition and abundance. Before sampling species present within the plot should be recorded. Using the point intercept method, the number of "hits" per species is recorded for each of fifty points. The study areas should be defined and divided into marsh segments (e.g., tide-restricted, unrestricted, upstream, downstream, etc.). Permanent quadrats must be arranged in transects and spaced a minimum of 10-20 m. Transects should be randomly located within each marsh segment. Additional environmental parameters that can be recorded include: water table level, soil salinity, soil sulfide concentration, height of indicator species such as *Phragmites australis*, and elevation of the permanent plots.

Rozas, L. P. and T. Minello. 1997. Estimating densities of small fishes and decapod crustaceans in shallow estuarine habitats: a review of sampling design with focus on gear selection. *Estuaries* 20:199-213.

Author Abstract. Shallow estuarine habitats often support large populations of small nekton (fishes and decapod crustaceans), but unique characteristics of these habitats make sampling these nekton populations difficult. We discuss development of sampling designs and evaluate some commonly used devices for quantitatively sampling nekton populations. Important considerations of the sampling design include the size and number of samples, their distribution in time and space, and control of tide level. High, stable catch efficiency should be the most important gear characteristic considered when selecting a sampling device to quantify nekton densities. However, the most commonly used gears in studies of estuarine habitats (trawls and seines) have low, variable catch efficiency. Problems with consistently low catch efficiency can be corrected, but large unpredictable variations in this gear characteristically pose a much more difficult challenge. Study results may be biased if the variability in catch efficiency is related to the treatments or habitat characteristics being measured in the sampling design. Enclosure devices, such as throw traps and drop samplers, have fewer variables influencing catch efficiency than do towed nets (i.e., trawls and seines); and the catch efficiency of these enclosure samplers does not appear to vary substantially with habitat characteristics typical of shallow estuarine areas (e.g., presence of vegetation). The area enclosed by these samplers is often small, but increasing the sample number can generally compensate for this limitation. We recommend using enclosure samplers for estimating densities of small nekton in shallow estuarine habitats because these samplers provide the most reliable quantitative data, and the results of studies using these samplers should be comparable. Many kinds of enclosure samplers are now available, and specific requirements of a project will dictate which gear should be selected.

Shafer, D. J. and D. J. Yozzo. 1998. National guidebook for application of hydrogeomorphic assessment of tidal fringe wetlands, 69 pp. U.S. Army Engineer, Waterways Experiment Station, Vicksburg, Mississippi. Technical Report WRP-DE-16. http://www.wes.army.mil/el/wetlands/pdfs/wrpde16.pdf

Authors described in the regional guidebook the HGM approach used for assessing tidal wetlands. The procedures used to assess wetland functions in relation to regulatory, planning or management programs are described (Smith et al. 1995). The Application Phase includes characterization, assessment analysis, and application components. Characterization describes the wetland ecosystem and the surrounding landscape, describes the planned project and potential impacts, and identifies wetland areas to be assessed. Assessment and analysis involves collecting field data that is needed to run the assessment models and calculating the functional indices for the wetland assessment areas under the existing conditions.

The Tidal Wetland HGM Approach Application Phase involves determining the wetland assessment area (WAA) and the indirect wetland assessment area (IWAA) and, determining wetland type. The boundaries of the area and the type of tidal wetland to be assessed are identified. The WAA is the wetland area impacted by a proposed project. The WAA defines specific boundaries where many of the model variables are ascertained and directly contributes to calculations for other variables (e.g., maximum aquatic and upland edge). Methods for determining WAA are discussed in detail in the procedural manual of the HGM approach (Smith et al. 1995). The IWAA is any adjacent portions of hydrologic unit that may not be affected by the project directly but indirectly affected through hydrologic flow alterations. Wetland types are determined by comparing the hydroperiod, salinity regime, and vegetation community structure with those described in the wetland type profiles for each region. Plant communities react to change in the environment (e.g., salinity and hydrologic alterations) so are considered good indicators of a wetland type. Descriptions of the vegetation present, salinity levels, and hydrological conditions for each wetland type are presented in each regional wetland type profile. To determine the salinity regime of an area, one can refer to available references on salinity and or wetland distribution. Data collected on average salinity or the range of salinity helps to sort each site into one of the four categories of the Cowardin system.

Shuman, C. S. and R. F. Ambrose. 2003. A comparison of remote sensing and ground-based methods for monitoring wetland restoration success. Restoration Ecology 11:325-333.

Author Abstract. Efficient and accurate vegetation sampling techniques are essential for the assessment of wetland restoration success. Remotely acquired data, used extensively in many locations, have not been widely used to monitor restored wetlands. We compared three different vegetation sampling techniques to determine the accuracy associated with each method when used to determine species composition and cover in restored Pacific coast wetlands dominated by Salicornia virginica (perennial pickleweed). Two ground-based techniques, using quadrat and line intercept sampling, and a remote sensing technique, using low altitude, high resolution, color and color infrared photographs, were applied to estimate cover in three small restoration sites. The remote technique provided an accurate and efficient means of sampling vegetation cover, but individual species could not be identified, precluding estimates of species density and distribution. Aerial photography was determined to be an effective tool for vegetation monitoring of simple (i.e., single-species) habitat types or when species identities are not important (e.g., when vegetation is developing on a new restoration site). The efficiency associated with these vegetation sampling techniques was dependent on the scale of the assessment, with aerial photography more efficient than ground-based sampling methods for assessing large areas. However, the inability of aerial photography to identify individual species, especially mixed-species stands common in southern California salt marshes, limits its usefulness for monitoring restoration success. A combination of aerial photography and ground-based methods may be the most effective means of monitoring the success of large wetland restoration projects.

Smart, R. M. and G. O. Dick. 1999. Propagation and establishment of aquatic plants: a handbook for ecosystem restoration projects. 37 pp. Technical Report A-99-4, U.S. Army Engineer Waterways Experiment Station, Vicksburg, MS. http://www.wes.army.mil/el/elpubs/pdf/tra99-4.pdf

Smart and Dick have prepared an excellent document to help guide practitioners through the many steps necessary to grow and transplant aquatic plants for restoration or mitigation purposes. The first step in the process is the establishment of pioneer colonies on site. These are small groups of a variety of plant species, grown in wire cages to protect them from herbivores. Pioneer colonies should be scattered throughout the area to be restored. Through monitoring, it can be determined which plant species perform best under existing site conditions. These species then can be grown for the restoration project. The authors explain why it is advisable to grow one's own plants, what the physical and chemical requirements of different aquatic plants types are, and how to prepare and build off-site and in-place facilities. They include a chapter on how to implement the planting project containing information on proper site selection, planting depth, species selection, and timing of planting projects. The authors also include a variety of methods for protecting plantings from herbivores, a critical part of successful planting projects.

[1] Note: Growing one's own plants for restoration projects can be a cost effective means for supplying propagules for a restoration project. However, it requires that the hydrodynamics of the area in question are relatively predicable from one year to the next. Coastal wetlands of the Great Lakes for example are subject to water level fluctuations of the lakes that can drastically alter available habitat type. Unless water level fluctuations can be controlled or reliably predicted from year to year, the expense of growing your own plants may not be worthwhile.

Smith, R. D., R. C. Solomon and N. R. Sexton. 1994. Methods for evaluating wetland functions, 7 pp. WRP Technical Note WG-EV-2.2, U.S. Army Engineer Waterways Experiment Station, Vicksburg, MS.

The purpose of this technical note is to review the major wetland evaluation methods currently in use among wetland professionals and to provide a comprehensive list of these methods for use by field biologists and managers. Method selection can be based on study objectives; amount of time, budget and personnel available; regional or local controversy; and degree of precision and accuracy required.

Steyer, G. D., R. C. Raynie, D. L. Steller, D. Fuller and E. Swenson. 1995. Quality management plan for Coastal Wetlands Planning, Protection, and Restoration Act monitoring program, 82 pp. Open-File Report 95-01, Louisiana Department of Natural Resources, Coastal Restoration Division, Baton Rouge, LA. http://www.lacoast.gov/cwppra/reports/MonitoringPlan/index.htm

This document is a Quality Assurance Project Plan (QAPP) used for all restoration projects conducted under the Coastal Wetlands Planning, Protection, and Restoration Act (CWPPRA) and similar legislation for coastal Louisiana. Though it does not explain how to develop a QAPP for new wetland restoration monitoring projects, it can be used as a template by which monitoring plans can be developed. Detailed explanations of how to data is to be collected, acceptable error rates, and methods to ensure high quality data is collected, recorded, and analyzed are included. Quality assurance guidelines are provided for field data collection, remote sensing and airphoto interpretation, computer systems to be used, data entry procedures, data review, laboratory procedures, and documentation and reporting. Any restoration practitioner attempting to develop a monitoring plan or preparing a QAPP for their project may find this document a valuable example to follow.

Thursby, G. B., M. M. Chintala, D. Stetson, C. Wigand and D. M. Champlin. 2002. A rapid, non-destructive method for estimating aboveground biomass of salt marsh grasses. *Wetlands* 22:626-630.

Author Abstract. Understanding the primary productivity of salt marshes requires accurate estimates of biomass. Unfortunately, these estimates vary enough within and among salt marshes or require large numbers of replicates if the averages are to be statistically meaningful. Large numbers of replicates are rarely taken, however, because they involve too much labor. Here, we present data on a fast, non-destructive method for measuring aboveground biomass of *Spartina alterniflora* and *Phragmites australis* that uses only the average height of the five tallest shoots and the total density of shoots over 10 cm tall. Collecting the data takes only a few minutes per replicate, and calculated values for biomass compare favorably with destructive measurements on harvested samples.

Tiner, R. W. 1987. A Field Guide to Coastal Wetland Plants of the Northeastern United States. University of Massachusetts Press, Amherst, MA.

Tiner has compiled a simple to use guide designed help nonspecialists identify common vascular wetland plants from the northeastern coast of the United States. He has included an overview of the ecology of northeastern coastal systems along with maps showing their general distribution. The types of coastal systems covered includes rocky shores, tidal flats, salt marshes, brackish marshes, tidal fresh marshes, tidal swamps, and coastal aquatic beds. Keys to identify about 280 different species are provided, with black and white drawing to aid in the identification of about 150. As with Tiner's *Field Guide to Coastal Wetland Plants of the Southeaster United States* this is only one of many resources available to help the beginner learn to identify wetland plant species. These introductory books should not be used as the final authority on plant identification if results from the monitoring effort are to be published. More thorough books that provide identification for ALL species present in an area should be consulted. Examples for the north and northeast regions include Maggee, Rorer, and Ahles' *Flora of the Northeast: A Manual of the Vascular Flora of New England and Adjacent New York*, Voss' three-volume *Michigan Flora*, Crow and Hellquist's *Aquatic and Wetland Plants of Northeastern North America: Pteridophytes, Gymnosperms and Angiosperms: Dicotyledons* and *Aquatic and Wetland Plants of Northeastern North America: Angiosperms: Monocotyledons (Volume II)*.

Tiner, R. W. 1993. Field Guide to Coastal Wetland Plants of the Southeastern United States. University of Massachusetts Press, Amherst, MA.

Tiner has compiled a simple to use guide designed help nonspecialists identify common vascular wetland plants from the southeastern and gulf coasts of the United States. He has included an overview of the ecology of southeastern coastal systems along with maps showing their general distribution. The types of coastal systems covered include mangrove swamps, salt marshes, salt barrens and flats, brackish marshes, tidal fresh marshes, tidal swamps, tidal flats, and coastal aquatic beds. Keys to identify about 450 different species are provided, with black and white drawing to aid in the identification of about 250. As with Tiner's *Field Guide to Coastal Wetland Plants of the Northeastern United States* this is only one of many resources available to help the beginner learn to identify wetland plant species. These introductory books should not be used as the final authority on plant identification if results from the monitoring effort are to be published. More thorough books that provide identification for ALL species present in an area should be consulted. Examples for the southeast region include Godfrey and Wooten's *Aquatic and Wetland Plants of Southeastern United States: Dicotyledons* and *Aquatic and Wetland Plants of Southeastern United States: Dicotyledons*.

U.S. Department of Agriculture, Natural Resources Conservation Service (USDA/NRCS). 1994. Evaluation of restorable salt marsh in New Hampshire, 43 pp. Natural Resources Conservation Service. Durham, NH. http://www.nh.nrcs.usda.gov/technical/Ecosystem_Restoration/Ecosystem_Restoration.html

Researchers evaluated non-natural restrictions to tidal flow in the vegetated tidal marsh in New Hampshire and determined the potential restoration of the marshes that deteriorated ecologically due to past tidal restrictions. Methods used included field identification of sites that experienced tidal flow restrictions; and an engineering field survey was done of the structures and their relationship to the tide elevation. A modeling procedure was developed to analyze the level in which each opening and a preliminary cost estimate of remedial measures were arranged. A field evaluation of marsh health in segments was performed along with an analysis of economic and social impacts. Restriction locations and the evaluated marsh segments were digitized into a geographic information system (GIS) format and a database. By using this method, researchers were able to observe trends over time, such as how much wetland deterioration occurred due to tidal flows. In addition it also assisted in establishing a successful restoration method. Details of the methods used can be seen in the report.

U.S. EPA. 1992. Monitoring guidance for the National Estuary Program. United States Environmental Protection Agency, Office of Water, Office of Wetlands, Washington D.C. EPA Report 842-B-92-004.

This document provides guidance on the design, implementation, and evaluation of the required monitoring programs. It also identifies steps to be taken when developing and implementing estuarine monitoring programs and provides technical basis for discussions on the development of monitoring program objectives, the selection of monitoring program components, and the allocation of sampling effort. Some of the criteria listed for developing a monitoring program and described in this document include: monitoring program objectives, performance criteria, establish testable hypotheses, selection of statistical methods, alternative sampling designs, use of existing monitoring programs, and evaluate monitoring program performance. Additional information on guidelines for developing a monitoring program is described in this document.

U.S. EPA. 1993. **V**olunteer estuary monitoring: a methods manual, 383 pp. EPA 842-B-93-004, U.S. Environmental Protection Agency, Office of Water, Washington, D.C. http://www.epa.gov/owow/estuaries/monitor/.

This document presents information and methodologies specific to estuarine water quality. Information presented in the first eight chapters include understanding estuaries and what makes them unique, impacts to estuarine habitats and the human role in solving the problems; guidance on how to establish and maintain a volunteer monitoring program; guidance for working with volunteers and ensuring that they are well-positioned to collect water quality data safely and effectively; ensuring that the program consistently produces high quality data; and managing the data and making it readily available to data users. Also presented are water quality measures that determine the condition of the estuary including physical (e.g., substrate texture), chemical (e.g., dissolved oxygen), and biological parameters (e.g., plant and animal presence and abundance). The importance of each parameter and methods used to monitor the conditions are described in a gradual process. Proper quality assurance and quality control techniques must also be described in detail to ensure that the data are beneficial to state agencies and other data users.

U.S. EPA. 1996. The volunteer monitor's guide to quality assurance project plans, 59 pp. EPA 841-B-96-003, U. S. Environmental Protection Agency, Washington, D.C. http://www.epa.gov/volunteer/qapp/vol_qapp.pdf

Author Abstract. The Quality Assurance Project Plan, or QAPP, is a written document that outlines the procedures a monitoring project will use to ensure that the samples that participants collect and analyze, the data they store and manage, and the reports they write are of high enough quality to meet project needs.

U.S. Environmental Protection Agency-funded monitoring programs must have an EPA-approved QAPP before sample collection begins. However, even programs that do not receive EPA money should consider developing a QAPP, especially if data might be used by state, federal, or local resource managers. A QAPP helps the data user and monitoring project leaders ensure that the collected data meet their needs and that the quality control steps needed to verify this are built into the project from the beginning.

Volunteer monitoring programs have long recognized the importance of well-designed monitoring projects; written field, lab, and data management protocols; trained volunteers; and effective presentation of results. Relatively few programs, however, have tackled the task of preparing a comprehensive QAPP that documents these important elements. This document is designed to help volunteer program coordinators develop such a QAPP.

U.S. EPA. 2002. Assessing and monitoring floatable debris, 49 pp. EPA-842-B-02-002, Oceans and Coastal Protection Division, U.S. Environmental Protection Agency, Washington, D.C. http://www.epa.gov/owow/oceans/debris/floatingdebris/pdf.html

This manual is designed to help states, tribes, and local units of government develop assessment and monitoring programs for floating debris (trash) in coastal waterways. The manual is broken into five parts with appendices. Part 1 introduces the impacts of floating debris on the aquatic environment and describes current legislation to address the issue. Part 2 discusses the types and origins of trash in coastal waters. Part 3 describes a variety of plans and programs that have been developed and implemented in various coastal areas to assess and monitor trash. Part 4 provides recommendations for developing assessment and monitoring programs that were originally presented in NOAA's *Marine Debris Survey Manual* and the EPA's *Volunteer Estuary Monitoring: A Methods Manual*. Part 5 provides methods to prevent and mitigate the problems associated with floating debris. The Appendices include information on international coastal cleanup efforts, a National Marine Debris Monitoring Program data card, storm drain stenciling cards, and surveys from the *Marine Debris Survey Manual*.

U.S. EPA. 2002. Guidance for quality assurance project plans, 130 pp. EPA QA/G-5, U. S. Environmental Protection Agency, Washington, D. C. http://www.epa.gov/swerust1/cat/epaqag5.pdf

Author Abstract. This document is designed to guide those involved with Quality Assurance Project Plan (QAPP) development for environmental monitoring and data analysis. It describes various issues to be addressed when preparing a QAPP, with an emphasis on systematic planning. The report is divided into three chapters. An introduction that describes the target audience and the importance of systematic sampling. A second chapter describes all of the pieces of a QAPP, focusing on environmental data collection and analysis. The third chapter describes methods for developing QAPPs for projects that use previously collected data.

The importance of having high quality, reliable data cannot be over estimated. Use of this document or the EPA's *Volunteer monitor's guide to quality assurance project plans*, will help restoration practitioners develop monitoring plans that will provide the high quality, reliable data necessary to monitor and manage restoration projects. The step-by-step approach of this document takes restoration practitioners through the entire planning, data collection, data analysis, and reporting process from start to finish. Ensuring that all aspects of the monitoring project are well thought out ahead of time and that contingency plans are in place.

U.S. EPA. 2002. Methods for evaluating wetland condition: introduction to wetland biological assessment, 42 pp. Office of Water, U.S. Environmental Protection Agency, Washington, D.C. EPA-822-R-02-014. http://www.epa.gov/ost/standards or http://www.epa.gov/waterscience/criteria/wetlands/

Author Abstract. In 1999, the U.S. Environmental Protection Agency (EPA) began work on this series of reports entitled *Methods for Evaluating Wetland Condition*. The purpose of these reports is to help States and Tribes develop methods to evaluate (1) the overall ecological condition of wetlands using biological assessments and (2) nutrient enrichment of wetlands, which is one of the primary stressors damaging wetlands in many parts of the country. This information is intended to serve as a starting point for States and Tribes to eventually establish biological and nutrient water quality criteria specifically refined for wetland waterbodies. This purpose was to be accomplished by providing a series of "state of the science" modules concerning wetland bioassessment as well as the nutrient enrichment of wetlands. The individual module format was used instead of one large publication to facilitate the addition of other reports as wetland science progresses and wetlands are further incorporated into water quality programs. Also, this modular approach allows EPA to revise reports without having to reprint them all. A list of the inaugural set of 20 modules can be found at the end of this section.

More information about biological and nutrient criteria is available at the following EPA website: http://www.epa.gov/ost/standards

More information about wetland biological assessments is available at the following EPA websites: http://www.epa.gov/owow/wetlands/bawwg and http://www.epa.gov/waterscience/criteria/wetlands/

U.S. EPA. 2002. Methods for evaluating wetland condition: study design for monitoring wetlands. 21 pp. EPA-822-R-02-015, Office of Water, U.S. Environmental Protection Agency, Washington, D.C. http://www.epa.gov/waterscience/criteria/wetlands/

Author Abstract. State and Tribal monitoring programs should be designed to assess wetland condition with statistical rigor while maximizing available management resources. The three study designs described in this module—stratified random sampling, targeted/tiered approach, and before/after, control/impact (BACI)—allow for collection of a significant amount of information for statistical analyses with relatively minimal effort. The sampling design selected for a monitoring program will depend on the management question being asked. Sampling efforts should be designed to collect information that will answer management questions in a way that will allow robust statistical analysis. In addition, site selection, characterization of reference sites or systems, and identification of appropriate index periods are all of particular concern when selecting an appropriate sampling design. Careful selection of sampling design will allow the best use of financial resources and will result in the collection of high quality data for evaluation of the wetland resources of a State or Tribe. Examples of different sampling designs currently in use for State and Tribal wetland monitoring are described in the Case Study (Bioassessment) module and on http://www.epa.gov/owow/wetlands/bawwg/case.html.

U.S. EPA. 2002. Methods for evaluating wetland condition: developing an **invertebrate** index of biological integrity for wetlands, 45 pp. EPA-822-R-02-019, Office of Water, U.S. Environmental Protection Agency, Washington, DC. http://www.epa.gov/waterscience/criteria/wetlands/

Author Abstract. The invertebrate module gives guidance for developing an aquatic invertebrate Index of Biological Integrity (IBI) for assessing the condition of wetlands. In the module, details on each phase of developing the IBI are given. First, in the planning stage, invertebrate attributes are selected, the wetland study sites are chosen, and decisions are made about which stratum of the wetland to sample and what is the optimal sampling period or periods. Then, field sampling methods are chosen. The module describes field methods used in several States, and gives recommendations. Laboratory sampling procedures are reviewed and discussed, such as whether and how to subsample, and what taxonomic level to choose for identifications of the invertebrates. Specific categories of attributes, such as taxa richness, tolerance, feeding function, and individual health are discussed, with examples. Appendices to the invertebrate module give details about the advantages and disadvantages of using invertebrates, of the different attributes, of various field sampling methods, and of lab processing procedures as used by several State and Federal agencies. The module and appendices give a detailed example of one State's process for developing an invertebrate IBI, with a table of metrics with scoring ranges, and a table of scores of individual metrics for 27 wetlands. A glossary of terms is provided as well as sampling methods.

U.S. EPA. 2002. Methods for evaluating wetland condition: using vegetation to assess environmental conditions in wetlands, 46 pp. EPA-822-R-02-020, Office of Water, U.S. Environmental Protection Agency, Washington, DC. http://www.epa.gov/waterscience/criteria/wetlands/

Author Abstract. Vegetation has been shown to be a sensitive measure of anthropogenic impacts to wetland ecosystems. As such it can serve as a means to evaluate best management practices, assess restoration and mitigation projects, prioritize wetland related resource management decisions, and establish aquatic life use standards for wetlands. The basic steps necessary for developing a vegetation-based wetland biological assessment and monitoring program are relatively straightforward, but their simplicity belies their effectiveness. By building upon such monitoring tools, we will be able to more fully incorporate wetlands into water quality assessment programs.

Some methods for sampling vegetation in coastal marshes are presented.

U.S. EPA. 2002. Methods for evaluating wetland condition: biological assessment methods for **birds**, 22 pp. EPA-822-R-02-023, Office of Water, U.S. Environmental Protection Agency, Washington, DC. http://www.epa.gov/waterscience/criteria/wetlands/

Author Abstract. Birds potentially detect aspects of wetland landscape condition that are not detected by the other groups commonly used as indicators. Moreover, birds are of high interest to a broad sector of the public. When using birds as indicators, one must pay particular attention to issues of spatial scale. This requires an understanding of home range sizes of the bird species being surveyed. The development of wetland and riparian bird indices of biological integrity is still in its infancy, but holds considerable promise.

Methodologies for sampling birds in coastal habitats are also presented.

Vasey, M., J. Callaway and V. T. Parker. 2002. Data collection protocol, tidal wetland vegetation. San Francisco Estuary Wetlands Regional Monitoring Program Plan, San Francisco CA. http://www.wrmp.org/documents.html.

The goal of the data collection protocol is to encourage wetland scientists to monitor all tidal wetlands in the San Francisco Bay Estuary with a consistent theoretical approach and standard methods to produce tidal wetland vegetation. This protocol is designed to evaluate three important plant community parameters in tidal marshes: 1) plant species diversity, 2) community physical structure, and 3) the invasion of non-native species. Methods used include: a stratified-random sampling approach to characterize the plant community along major gradients of environmental factors expected to influence community structure including heterogeneity. The sampling takes place along these gradients within self-evident drainage basins within the sampling sites. In tidal marshes, tidal hydroperiod, environmental moisture, aqueous salinity, invasion by NIS plants, and edaphic chemical factors vary with intertidal elevation and distance from tidal source are primarily taken into consideration.

Any reference site or wetland project, a permanent transect should be established and extends from the starting point from foreshore to backshore to evaluate vegetation changes over time. Data on percent cover and maximum height per species are collected every 1 meter for the first 30 meters. Sampling should take place at low tide to allow access to sample sites; taken yearly so that annual variation in vegetation can be traced and correlated with other physical and wildlife patterns. Each stratum is analyzed for frequency of occurrence of each species, average cover per occurrence of each species, and maximum plant height per species. Data collected can then be used to assess dominant, common, and rare species in these different habitats. This allows plants to be classified and show the effect of stressors and habitat heterogeneity on biodiversity within and among marshes.

Wells National Estuarine Research Reserve. 1999. Regional standards to identify and evaluate tidal wetland restoration in the Gulf of Maine, pp. 6-18. In Neckles, H. and M. Dionne (eds.), Global Program of Action Coalition for the Gulf of Maine (GPAC Report). http://www.pwrc.usgs.gov/resshow/neckles/Gpac.pdf

A monitoring protocol was designed for tidal wetlands based core variables that are in general categories of wetland structural and functional responses to restoration. The natural marsh and restoration site are monitored before and after restoration is complete. The natural marsh serves as a reference site for determining whether restoration reached the set goals made during the planning process. The natural marsh and restoration site must be in a similar physical environment. The core variables include: hydrology, soils and sediments, vegetation, fish, and birds. Hydrology was measured using automatic water level recorders which were operated simultaneously for a minimum of two weeks. Five stations were used to establish the soil's salinity by using wells for sampling. Soil water was collected 5-20 cm deep. A 19 mm diameter CPVC plastic pipe with seven pairs of 4 mm holes at sediment depths of 5-20 cm was used to determine salinity. Vegetation was sampled using 1m^2 quadrats. Visual animation was used to estimate percentage cover for each species. The tallest three individuals of each species in each plot were measured and the average recorded. Fish samples were measured using throw traps for sampling on open water of creeks and channels and fyke net were used on the vegetated marsh surface. Birds were evaluated by simple observations only in the morning. Details for techniques used can be seen in this report.

Wenner, E. L. and M. Geist. 2001. The National Estuarine Research Reserve's program to monitor and preserve estuarine waters. *Coastal Management* 29:1-17.

The National Estuarine Research Reserve (NERR) sites in 1992 coordinated a program that would attempt to identify and track short-term variability and long-term changes in representative estuarine ecosystems and coastal watersheds. Water quality parameters monitored include: pH, conductivity, temperature, dissolved oxygen, turbidity, and water level. Standardized protocols are also used at each site so that sampling, processing, and data management techniques are consistent among sites. Statistical techniques are being used to identify periodicity in water quality variables. Periodic regression analysis indicated that diel periodicity in dissolved oxygen is a larger source of variation than tidal periodicity at sites with less tidal amplitude. Authors of this document stress how understanding the functions of estuaries and how they change over time will help predict how these systems respond to changes in climate and anthropogenic sources.

APPENDIX III: LIST OF COASTAL MARSH EXPERTS

The experts listed below have provided their contact information so practitioners may contact them with questions pertaining to the restoration or restoration monitoring of this habitat. Contact information is up-to-date as of the printing of this volume. The list below includes only those experts who were 1) contacted by the authors and 2) agreed to submit their contact information. Some of those listed also reviewed the associated habitat chapter. In addition to these resources, practitioners are encouraged to seek out the advice of local experts as well faculty members and researchers at colleges and universities. Engineering, planning, and landscape architecture firms also have experts on staff or contract out the services of botanists, biologists, ecologists, and other experts whose skills are needed in restoration monitoring. These people are in the business of providing assistance in restoration and restoration monitoring and are often extremely knowledgeable in local habitats and how to implement projects on the ground. Finally local, state, and Federal environmental agencies also house many experts who monitor and manage coastal habitats. In addition to the National Oceanic and Atmospheric Administration (NOAA), the Environmental Protection Agency (EPA), the Army Corps of Engineers (ACE), Fish and Wildlife Service (FWS), and the United States Geologic Survey (USGS) are important Federal agencies to contact for assistance in designing restoration and monitoring projects as well as potential sources of funding and permits to conduct work in coastal waterways.

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CHAPTER 11: RESTORATION MONITORING OF MANGROVES

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INTRODUCTION

Mangroves are woody plants found in tropical and subtropical regions in brackish and saltwater conditions along the margins between the ocean and land. There are nearly 70 species of mangroves worldwide. These species include trees and shrubs (Chapman 1976; Teas 1984) and cover approximately 240,000 km^2 of sheltered coastlines (Lugo et al. 1990). In the United States and its protectorates, they are distributed primarily along the Atlantic and Gulf coasts of Florida as well as Puerto Rico, the US Virgin Islands, Hawaii, and the Pacific Trust Territories (Hoff et al. 2002). Species of mangroves commonly found in these areas include:

- Red mangroves *(Rhizophora mangle,* Figure 1)
- Black mangroves *(Avicennia germinans,* Figure 2)
- White mangroves *(Laguncularia racemosa*) (Massaut 1999), and
- Button-mangrove or buttonwood (*Conocarpus erectus* is also found in the warmer climates of the Gulf of Mexico and Caribbean). Button-mangrove, however, is not always considered a true mangrove (Hoff et al. 2002)

In more northern areas along Texas, Louisiana, and Mississippi where temperatures are cooler, black and button-mangroves dominate along the coastline because they have the ability to withstand relatively low temperatures (Markley et al. 1982; Sherrod et al. 1986), whereas red, white, and black mangroves generally dominate more tropical areas.

Species of mangroves are often found in association with coral reefs and seagrasses (Ogden 1988; Yáñez-Arancibia et al. 1993; Nagelkerken 2001; Mumby et al. 2004) and therefore function as an integrated system that supports many species such as birds, fishes, invertebrates, and crustaceans. Juvenile coral reef fish, for example, commonly inhabit mangroves (Mumby et al. 2004) and utilize these habitats as nursery grounds (Nagelkerken

Figure 1. Red Mangroves along the Anne Kolb Nature Center. Photo courtesy of Felicity Burrows, NOAA National Centers for Coastal and Ocean Sciences.

[1] 1305 East West Highway, Silver Spring, MD 20910.
[2] 1315 East-West Highway 9th Floor F/CS, Silver Spring, MD 20910.

Figure 2. Black mangroves. Photo courtesy of the South Florida, United States Geological Survey. http://sofia.usgs.gov/virtual_tour/images/photos/wlak/ak_blackmang.jpg

Figure 3. Kayakers enjoying a day on the water amongst mangrove communities in Thailand. Photo courtesy of the Mangrove Action Project, Port Angeles, WA. http://www.earthisland.org/map/mngim_thailand_sn.htm

2001). The distribution and abundance of organisms that occupy mangroves may be used as indicators of mangrove health.

There are over 500 species of animals associated with mangrove habitats in the United States including 200 species of fish. Not only are mangroves used by many organisms, but they are also harvested to produce paper and textiles, as well as for fuel wood (Novelli and Cintron-Molero 1991; Bandaranayake 1998; Shunula 2001; Fast and Menasveta 2003). In some cultures (European, African, and Caribbean), the wood of mangrove trees is used to build boats and community houses (Bandaranayake 1998; Dahdouh-Guebas et al. 2000; Shunula 2001). Mangrove communities also provide an environment that is enjoyed by persons fishing, kayaking, or canoeing (Figure 3) along the coastline.

Despite their tremendous economic, ecological, and cultural importance, mangroves are threatened by a number of human activities that deteriorate the habitat's structural and functional characteristics (Spalding et al. 1997). These human impacts include coastal development, shrimp farming and aquaculture practices, and coastal pollution (sewage, nutrient pollution, chemical discharge, and oil spills). Detailed information on how such pressures affect mangrove communities is discussed in the following section.

HUMAN IMPACTS TO MANGROVES

Coastal Development

Mangroves are threatened by a number of human activities that deteriorate the structural and functional characteristics of these complex ecosystems (Spalding et al. 1997). One of the leading threats to mangroves is coastal development and channel construction. In Florida, a residential project eliminated approximately 24% of mangrove cover (Twilley 1998). In Ecuador, along the El Oro River, approximately 45-63% of mangrove habitat was lost due to mariculture pond construction (Twilley 1989). Mangroves are also removed and replaced by dredged channels, seawalls, pond development, and other commercial and residential construction (Burchmore 1993; Primavera 1993; Thompson 2003). Also associated with such development is the diversion of freshwater with the use of dams to control river flows. If mangrove communities do not receive freshwater inflow, the salinity levels in the water may increase significantly decreasing mangrove productivity (Harrison et al. 1994; McIvor et al. 1994; Kulkarni 2002).

Cultural Practices

Deforestation of mangroves for cultural purposes is also a concern. For many years, mangrove harvesting practices have been sustained, but over time, increasing human populations along the coast have led to unsustainable practices (Twilley 1998). In some countries such as Africa, Sundarbans (India, Bangladesh), Indonesia, Peninsular Malaysia, and Thailand, red mangroves are considered a valuable commodity and are a primary source of firewood and charcoal sold locally and commercially. Mangrove wood is also relied on as fuel wood for cooking and heating; used to construct houses (Figure 4), furniture, and small boats to perform local fishing, and create pulp to produce paper and paper products (Snedaker 1978; Bandaranayake 1998). Mangroves may also be used in agriculture and as pastures for livestock.

Shrimp Farming and Aquaculture

Shrimp farming and aquaculture practices that use ponds also threaten mangrove communities by polluting waters or by removal of mangroves in order to create areas suitable for shrimp

Figure 4. Community houses in Indonesia using wood of mangrove trees. Photo courtesy of the Mangrove Action Project, Port Angeles, WA 98362-0279 USA. http://www.earthisland.org/map/mngim.htm

farming and aquaculture (Boyd 2001; Fast and Menasveta 2003). In addition to direct habitat loss due to the conversion of forests to shrimp ponds, effluents from ponds enter the remaining mangrove areas, altering environmental conditions and affecting mangrove growth (Rajendran and Kathiresan 1996). During shrimp farming, channels are created to control the supply of freshwater and seawater to the ponds. Diverting the natural water flow may negatively affect mangrove establishment and growth as seeds cannot be properly dispersed, seedlings cannot establish themselves, and changes in salinity levels decrease mangrove growth (Chapman 1976; McIvor et al. 1994). Animal communities may also change as a result. In some cases, fertilizers used in shrimp farming contaminate the mangrove water supply (Figure 5), affecting mangrove growth as well as impacting animal communities by reducing species composition, abundance, and diversity (Paez-Osuna et al. 2003).

Pollution

Coastal pollution in mangrove communities from human activities includes thermal pollution (hot-water outflows), nutrient pollution (including sewage), heavy metals, industrial chemicals, and oil spills.

Thermal pollution

One source of pollution that may affect mangroves by reducing leaf area, causing partial defoliation (loss of leaves on a plant or tree), or dwarfed seedlings is thermal pollution. This refers to significantly high water temperatures in marine, fresh, and brackish water systems as a result of discharge of hot effluents from thermal generating plants and heated water during industrial processes. Mangrove seedlings are more vulnerable to thermal discharges and show close to 100% mortality once water temperatures elevate between 7 and 9 ºC (Hogarth 1999). Although thermal discharges are a threat to mangroves in some areas, it is not very common in the tropics.

Nutrient pollution

In some cases, sewage discharge when managed correctly, adds nutrients such as nitrogen and phosphorous to the water column, promoting mangrove growth and productivity (Twilley 1998). If the rate of discharge, however, is more than the uptake rate of the mangrove, excess nutrients will accumulate in mangrove

Figure 5. Polluted sludge waste discharged from shrimp pond next to mangroves - southwest coast of Thailand. Photo courtesy of the Mangrove Action Project, Port Angeles, WA. http://www.earthisland.org/map/mngim_thailand.htm

[3] Specialized roots formed on several species of plants occurring frequently in inundated habitats; the root is erect and protrudes above the soil surface.

communities causing reduced water quality and increased algal growth that can block mangrove pneumatophores[3] and reduce oxygen exchange. Excessive algal growth may also obstruct growth of mangrove seedlings (Hogarth 1999). For example, in sheltered mangroves, located in two aquatic reserves in Australia, nutrient loads increased as a result of the Bolivar Sewage Treatment Works causing increased growth of sea lettuce (*Ulva*). Increased sea lettuce growth resulted in high mortalities in young mangrove seedlings by smothering seeds and reducing photosynthetic ability (Edyvane 1991). In addition, microbes may become present because of excess nutrients and reduce dissolved oxygen content in the water, also negatively affecting mangrove fauna (Hoff et al. 2002).

Heavy metals and agriculture chemicals

Metals (such as mercury, lead, cadmium, zinc, and copper) from mining and industrial wastes can affect mangroves. Once heavy metals enter mangrove ecosystems, they have the potential to decrease mangrove growth and respiration rates and negatively impact the animal community. High concentrations of mercury, cadmium, and zinc can be toxic or cause physiological stress to invertebrate and fish larvae (Hoff et al. 2002). Pesticides, also used on farms, may runoff into surface waters and may be taken up and absorbed by animals such as fish, shrimp, and mollusks that use mangroves and affect their growth and development (Hoff et al. 2002).

Oil spills

Hazardous spills such as oil spills may also contribute to the loss of mangrove habitats. If high concentrations of oil or any other pollutant enter the soil or water supply within mangrove forests, the results may include death in plant species, change in normal development, reduced functional ability, and mortality in birds that use mangrove habitats for feeding and breeding grounds (Lewis 1980; Samarasekara 1994; Hoff et al. 2002). Following the 1986 Bahía las Minas (Galeta) oil spill in Panama, investigators observed that oil in mangrove sediments affected root survival, canopy condition, and growth rates of mangrove seedlings. Six years after the oil spill event, surviving fringing forest near deforested areas continued to display canopy leaf biomass deterioration (Burns et al. 1993). Thus, the detrimental effects of oil spills on mangroves can be both serious and long lasting. Some researchers, however, may have contrasting views in regards to oil effects on mangroves (Snedaker 1997). There is some evidence to suggest that mangrove tolerance and sensitivity to oil spills varies by species, and that some species are able to tolerate exposure to moderate levels of oil on their roots (Snedaker 1997).

RESTORATION AND MONITORING EFFORTS

Mangrove restoration projects aim to restore the habitat's physical structure and functional capacity so that it can continue to support many species of plants, fish, and wildlife (Hamilton and Snedaker 1984, Lewis et al. 1985). Planting of propagules or transplanting of mangroves is not always necessary when restoring mangroves. This is because they have the ability to repair themselves once normal tidal hydrology and the availability of waterborne seeds or seedlings (propagules) of mangroves from adjacent areas is restored (Lewis 1982a, Cintron-Molero 1992). Mangrove planting is only necessary if:

- Natural recruitment is not likely to occur due to lack of propagules
- Soil conditions prohibit natural establishment
- Waterborne seeds or seedlings (propagules) cannot reach the restoration site under normal hydrological conditions (Lewis et al. 2000)

Mangrove propagules can be planted bare or with the use of PVC pipes (Figure 6). When using PVC pipes, small holes are cut along the

Figure 6. One year after mangrove seedlings were placed in PVC pipes. Photo courtesy of Mike Devany and Marine Resource Council, NOAA Restoration Center. Publication of the National Oceanic & Atmospheric Administration (NOAA), NOAA Central Library. http://www.photolib.noaa.gov/habrest/r0008735.htm

length of each pipe to allow water flow and then filled with muddy sediment. The propagules are then planted in sediment at the top of the pipe where they are left to grow.

NOAA's Community-Based Restoration Program in partnership with other Federal agencies, states, local governments, non-governmental, and non-profit organizations provides financial and technical assistance for restoration of mangrove and other coastal habitats throughout the United States and its protectorates. To find out additional information pertaining to NOAA-related mangrove restoration projects and possible funding opportunities for coastal restoration efforts, contact the NOAA Community-Based Restoration Program, NOAA Fisheries, Office of Habitat Conservation (F/HC3), 1315 East West Highway, Silver Spring, MD 20910.

Monitoring mangrove's structural and functional characteristics will help restoration practitioners understand their ecological and economical value, and determine what management actions need to be performed (Ellison 2000). Monitoring mangrove productivity and associated physical, biological, and chemical characteristics provides insight into which combination of factors may be influencing mangrove development. When monitoring mangrove areas, a survey and an inventory of the vegetation is performed, and site characteristics are identified and measured (Lewis and Streever 2000). These include:

- Species diversity and abundance
- Height and density
- Community structure
- Soil texture
- Salinity
- Moisture
- pH, and
- Overall mangrove health (Lewis and Streever 2000)

Monitoring is encouraged before implementing a restoration project to establish a baseline, during the project, and after the restoration effort is implemented to determine whether or not it is progressing as expected. Monitoring allows the practitioner to modify the restoration design to increase the project's effectiveness. Other factors that influence the planning of a good and feasible restoration monitoring project are sufficient funds, equipment, adequate labor, and suitable methods. It has been suggested that practitioners organize a priority list where, at a minimum, documentation is made of ground level photography from fixed photo stations, percent cover by all species of plants, percent and density of mangrove seedlings, and later mangrove trees (Lewis per comm. 2004). Monitoring begins with a Time Zero report and then typically continues quarterly the first year, then semi-annually, then annually up to 5-years post implementation. This can provide a series of 10 monitoring reports as follows:

Time Zero
Time Zero + 3 months
Time Zero + 6 months
Time Zero + 9 months
Time Zero + 12 months
Time Zero + 18 months
Time Zero + 24 months
Time Zero + 36 months
Time Zero + 48 months
Time Zero + 60 months + final report

Methods used for monitoring restoration success may, however, be costly depending on selected parameters. Fish sampling, for example, needs to be performed more than once a year, at one location. Obtaining a good representation of the habitat's fish community may involve multiple sampling measures, daylight and night-time sampling, and sampling various locations (e.g., fringe mangrove, tidal creeks, and black mangrove basin areas) using quadrats as a basic sampling unit. Not only is this type of sampling costly but can also be time consuming. Identifying invertebrate species and measuring their abundance, on the other hand, is considered very cost effective. Practitioners should therefore establish project goals and objectives that will fit budgetary limits and still produce efficient monitoring results over time.

In some cases, researchers may have to prioritize sampling measures based on factors such as cost, time restraints, and availability of funds or labor (Lewis per comm. 2004), while considering the goals of the project. The matrices presented at the end of this chapter provide structural and functional parameters that can be measured to track restoration success, and help prioritize the measures to be performed.

STRUCTURAL CHARACTERISTICS OF MANGROVES

This section presents the structural characteristics of mangroves that are applicable to restoration monitoring. The characteristics described in this section refer to the biological, physical, hydrological, and chemical features of the habitat that may be potential parameters used to gather baseline information and for monitoring restoration efforts and abiotic factors that may influence the restoration process. Not all structural characteristics described, however, are expected to be measured or monitored in every restoration project. Additional information provided is intended to help educate the reader on the ecology of mangroves such as the role each characteristic plays in supporting the structure of the habitat and plant and animal life.

The structural characteristics described in this section include:

Biological

- Habitat created by plants (i.e., mangroves)
  - Root structure
  - Community types
  - Invasives

Physical

- Turbidity/Light availability
- Sediment type and grain size
- Topography/Bathymetry

Hydrological

- Tides/Hydroperiods
- Water sources

Chemical

- Salinity

Since these structural characteristics can influence mangrove growth and productivity, practitioners should first conduct monitoring of these characteristics before project implementation to ensure conditions are favorable for successful restoration. After restoration efforts, monitoring may be performed to track the success of the project by comparing the restoration site to reference sites. Also presented are methods that can be used to sample, measure, and monitor each parameter whenever possible before, during, and after restoration.

BIOLOGICAL

Habitat Created by Plants

There are three types of mangrove species found in the United States: red, black, and white mangroves. Red mangrove leaves are 1-5 inches long, broad, shiny, deep green on top, and pale green on the underside of the leaf (Jimenez and Lugo 1985). Black mangroves leaves are oblong, shiny green on top, with hairy structures on the underside of the leaves. They are found in areas that are elevated and grow closer inland to the shore (Jimenez and Lugo 1985). The unique characteristic of white mangroves is their leaves, which are elliptical, yellowish in color, and have two well-defined glands at the base of each petiole. These glands regulate salt concentration (Elias 1980). White mangroves commonly grow at relatively higher land elevations compared to red and black mangroves. Some other vegetative species present within mangrove communities include:

Perennial glasswort (*Salicornia virginica)*,
Giant wild pine (*Tillandsia fasciculate),* and
Black needle rush (*Juncus roemerianus)*

Macrophytes (herbaceous aquatic plants) such as these serve as an important food source for fish and invertebrate species that directly graze on them. They are also an important link in the detrital food chain. Macrophytes are very sensitive to nutrients, light, temperature, contaminants, turbidity, salinity, and water level change (Crowder and Painter 1991). They are therefore considered good indicators of coastal ecosystem health and should be studied and monitored during restoration.

Root Structure

Roots act as anchors for mangroves growing in soft sediment as well as ensuring sufficient transportation of oxygen to belowground meristematic tissue responsible for the formation of new cells (Hogarth 1999). The aboveground portion of the root system (Figure 7) is comprised of porous tissues that help aerate the plant. Red mangroves develop aerial or prop stilt roots that arch from the main trunk in various directions until they reach bottom sediments. The prop root system also aids in dispersing wave energy, increasing surface area suitable for attachment of some organisms, such as sponges (Figure 8) and molluscs, and providing shelter for numerous other marine organisms such as fishes (Thayer et al. 1987; Thayer and Sheridan 1999).

Black mangroves do not possess prop roots but have an underground system of horizontal radiating roots that produce upward growing terminal branches called pneumatophores or breathing roots. White mangroves, however, have no prop roots or pneumatophores. There are also some organisms that actually live within each mangrove, such as *Sphaeroma,* an isopod that bores into the roots of mangroves. Although these boring crustaceans leave holes that may appear to be a sign of mangrove deterioration, they are actually indicators of mangrove health because they are found primarily in healthy mangroves. Mangrove root structures are very complex and therefore can be difficult to assess. Practitioners. however, can generally evaluate root communities and health primarily by visual assessment.

Community Types

Various mangrove community types develop due to hydrological and geological processes. These include: fringing, riverine, scrub or dwarf, overwash, basin, and hammock.

Fringing forests exist as a relatively thin fringe along coastal water bodies where elevations are higher than mean high tide. These forest types experience periodic flooding. Zonation patterns are from seaward to landward, typically red-black-white mangroves respectively (Odum et al. 1985).

Figure 7. Red mangroves in Florida showing above-ground root system. Photo courtesy of Felicity Burrows, NOAA National Centers for Coastal and Ocean Sciences, Silver Spring, MD.

Figure 8. Sponges attach to mangrove roots. Photo courtesy of NOAA Center for Coastal Monitoring and Assessment.

Riverine mangrove forests consist of tall floodplain trees along tidal rivers and creeks and are flushed daily by tides. Mangrove communities in these settings are enhanced by freshwater inputs and terrestrial nutrient inputs (Odum et al. 1985).

Scrub or dwarf forests are found in flat coastal fringes of southern Florida and the Florida Keys (Odum et al. 1985). Low nutrient levels and lack of freshwater inflows are limiting factors for growth of these forests (Mitsch and Gosselink 1993).

Overwash forests appear as islands that are washed over by tides regularly. The dominant mangrove species here are red mangroves with a prop root system that reduces wave energy (Mitsch and Gosselink 1993).

Basin forests are found in inland depressions or basins usually behind fringe mangroves and in drainage depressions where water moves slowly or is stagnant (Mitsch and Gosselink 1993). In most cases, these wetlands are dominated by white and black mangroves (Mitsch and Gosselink 1993).

Hammock forests are depressions that exist on slightly elevated ground due to peat accumulation (Odum et al. 1985).

Invasives

Plants not native to the area outgrow mangrove communities in some cases. These rapid and aggressive species are referred to as invasives. Invasives generally multiply due to changes in the environment, such as an increase or decrease in salinity caused by human inputs or channel diversions. Once established, they can become problematic for local plant and animal species. Invasives can limit the growth of mangroves by outcompeting them for light, water, and nutrients and become dominant to species that were not normally found in these areas. It is important to monitor the presence and distribution of invasives during mangrove restoration projects. If environmental conditions are suitable for invasives to establish themselves, they can disturb the success of mangrove restoration by overtaking and outgrowing mangrove habitats.

A well-known invasive species found amongst mangroves is the Brazilian pepper (*Schinus terebinthifolius)* (Renda and Rodgers 1995;

Ferriter 1997) (Figure 9). In the United States, this species is found primarily in Florida. Seeds are distributed by birds and other mobile animals. These plants grow rapidly and contain an extensive root system. Able to grow in wet or dry soil, they are also salt tolerant (Ferriter 1997).

Sampling and Monitoring Methods

During restoration, plant growth, species composition, and abundance are measured and monitored over time. Monitoring methods used to measure these community characteristics include point-sampling, quadrats, and remote sensing techniques, involving aerial or satellite photography.

Point sampling - Point sampling methods evaluate mangrove presence or absence at specific points. In this method, a point frame, about a meter long is marked at regular intervals to represent sampling points. Mangrove density, growth rate, presence/absence, and other characteristics are evaluated by performing point sampling to estimate stand basal area without direct measurement of plot or tree diameter; measuring tree diameter and density and; conducting quadrat sampling in selected areas randomly along a transect line (Cintron-Molero and Novelli 1984).

Quadrats - Quadrats can be used to obtain a representative sample of the mangrove study site. They are square or circular sampling areas of various sizes (e.g., 1 ft^2 to 100 ft^2). Quadrats are commonly used to estimate cover, density, and biomass placed randomly in an area. They can also be permanently fixed for repeated sampling. Data obtained using quadrats can determine species density, total stand density, and species dominance (Cintron-Molero and Novelli 1984; Zhenji et al. 2003).

Remote sensing - Remote sensing techniques such as color-infrared (CIR) aerial photography and Landsat TM imagery can also be used to assess mangroves before, during, and after the restoration effort (Everitt and Judd 1989; Lin et al. 1994). These methods can provide baseline information on the mangrove community, such as its distribution and abundance, as well as identify coastal activities in adjacent areas that may potentially affect restoration success. Remote sensing allows the processing and interpretation of images and other related data taken from aircrafts and satellites. Color-infrared (CIR) aerial photography and Landsat TM image-CCT digital image magnetic tape can also be used to measure the distribution of mangroves over time (Everitt and Judd 1989; Lin et al. 1994), then map and record distribution, and determine whether their communities have increased or decreased since the restoration effort. Time-series data from aerial photography is an effective way to monitor and assess mangroves response to environmental change, including hydrological variations and sea level rise (Lucas et al. 2002). Aerial photographs can be used to evaluate mangrove coverage (Figure

Figure 9. Brazilian peppers with red berries. Photo courtesy of NOAA Restoration Center, Mike Devany and Marine Resource Council. Publication of the National Oceanic & Atmospheric Administration (NOAA), NOAA Central Library. http://www.photolib.noaa.gov/habrest/r0008713.htm

10) using the digital imagery or height maps that show a two-dimensional view of a three-dimensional area (Everitt et al. 1991; Lucas et al. 2002; Sulong et al. 2002). Groundtruthing[4] of aerial photos can be done using low-level helicopter flights and field observations. Although the average layperson is not expected to perform these methods, data can be obtained from scientists and agencies that perform these methods to determine whether the designated area is suitable for restoration.

Airborne color-infrared (CIR) video imagery - Infrared aerial imagery can also be used to map different species of mangroves (Everitt et al. 1991). Along the Texas coast, video imagery was used to identify populations of black mangrove and their distribution and abundance. When using video imagery, black mangroves generally show a distinct red color on the CIR video imagery that distinguishes it from other types of vegetation, soil, and water. Using this method can therefore be useful for assessing mangrove density and distribution (Everitt et al. 1991).

Figure 10. Aerial photograph of mangrove shoreline. Photo courtesy of Ben Mieremet, NOAA Office of Sustainable Development. Publication of the National Oceanic & Atmospheric Administration (NOAA), NOAA Central Library. http://www.photolib.noaa.gov/mvey/mvey0291.htm

PHYSICAL

Turbidity/Light Availability

It is recommended that light availability be measured during restoration because of its direct affect on mangrove establishment, growth, and survival. While adult mangroves are generally considered shade intolerant, tolerance to shade varies among species. Some researchers have observed the response of black mangroves, yellow mangroves (*Cerios tagal*), and red mangroves to light availability at different life stages (Twilley et al. 1999). Results showed that adult mangroves continued to grow successfully while the seedlings under the canopy received significantly less sunlight and therefore did not grow productively. Seedling survival and growth for the three mangrove species mentioned was minimal. Light, therefore, proved in this study to be a limiting factor for seedling survival and growth and an essential factor for continuing growth of adult mangroves (Twilley et al. 1999). In another study, adult mangrove tolerance to shading was observed. Results showed that growth in black and white mangroves was much slower when exposed to lower light levels, whereas red mangroves were able to thrive in areas where light is limited compared to the other two mangrove species studied (McKee 1993b). Light is therefore an important parameter to measure because it is needed for seed germination, which is the first step of many successful restoration efforts and because minimum light may affect the growth of adult mangroves.

Sampling and Monitoring Methods

Turbidity - A turbidimeter measures turbidity in water by passing a beam of light through the water sample and measuring the quantity of light scattered by particulate matter (Clesceri 1998; Rogers et al. 2001). The turbidity measurements are then shown in Nephelometer Turbidity Units (NTU'S) on the display (Rogers et al. 2001).

[4] The use of a ground survey to verify the results of an aerial survey.

Transparency - Depth of light penetration (water clarity) can also be measured using a secchi disc. It is a painted disc attached to a cord. To use properly, the disc should be lowered slowly from the water's surface. As light travels through the water column, some of it is absorbed by phytoplankton and dissolved material. The remaining light reflects off the secchi disc and travels back through the water column where more is absorbed. The deeper the disc is lowered in the water, the harder it is to see the disc as increasing amounts of light are absorbed. The depth in which the disc can no longer be seen is the depth at which all the light is being absorbed as it passes down and back up through the water column. Usually three measurements from the same point are recorded. The practitioner can then determine the depth in which light penetrates through the water column by multiplying 1.7 times the mean of these three measurements.

Light penetration - Photosynthetically active radiation (PAR) and ultraviolet radiation (UV) can be measured to determine light availability reaching mangroves. PAR refers to the amount of sunlight that reaches plants/algae and is used for photosynthesis (wavelengths of 380 to 710 nm) (Rogers et al. 2001). A Li-Cor quantum meter with an underwater spherical sensor can be used to measure PAR. This instrument is lowered into the water using a cable and the PAR is recorded. (Rogers et al. 2001).

A Martek transmissometer can be used to measure the amount of light that is not scattered or absorbed within a 1-meter path of water, providing measurements that are not affected by angle of the sun or time of day (Bishop 1999; Rogers et al. 2001).

Sediment

Since sediment composition supports many animals and plants in mangrove communities and affects their abundance and distribution, it is important to assess sediment characteristics before and during restoration. Prior to restoration efforts, grain size and nutrients levels in sediment can be measured to determine whether the potential restoration site is suitable for restoration to be conducted. A large variation in sediment grain size or, significantly high nutrient levels within the restoration site may also be an indication of materials deposited or runoff during coastal development near the restoration project that may influence mangrove progress towards restoration goals.

Grain size

Most mangrove soils are generally formed when sediment derived from coasts, river banks, or from upland areas accumulates after being transported down rivers and creeks. Mangrove topsoil is generally sandy (coarse-grained), or contains clay (fine-grained) whereas the soil beneath the surface is a mixture of silt and clay (known as mud) (Lugo and Snedaker 1974). Sediment grain size as well as other environmental factors (e.g., salinity, inundation, nutrient availability, or pollution level) can influence floral and faunal species presence and distribution (Lugo and Snedaker 1974). Macrobenthos for example, is commonly found in fine and medium sandy grains within mangrove habitats. Transportation of coarser or finer grains during tidal movements into these habitats may result in migration of various species of macrobenthos to more suitable areas (Gueirrero et al. 1996).

Organic content and depositional environment

Mangrove soil consisting of a mixture of silt and clay is typically saturated and has minimal aeration which decreases with depth. Organic matter, deposited over time in mangrove soils, plays a significant role in supporting plants and animals by providing nutrients to support growth. The sediment acts as a sink, storing large amounts of organic matter that decomposes at a very slow rate. The source of organic matter found in mangrove sediments may have derived from plant (e.g., litterfall, wood litter) and animal detritus, bacteria or plankton as well as from sewage and agricultural run-off. These nutrients (i.e. organic matter) are then cycled throughout mangrove environments to be used by plants and animals (See “Nutrient Cycling”). Because the finer grained saturated soil has minute spaces between particles, no oxygen can infiltrate deeper than the top few horizons and therefore creates anoxic conditions (Lugo and Snedaker 1974). Such anoxic sediment conditions enable bacteria to survive in lower soil depths in which they produce hydrogen sulphide. The distinct scent of hydrogen sulphide reaching the soil surface is similar to that of rotten eggs.

Studies have been conducted by some researchers on mangrove development in relation to environmental factors, such as nutrient levels taking into consideration salinity. A gap dynamic model (FORMAN) was used to provide data on long-term mangrove recolonization along soil salinity gradients and nutrient resources for three Caribbean mangrove species (Chen and Twilley 1998). Results showed that (1) white mangrove dominated in fertile soils with low salinity during early stages of recovery but declined over time, (2) red mangrove dominated in low nutrient availability and low salinity areas only and, (3) black mangrove dominated at higher salinity levels and fertile soils.

Sediments also have the ability to retain pollutants that enter mangrove communities and affect mangrove growth (Wasserman et al. 2000). Chemicals such as mercury, for example, may seep into mangrove sediments from industrial waste and contribute significantly to mangrove degradation (Wasserman et al. 2000).

Sampling and Monitoring Methods

Many types of corer devices can be used to collect underwater sediment samples. They are generally operated by driving the instrument (e.g., collection tube or corer) into the bottom sediment, and extracting the sediment sample. Two examples of these sampling devices include hand cores and piston core samplers (Miller and Bingham 1987; US Army Corps of Engineers 1996; Radtke 1997). Hand cores are hollow tubes that are pushed into sediment to obtain samples (Radtke 1997). The core is driven into the sediment to the point marked on the instrument and then removed and stored. Once retrieved, the cores can be divided so that separate samples from different depths of sediment can be distinguished (Radtke 1997). Piston corers can use both gravity and hydrostatic pressure. As the instrument penetrates the sediments, an internal piston remains at the level of the sediment/water interface to prevent sediment compression (US Army Corps of Engineers 1996).

Sediment can be analyzed by measuring grain size and organic content. Grain size distribution can be determined by using a sieving analysis method (Pope and Ward 1998). Sediment samples can be analyzed by dried sieving or wet sieving the collected samples. A sediment sample is weighed and then passed through sieves with mesh sizes that decrease in diameter (Pope and Ward 1998). The sieves are then vibrated for a set time period allowing sediment grain to be separated based on its size. The weight of the sediment that remains on the sieve is measured, and the total sediment sample is determined (Pope and Ward 1998).

Organic matter in sediment includes Total Nitrogen (TN) and Total Organic Carbon (TOC). Total Nitrogen can be determined by drying and grinding the sediments into fine particles and then weighing a small sample (<1g) into a digestion tube (Bremner 1965a; Snedaker and Snedaker 1984). Organic N is then converted to ammonium-nitrogen using any of the Kjeldahl reagents (acid and a catalyst). Following ammonium-nitrogen conversion, steam distillation of the converted sample can be done to estimate the amount of ammonium-nitrogen (Snedaker and Snedaker 1984). Auto analyzers such as the carbon, hydrogen, and nitrogen (CHN) analyzer can also be used to rapidly determine nitrogen content for large numbers of sediment samples (Prochnow et al. 2001; Tung and Tanner 2003).

Total organic carbon can be measured using wet oxidation methods (Walkley 1974; Snedaker and Snedaker 1984; Tam and Yao 1998) such as the Walkley-Black method (Walkey 1947). Some researchers have modified the Walkley-Black wet oxidation method to determine total organic carbon (TOC) in mangrove and marine sediments (Tam and Yao 1998). A study was performed using a modified Walkley-Black method by assimilating sediment samples with acid dichromate in a domestic microwave for 7 minutes. The TOC results were comparable to the results of the traditional Walkley-Black method. The modified method used in this experiment proved in this study to be simpler, easy to duplicate, accurate, and precise compared to the traditional Walkley-Black method (Tam and Yao 1998).

Organic matter content in a sediment sample can be determined by measuring weight loss in subsamples after drying then sequential heating/burning at selected temperatures (550 °C and 950 °C) in a muffle furnace (Heiri et al. 2001). If the samples are from freshwater areas, the majority of "loss-of-ignition" (LOI) will stem from organic carbon oxidizing to CO_2. The results are typically accurate to 1-2% for sediment with over 10% organic matter. In high clay sediments, water may be lost during the burn resulting in additional error. If the samples are from saline environments, additional steps must be taken to subtract weight loss due to oxidation of sulfur to SO_2. Some researchers demonstrated that LOI is an accurate and cost and labor-efficient technique for determination of organic carbon and organic matter in sediment samples (Schulte and Hopkins 1996).

Topography/Bathymetry

Topography is an important structural feature in mangrove habitats, as any change in topography/bathymetry may alter ecological communities. When less inundated mangrove zones suddenly experience frequent inundation due to diking or flooding, animal and plant composition and abundance may be altered (Chow and Booth 1994). Mangroves are commonly found in mudflats as well as sloping areas with specific elevations. In most instances, relatively level or flat mangrove depressions are not as productive due to stagnant, standing water. Therefore, restoration practitioners must measure and monitor slope changes and record sources responsible for the change (Crewz and Lewis 1991).

The three zones in mangrove communities are seaward, middle, and landward. Along the Florida coastline and the Gulf Coast, distinct mangroves zonation patterns are seen in relation to elevation. In many areas, red mangroves grow closer to the shoreline (seaward) where the area is relatively flat. Black mangroves are found in areas that are more elevated and grow closer inland (Jimenez and Lugo 1985). White mangroves grow at relatively higher land elevations (landward) compared to red and black mangroves (Elias 1980).

Regardless of geographic location, mangroves tend to grow in specific topographic/bathymetric zones. Some researchers assessed the variation in structure and composition of mangroves from the eastern and western areas of the Sunderbans Islands in India in relation to topography (Matilal and Mukherjee 1989). Black mangroves and river mangroves (*Aegiceras* sp.), for example, were abundant in low-lying areas towards western and eastern areas of Sunderbans respectively while scrub tree *(Excoecaria*) and yellow mangrove (*Ceriops decandra*) were present throughout the entire forest. This shows that mangroves species prefer specific elevations and may not be as productive in altered elevations.

Sampling and Monitoring Methods

A Landsat TM satellite may be used to map mangroves and assess mangrove topography. Accuracy of the map can be enhanced with a Geographic Information System (GIS) using ecological information pertaining to mangroves found in tidally inundated areas. This system can be used to subdivide the mangrove areas identified by satellite data image processing on their proximity to water, ground elevation (above and below 10 m above mean sea level), and distance from water (greater than 2 m and less than 2 km). Each zone can then be verified using 1:50,000 aerial photographs allowing mangrove zones to be identified (Long and Skewes 1996).

Analyzing topographical maps and temporal, remotely sensed satellite data is an effective method to monitor and quantify mangrove cover (Samant 2002). Digital image processing of Remote Sensing Satellite in a Personal Area Network (PAN)[5] along with LandSat4 TM multispectral data can identify whether mangrove cover increased or decreased over time and what topographical changes occurred (Samant 2002). This method can provide a good representation of mangrove distribution and topography changes that may occur over time.

HYDROLOGICAL

Tides/Hydroperiods

Hydroperiod refers to the pattern of water level fluctuations in a habitat. Mangroves can be regularly or irregularly exposed to tides or irregularly inundated for long periods of time (Mitsch and Gosselink 1993). Tidal patterns, measured by the hydroperiod, influence mangrove productivity and are responsible for circulating nutrients, aerating the soil, and stabilizing soil salinity. To ensure healthy growth, mangrove areas require consistent tidal flushing to prevent sediment and nutrient build up and prevent standing water that may eventually drown some species intolerant of constant inundation. A mangrove restoration project may not succeed if there are no channels or tidal creeks to allow consistent tidal flushing. Tidal flushing also distributes propagules along the coast allowing mangroves to become established in new areas. If a natural supply of propagules is available, this process can more cheaply and efficiently restore mangroves than transplanting seedlings by hand. In addition, monitoring tidal patterns during restoration is important because tides influence both propagule distribution (affecting mangrove establishment and development) and nutrient availability needed for mangrove growth.

Tidal influence may also influence seedling establishment and survival, surface salinity, and pH in mangroves. These parameters were monitored in three red mangrove forests at Hutchinson Island, Florida (Lahmann 1989). The study sites included:

- A managed impounded mangrove forest that was artificially flooded with seawater during the summer for mosquito-control purposes
- An unmanaged (not artificially flooded) mangrove impoundment, and
- A fringe mangrove forest exposed to daily tidal exchange

The net aboveground primary production was estimated to be 4,335 g m^{-2} yr^{-1}, 4,016 g m^{-2} yr^{-1}, and 5,384 g m^{-2} yr^{-1} respectively. This shows that daily tidal fluctuations played a significant role in distributing nutrients throughout the mangrove habitat and contributed to higher levels of primary productivity.

Sampling and Monitoring Methods

Hydroperiods can be assessed by measuring flood frequency and duration (Mitsch and

[5] Allows devices to work together and share information and services.

Gosselink 1993). Flood frequency is the average number of times that a wetland is flooded within a specific time period. Flood duration refers to the amount of time that the wetland is actually covered with water. Water level recorders measure flood frequency and duration (Twilley and Rivera-Monroy 2003). These recorders are pressure-based[6] and can be applied for short- or long-term use, to create a hydrograph that shows changes in water levels over time.

Tide gauges are mechanical devices that are usually placed on piers or pilings and may be used for recording water level (IOC 1985; Emery 1991; Giardina et al. 2000). The tide gauge consists of a data logger that reads and stores data from different sensors and a modem that communicates with a computer (IOC 1985). The water level sensor should be even from a stable bench mark and calibrated at regular intervals to ensure accurate water level measurements.

Acoustic Doppler flow meters can also be used to evaluate tidal flow by measuring velocity and particles moving through the water. When using this instrument, the acoustic signals are transmitted, then reflected from particles, and collected by a receiver. The signals that were received are then analyzed for frequency changes. The mean value of the frequency changes can directly relate to the average velocity of the particles moving through the water (Gross and DeAngelis 1999).

Water Sources

Sources of water entering mangrove forests can influence the success or failure of a restoration project. Diversion channels may reduce the amount of nutrients entering the mangrove restoration site or may not readily distribute mangrove propagules. Also, upstream land uses may result in run-off containing agricultural or industrial chemicals that enter mangrove habitats. One of the potentially detrimental impacts of these chemicals on mangrove forests is increased algal growth that may out-compete other plant species that live there. Industrial chemicals that runoff into the water column may contaminate fish and bird food supplies affecting their health and survival. Other water sources that enter mangroves include groundwater and surface water. By evaluating mangrove water sources and the potential impacts that can result from these inputs, restoration practitioners can design a more effective restoration plan that includes parameters that can be used to monitor and measure water quality. Discussed below are examples of two water sources and how they may affect mangrove communities.

Groundwater

The relationship between hydrology and nutrient dynamics in a mangrove-fringed creek influenced by groundwater was studied (Kitheka et al. 1999). Nutrient concentrations increased in the creek during flood tide, about 2-3 hours prior to high waters. Nitrite and nitrate ($NO_2^- + NO_3^-$) concentrations, however, declined significantly during ebb tide. Groundwater outflow added to the nutrients flux in the dry seasons help to maintain mangrove productivity.

Surface Water

Surface waters may also affect mangrove biological communities (Elster and Polania 2000). In some cases, mangrove communities experience higher than normal salinities from industrial run-off, causing a decrease in animals and plants. Introducing surface freshwater to mangrove communities may help to restore them (Elster and Polania 2000). Some mangrove forests in Colombia recovered after obstructed channels were re-opened to introduce additional freshwater into degraded mangrove areas (Elster and Polania 2000). Studies in mangrove growth changes at different sites showed regrowth of degraded mangrove forests with black mangroves, white mangroves, and red mangroves occurred once freshwater inflow was restored (Figure 11). Restoring the hydrology will not always lead to reestablishment or

[6] Sensitive to the amount of water over them.

enhancement of mangrove productivity. This will only occur when hydrology is one of the main factors preventing successful mangrove growth (Elster and Polania 2000).

CHEMICAL

Salinity

Mangroves often grow in areas that receive large amounts of freshwater yet can still tolerate saline waters, giving them a competitive advantage over salt-intolerant species (Mitsch and Gosselink 1993). Some mangrove species such as red and black mangroves have the ability to extract salt from seawater by osmosis. Although mangroves regulate the amount of salt entering their roots, their salinity levels are still significantly higher than most other plants. White mangroves have salt glands in their leaves that allow them to secrete a significant amount of salt that enters the plant through the roots. Although mangroves are salt-tolerant plants, hypersaline conditions (greater than 35 ppt) can affect productivity (Hogarth 1999). In south Florida Everglades, red mangrove seedlings when exposed to hypersaline conditions (greater than 45 ppt), caused structural changes of mangrove terminal buds, preventing them from developing (Koch and Snedaker 1997).

Sampling and Monitoring Methods

Commercial instruments, such as a refractometer may be used to measure salinity. It is a hand-held instrument that measures the bending of light between dissolved salts as it passes through seawater (Rogers et al. 2001). Salinity is measured on a calibrated refractometer by placing a few drops of the seawater sample under the transparent slide, and then reading the salinity measurement through the eye-piece (Rogers et al. 2001).

A hydrometer can measure salinity by comparing the weight of the seawater sample to fresh water (Rogers et al. 2001). The glass hydrometer is placed into a cylinder containing the seawater sample and measured for buoyancy. The number on the hydrometer scale at the water surface and the temperature of the water are then identified, and salinity is determined by comparing these values with those on specific tables that are associated with hydrometers (Rogers et al. 2001).

Figure 11. Mangrove seedlings planted by Forestry Department and Village Government without restoring hydrology experienced 30% mortality in the first week. After two months 10% of seedlings remain, all the same species. Photo courtesy of the Mangrove Action Project, Port Angeles, WA. http://www.earthisland.org/map/mngim_indonesia.htm

FUNCTIONAL CHARACTERISTICS OF MANGROVES

Mangrove forests provide a habitat that shelters many plant and animal species adapted to tidal influences and changes in temperature and salinity. Mangroves:

Biological

- Habitat created by plants (i.e., mangroves)

Chemical

- Supports nutrient cycling

Physical

- Modifies water quality
- Reduces shoreline erosion

By performing these functions, mangroves are able to support important local and commercial fisheries as well as maintain plant and animal diversity and abundance. If the health of the mangrove is degraded in any way, it can affect the functioning of this habitat, such as affecting its ability to provide food for animals (e.g., fish, crustaceans, etc.) or provide healthy nursery and breeding grounds for some species. Understanding how this habitat functions is important when attempting to restore it. In addition, monitoring should be performed before, during, and after restoration efforts to determine whether the habitat is suitable for restoration and to track the success of the restoration project.

This section concentrates on the biological, physical, and chemical functions performed by mangroves. Also provided are some methods that can be used to sample, measure, and monitor functional parameters affiliated with each characteristic described. For example, mangroves are used as breeding, feeding, and nursery grounds by many species of animals. These functions are measured by counting the number of animals that use the habitat for these reasons. Also recorded is the type of species that utilize the habitat. Not all functional characteristics described, however, are expected to be measured. The additional information provided simply illustrates the importance of the habitat. The examples provided are just a few of the many methods that can be used. Sources cited throughout the text and in the Appendices of this chapter can be used to guide readers to additional information.

BIOLOGICAL

Habitat Created by Plants (i.e., Mangroves)

Mangroves support high biomass production, high biodiversity, and a complex trophic structure.

Some fauna occupying this habitat include:

Oysters (*Crassostrea* spp.)
Invertebrates, such as (*Chthamalus* spp.) and tunicates (*Cnemidocarpa* spp.)
Crustaceans, such as crabs (*Aratus pisonii*)
Fishes, such as
Mangrove snapper (*Lutjanus griseus*) (Figure 12)
Spotted seatrout (*Cynoscion nebulosus*)
Sheep-head minnows (*Cyprinodon variegates*) (Figure 13)
Goldspotted killifish (*Floridichthys carpio*)
Rainwater killifish (*Lucania parva)*
Sailfin molly *(Poecilia latipinna*), and
Exotic Mayan cichlid (*Cichlasoma urophthalmus*)
Reptiles including alligators (*Alligator mississippiensis*) and crocodiles (*Crocodylus acutus*), and
Birds such as blue herons (*Egretta caerulea*) (Figure 14) and pelicans (Pelecanidae) (Figure 15)

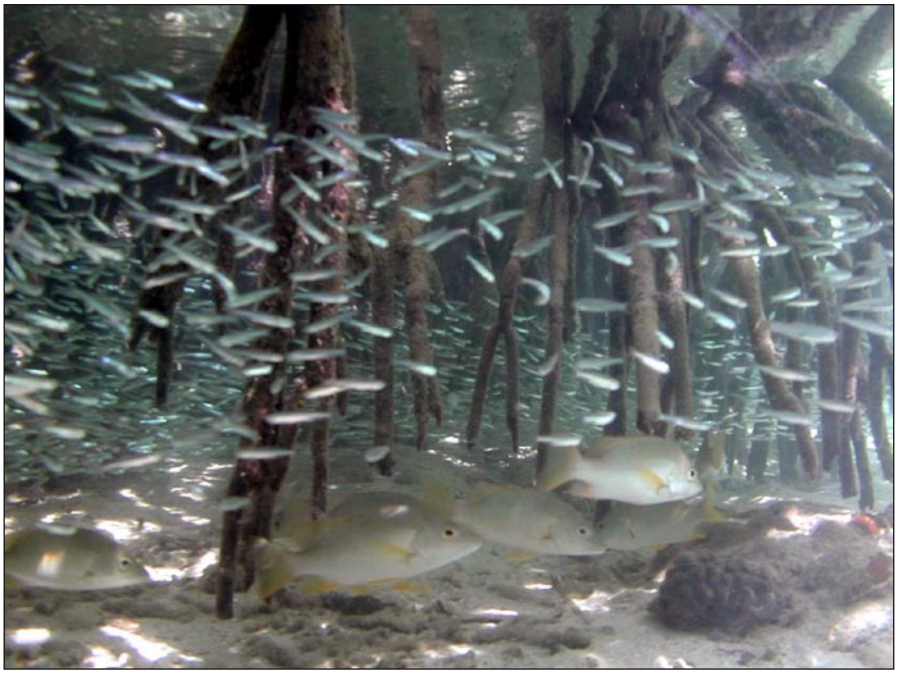

Figure 12. Mangrove snapper found amongst mangrove roots. Photo courtesy of NOAA Center for Coastal Monitoring and Assessment.

Figure 13. Species of minnows found near mangrove roots. Photo courtesy of NOAA Center for Coastal Monitoring and Assessment.

Vegetative species commonly found in and around mangroves include:

- Tropical hammocks
- Buttonwood
- Invasive Brazilian peppers
- Longleaf pine trees (*Pinus palustris*)
- Sea oats (*Uniola paniculata*
- Seagrass (*Thalassia testidinum*) (Figure 16)
- Saltwort (*Batis maritima*)
- Epiphytic algae (e.g., diatoms and blue-green algae), and
- Phytoplankton

Fish species, shorebirds, wading birds, and seabirds commonly use mangrove habitats as feeding grounds, nursery grounds, or for shelter amongst mangrove roots (Butler et al. 1997; Lorenz et al. 1997).

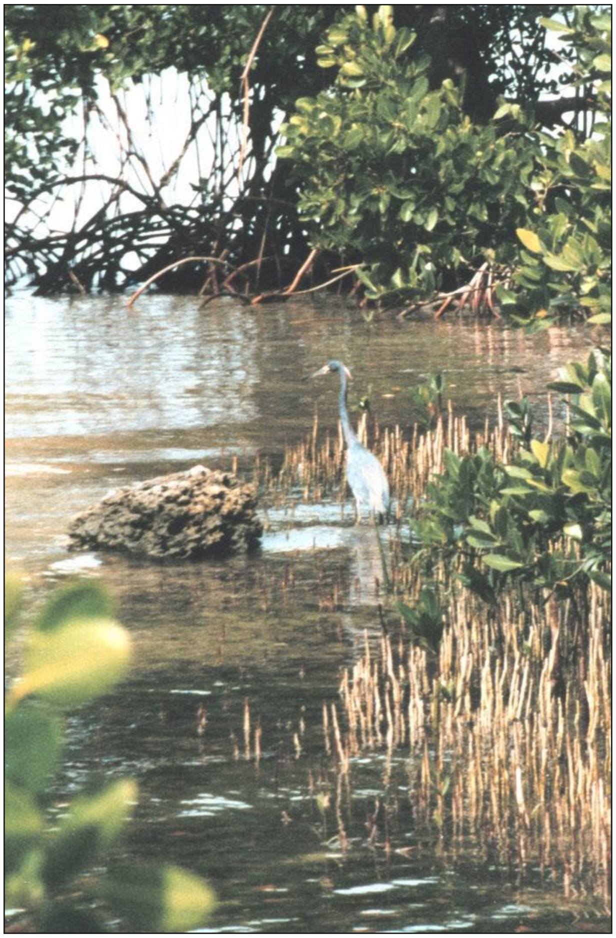

Figure 14. Blue Heron along a mangrove shoreline. Photo courtesy of Alison G. Delaplaine. Publication of the National Oceanic & Atmospheric Administration (NOAA), NOAA Central Library. http://www.photolib.noaa.gov/coastline/line1141.htm

Figure 15. Pelicans perching on red mangroves in Florida. Photo courtesy Larry Richardson, Florida Wildlife Service District. http://southeast.fws.gov/august04/Pelicans.jpg

Provides breeding grounds

Mangroves provide breeding grounds for fish, reptiles, resident and migratory birds, and mammals. Species are protected by the canopy and roots where they can consume nutrients, such as decayed leaves, algae, fruits, and seeds found in the water column or along the shore. Birds such as the white-crowned pigeon[7] (*Columba leucocephala)* typically nests higher up on mangrove trees to produce young successfully (Bancroft et al. 1991; Bancroft 1996). Nesting takes place on isolated mangrove islands where there are few predators. These birds build their nest using mangrove branches from ground level to high in the canopy (Wiley and Wiley 1979).

Figure 16. Seagrass found near mangrove roots and is used by organisms such as fishes and crustaceans as breeding grounds. Photo courtesy of NOAA Center for Coastal Monitoring Assessment.

[7] Typically found in the Florida Keys, the Bahamas, and in the Antilles, the Cayman Islands, and islands of the western Caribbean Sea.

The eggs are then laid in the nest and protected by branches and incubated with brooding duties by both the male and female parents. Of course, there are many other species of birds that breed in mangrove communities as well.

Some researchers have also studied breeding patterns of crustaceans to determine how frequently they breed in mangrove forests. In mangrove areas in South Africa, continuous breeding of burrowing crabs (*Macrophthalmus grandidieri*) occurred in the low shore while seasonal breeding took place on the middle to high shore (mangrove crabs, fiddler crabs, *Uca* and marsh crab, *Sesarma* spp. - Emmerson 1994). Higher up the intertidal zone, breeding season was more defined (*Sesarma meinerti*). Crab species, such as marsh crab (*Sesarma catenata*), began breeding in August, while the high intertidal species of brackish water crab (*Uca lactea annulipes)* was in March. Overall the breeding activity varies over time and within mangrove zones. During and following restoration activities, practitioners should conduct seasonal surveys on crab and bird breeding patterns to show whether breeding activities have changed over the years. Such changes can be an indication of whether the habitat is functioning successfully.

Provides feeding grounds

Many species use mangroves as feeding grounds. Mangrove snapper and spotted seatrout feed on decayed leaves, fruits, and seeds floating in the water column and on bottom sediments, as well as benthic organisms. Red drum (*Sciaenops ocellatus*) and spotted seatrout feeding behavior was observed in a restored, mangrove-rimmed impoundment in Tampa Bay, Florida, and a nearby, natural mangrove site (Llanso et al. 1998). Smaller red drum species fed mainly on amphipods, mysids, Nereid, and thick fleshy polychaetes, while large (200-590 mm) red drum preyed on polychaetes xanthid crabs shrimp, and small fishes. Spotted seatrout, however, fed primarily on mysids, shrimp, and small fishes (Llanso et al. 1998). In general, both species fed primarily on the abundance of amphipods and detritus.

In most mangrove communities, insects such as beetles, and some crab species feed on mangrove propagules. Birds as well as other organisms feed on insects that occupy mangrove communities (Hogarth 1999). Some invertebrates such as prawns, polychaetes, amphipods, gastropods, and crabs that occupy mangroves are also food sources for commercial fishes (Oluoch 1993). Snails and crabs play a significant role in breaking down organic material, such as leaf litter so that materials can be utilized by other organisms (Smith 1987). Macrophytes and algae in or near the water are also a good food source for fish, isopods, and amphipods.

During low tide, mudflats provide good feeding grounds for wintering, foraging, and wading birds (Nitsure and Pejaver 2002). Bird species that feed in mangrove habitats include:

Herons *(Ardeidae)*
Roseate spoonbill *(Ajaja ajaja)*
Sandpipers *(Scolopacidae)*
Plovers *(Charadriidae)*
Brown pelican (*Pelecanus occidentalis*)

They feed by diving down, snatching fish from the water, and then flying to nearby land to consume the fish (Nitsure and Pejaver 2002). They also feed on decayed fruits and their seeds as well as on benthic organisms, such as insects, shrimps, and polychaetes.

Provides nursery grounds and refuge from predation

Mangroves also provide nursery grounds for commercial and recreational fish species, birds, crustaceans, and other wildlife (Tobias 2001). The examples provided here are by no means a complete listing of the all of the types of organisms that use mangroves as nursery grounds. Fish and crustaceans for example spawn in different areas along the roots of the trees (Thayer and

Sheridan 1999) where nutrients are readily available. Because the roots and aboveground features have such strong structures, they protect juveniles from predation. Birds also use the canopy of the mangrove trees to shelter their juveniles. The advantage to using canopy areas as nursery grounds is that it makes it difficult for some predators to reach juveniles.

Sampling and Monitoring Methods

Birds

Birds can be monitored using aerial surveys and direct counts along coastal and estuarine habitats. Aerial surveys can inventory migrant shorebirds (Erwin et al. 1991) and monitor wintering populations (Morrison and Ross 1989). Surveys are also used to estimate relative abundance of migratory and wintering populations and for assessing population trends of migratory shorebirds. Direct counts can also be used to estimate the number of shorebirds or bird density. Data collected can be recorded using tape recorders and then transferred onto data sheets. In some cases, video cameras and aerial photography are used along with aerial surveys (Dolbeer et al. 1997). In addition to providing precise estimates of birds, aerial photography creates visual records of the structure of mangrove habitats.

Counting birds within fixed-width transects is a method used for determining bird types and densities (Noske 1995). This can be done by first selecting a study site and placing transects within that specified area. The practitioner then records the species type and the number of each individual species along each transect. This helps the practitioner to determine species of birds, their diversity, and abundance within a habitat.

Fish

Beach seines - Beach seines are nets that can be used to temporarily capture fish for the purpose of identification and counting. The nets contain a bunt (bag or lose netting) and long wings that are extended. Ropes are used for towing the seine along the shore to sample fish. The seine prevents fish from escaping from the area enclosed by the net. Seines as well as traps can be used for quantitative sampling of species composition and abundance (Tobias 2001). Methods used to estimate fish species abundance include random stratified sampling and fixed station sampling (Trippel 2001). Stratified sampling involves selecting a representative sample of the habitat within a larger area. Fixed station involves continuous sampling at permanent points. Using these standardized procedures helps maintain sampling precision.

Gill nets - Gill nets can be used to sample fish in mangrove habitats for small-scale projects. They consist of smaller panels of netting connected together with bridles so that the net can be extended to any size (Adkins and Bourgeois 1982). The nets contain a floatline consisting of air filled structures that keeps one end of the net afloat and a leadline containing weights that keeps the bottom of the net below the water surface. Once the net is deployed, fish swim into the invisible mesh nets where they are trapped. Samplers then remove fish from the net for identification, count the number of each species, record length and width of each individual, and note the condition of each (Adkins and Bourgeois 1982). Other measurements or samples may be taken at that time as well.

Fish species can also be monitored using point counts and transect surveys (Hodgson et al. 2004). Point-count surveys are performed by a SCUBA diver observing and recording fish species within a targeted area, for a set time interval. Transect surveys are performed by a diver who swims a certain distance and monitors fish by counting them on either side of the transect. Divers and researchers then estimate abundance by calculating the number of fish per sample area.

Crustaceans

The diversity, abundance, and biomass of macrofauna, such as molluscs and crustaceans within a mangrove forest can be sampled using quadrats at each study site. A quadrat is a square or rectangular object that is used as a sample unit and can vary in size. The size used will depend on the size of the sample area. Species abundance is estimated by calculating the mean of two to three samples collected from each study area. To keep track of organisms counted in quadrats, some organisms, if not too small, can be marked as they are counted and then recorded on a data sheet. Quadrats can be fixed so that a sample area can be measured repeatedly. Crustaceans can also be sampled using a 3 x 15 minute timed hand catch per site. This method allows practitioners to effectively assess macrofauna species in selected areas throughout mangrove habitats at certain time periods (MacIntosh et al. 2002; Ashton et al. 2003). Transects are also used to collect observational data by recording or collecting species samples along a line within a habitat (Dittman 2000). Quadrats and transects can be used along with photography to record species type and density in each study site.

Crustaceans such as fiddler crabs (*Uca annulipes)* can be evaluated for abundance by visual counts using binoculars and by counting burrows to estimate population density (Macia 2001). Binocular and direct burrow count methods can be used along with quadrats to quantify crustacean densities. In some cases burrow counts may give better density estimates than binocular counts (Macia 2001). Selection of methods, however, will vary between projects. Both methods can help determine whether the habitat is functioning effectively by supporting a large number of crustaceans.

Counting the number of individual crabs escaping from burrows is also used to assess crab densities in mangroves (Nobbs and McGuinness 1999). Counts made can be assessed using quadrats, recording distance of observer, and selecting a suitable quadrat size and recovery time. For species such as fiddler crabs, activity can be recorded during the first 10 min of the 30 min period. Long-term sampling, however, is suggested for efficiently determining crab abundance (Nobbs and McGuinness 1999).

PHYSICAL

Modifies Water Quality

Mangrove roots and branches can deflect wave energy and improve water quality by filtering sediments and nutrients and assimilating pollutants present in the water column. This provides a healthier environment for plants and animals. By performing this filtering process, mangroves also protect other coastal habitats, such as seagrasses, oyster beds, and coral reefs, from high sedimentation and pollutants. When monitoring water quality in mangroves, there are basic performance measures that can be evaluated:

- Total and/or dissolved inorganic forms of nitrogen and phosphorus can be used as measures of the mangrove's ability to remove or process nutrients
- Light penetration through the water column can be used to evaluate mangrove's ability to reduce sediment load, and
- Dissolved oxygen can be used to indicate the water body's recovery after being affected by pollutants (Twilley and Rivera-Monroy 2002)

Reduces Shoreline Erosion

Mangrove trees act as a protective barrier for coastlines against erosion, storm damage, and wave action by absorbing the energy of the waves in and amongst the variety of their root structures. The extensive root systems of mangrove trees reduce current velocities and increase sedimentation rates and retention, thus reducing coastal erosion (Augustinus 1995).

Mangrove root systems and leaves also help stabilize land elevation by sediment accretion (Carlton 1974). Erosion along the coastline may be more frequent because mangrove vegetation is eliminated for development or deteriorated due to long-term human impacts such as industrial run-off (Mazda et al. 2002). If reduction of mangrove forests along coastlines increases, so does erosion along the shoreline.

CHEMICAL

Nutrient Cycling

Mangroves are one of the most productive intertidal ecosystems with gross primary production[8] estimated at 3-24 g C/m^{-2} day^{-1}, and net production[9] estimated at 1-12 g C/m^{-2} day^{-1} (Lugo and Snedaker 1974; Lugo et al. 1976). These plants provide nutrients for many species and accumulate nutrients such as nitrogen and phosphorus, but also heavy metals and trace elements that are deposited into estuarine waters from land. Mangrove roots, invertebrates, epiphytic algae, and other microorganisms, take up and sequester nutrients over time. The nutrient cycling process within mangrove communities begins when plants use carbon present from carbon dioxide in the atmosphere for photosynthesis. Organisms such as fish, birds, invertebrates, and other consumers then feed on living biomass and decomposed materials such as leaves (litterfall), stems, twigs, prop roots, flower parts, and decayed fruits (Odum 1971; Feller et al. 1999). Plant material is then converted to organic material by organisms such as macro-invertebrates (e.g., insects and snails) and further reduced microbially to dissolved organic carbon. When benthic organisms in mangrove communities (such as polychaetes and shrimp) die, their remains seep into the soil contributing to the organic content and are utilized as nutrients (primarily nitrate) by understory vegetation and mangroves (Mitsch and Gosselink 1995; Feller et al. 1999) (carbon and nitrogen assessments in soil is discussed under "Sediment: Sampling and Monitoring Methods"). Tidal movements also assist in distributing decomposed material to areas within mangrove communities where other organisms can consume it.

Sampling and Monitoring Methods

Litterfall, containing both vegetative and reproductive features, represent a portion of the net primary production that can be accumulated on the floor, remineralized through decomposition or exported (Lugo and Snedaker 1974). One common method used to determine litter production is litter traps (Lugo and Snedaker 1974). Litter traps may be square, circular or triangular and consists of a wooden frame with a plastic screen bottom. The bottom of the trap is covered with flexible, plastic coated, fibre-glass window screening with a mesh size of approximately 1x1 mm. Attached at each corner of the trap are wooded stakes which secures the trap in the ground. Litter collected in each trap is placed in bags, labeled according to location, dried (dried at about 70 °C for 3 days), sorted into compartments and then weighed. The total amount of litter in each trap as well as in each compartment is used to determine the total amount of litter produced and phenological[10] patterns (Lugo and Snedaker 1974).

In addition to litterfall, net primary production can also be determined by biomass change of the plants and photosynthetic production. Above ground-biomass estimates (which include stem growth) can be made using allometric techniques[11] (Gwado 1993; Ross et al. 2001). A light attenuation approach can also be used to determine net canopy photosynthetic production (Bunt et al. 1979; Cox and Allen 1999). See references for a detailed description on each method mentioned.

[8] Refers to the total energy accumulated.
[9] The difference between material accumulated and material available for the food web.
[10] Change in plant growth and development over time during growth stages.
[11] Method used to assess the relative growth of various parts of plants or organisms.

PARAMETERS FOR MONITORING STRUCTURAL/FUNCTIONAL CHARACTERISTICS

The matrices provided below present the structural and functional parameters for restoration monitoring. Parameters selected for monitoring were based on information obtained from mangrove restoration, ecological monitoring-related literature, and from consulting with experts in the field of mangrove restoration. Parameters with closed circle (●) denote a parameter that, at a minimum, should be considered in monitoring restoration performance. Variables with an open circle (❍) may also be measured depending on specific restoration goals. This matrix is not exhaustive but represents those elements commonly used in restoration monitoring of mangrove communities.

Parameters to Monitor the Structural Characteristics of Mangroves

Structural Characteristics

Parameters to Monitor	**Biological**	Habitat created by plants	**Physical**	Sediment grain size	Topography / Bathymetry	**Hydrological**	Current velocity	Tides / Hydroperiod	Water sources	Wave energy	**Chemical**	Nutrient concentrations	pH, salinity, toxics, redox, DO[12]
Geographical													
Acreage of habitat types		●											
Biological													
Plants													
Species, composition, and % cover of:													
Algae		❍											
Herbaceous vascular		❍											
Woody		●											
Epiphytes		❍											
Canopy aerial extent and structure		❍											
Plant height		❍											
Seedling survival		❍											
Stem density		❍											
Hydrological													
Physical													
Temperature								❍	❍				
Upstream land use									●				
Water level fluctuation over time								●	●				
Chemical													
Nitrogen and phosphorus												❍	
Salinity (in tidal areas)								●	●				●
Toxics													❍
Soil/Sediment													
Physical													
Geomorphology (slope, basin cross section)					●			●					
Organic content				❍				❍					
Percent sand, silt, and clay				❍									
Sedimentation rate and quality				❍	❍		❍	❍					

[12] Dissolved oxygen.

Parameters to Monitor the Functional Characteristics of Mangroves

Parameters to Monitor	Biological	Contributes primary production	Produces wood	Provides breeding grounds	Provides feeding grounds	Provides nursery areas	Provides refuge from predation	Provides substrate for attachment	Supports a complex trophic structure	Supports biomass production	Supports biodiversity	Physical	Affects transport of suspended/dissolved material	Alters turbidity	Modifies water temperature	Provides temporary floodwater storage	Reduces erosion potential	Reduces wave energy	Chemical	Supports nutrient cycling
Geographical																				
Acreage of habitat types		●	●	●	●	●	●	●	●	●	●		●	●	●	●	●	●		●
Biological																				
Plants																				
Species, composition, and % cover of:																				
Algae		○		○	○	○	○	○	○	○	○		○	○			○	○		○
Herbaceous vascular		○		○	○	○	○	○	○	○	○		○	○	○		○	○		○
Woody		●	●	●	●	●	●	●	●	●	●		●	●	●	●	●	●		●
Epiphytes		○			○				○	○	○		○							○
Invasives				○	○	○	○		○		○									
Interspersion of habitat types				○	○	○	○		○	○	○		○	○	○	○	○	○		○
Litter fall		○			○				○	○				○						○
Plant health (herbivory damage, disease[13])					○															
Rate of canopy closure		○	○							○					○					
Seedling survival[9]			○														○			
Woody debris (root masses, stumps, logs)			○	○	○	○	○	○	○		○						○	○		
Biological																				
Animals																				
Species, composition, and abundance of:																				
Amphibians				○	○	○	○		○	○	○									
Birds				●	●	●	●		●	●	●									
Fish				○	○	○	○		○	○	○									

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Parameters to Monitor the Functional Characteristics of Mangroves (cont.)

Parameters to Monitor	Biological: Contributes primary production	Biological: Produces wood	Biological: Provides breeding grounds	Biological: Provides feeding grounds	Biological: Provides nursery areas	Biological: Provides refuge from predation	Biological: Provides substrate for attachment	Biological: Supports a complex trophic structure	Biological: Supports biomass production	Biological: Supports biodiversity	Physical: Affects transport of suspended/dissolved material	Physical: Alters turbidity	Physical: Modifies water temperature	Physical: Provides temporary floodwater storage	Physical: Reduces erosion potential	Physical: Reduces wave energy	Chemical: Supports nutrient cycling
Biological (cont.)																	
Animals																	
Species, composition, and abundance of:																	
Invertebrates			○	○	○	○		○	○	○							
Mammals			○	○	○	○		○	○	○							
Reptiles			○	○	○	○		○	○	○							
Hydrological																	
Physical																	
Fetch											○	○			○	○	
PAR	○								○		○	○					
Secchi disc depth	○								○		○	○					
Trash				○							○	○					
Water column current velocity											○	○			○		
Water level fluctuation over time			●	●	●	●					●	●		●	●		●
Chemical																	
Nitrogen and phosphorus	○								○			○					○
Toxics			○	○	○												
Soil/Sediment																	
Physical																	
Geomorphology (slope, basin cross section)			●	●	●	○	○			○	○	○	○	○	○		
Sediment grain size (OM[14]/sand/silt/clay/gravel/cobble)							○		○		○	○			○	○	○

[14] Organic matter.

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APPENDIX I: MANGROVES - ANNOTATED BIBLIOGRAPHY

This annotated bibliography contains summaries of restoration case studies and basic ecological literature. It is designed to provide restoration practitioners with examples of previous restoration projects as well as overviews of papers from the ecological literature that offer more detail than that covered in the associated chapter. Entries are presented from both peer reviewed and grey literature. They were selected through extensive literature and Internet searches as well as input from reviewers. They are not, however, a complete listing of all of the available literature. Entries are arranged alphabetically by author. Wherever possible, web addresses or other contact information has been included in the reference to assist readers in more easily obtaining the original resource. Summaries preceded by the terms '*Author Abstract'* or *'Publisher Introduction*' or similar descriptors were taken directly from their original source. Summaries without such descriptors were written by the authors of the associated chapter.

Akil, J. M. and. N. S. Jiddawi. 2001. A preliminary observation of the flora and fauna of Jozani-Pete mangrove creek, Zanzibar, Tanzania. *Marine Science Development in Tanzania and Eastern Africa* 1:343-357.

Author Abstract. In this study researchers observed and documented the living organisms present in the Jozani-Pete mangrove creek, by first surveying the area from December 1997 and March 1998 (northeast monsoon). One section of the creek has become a popular tourist-visiting site with some constructed features such as the presence of a boardwalk initiated in 1997. No prior studies on this site had been conducted and therefore the present survey aimed at establishing baseline information on the biodiversity of the flora and fauna present in the area, which could be, used for comparison in future studies. See publication for more information on techniques used for monitoring. There were twenty 10 m^2 randomly selected quadrats observed both at low and high tides. The benthic organisms observed in transects were collected and classified up to species level. Based on the results, there were five mangrove species and nine other major groups of plants comprising 65 species present. There were also nineteen families of animals comprising 76 species identified, which included mainly fishes, crustaceans and molluscs. Exploitation of the mangrove plants, which cover 75% of the total area, was also recorded from various parts especially along the lower rim of the creek. Researchers suggested that an in-depth study and monitoring of the flora and fauna of the area is important as well as educating the community on ways to utilize resources to ensure the sustainability of the mangroves with the associated organisms.

Bosire, J. O. 1999. Floral and faunal secondary succession in a restored mangrove system in Kenya, 89 pp. In Bosire, J. O. (ed.), Floral and faunal secondary succession in a restored mangrove system in Kenya. Ecological Marine Management thesis, Vrije Universiteit Brussel, Brussels, Belgium.

Author Abstract. The environmental variables, vegetation structure and floral and faunal recruitment of *Rhizophora mucronata, Sonneratia alba,* and *Avicennia marina* reforested plots (5-yrs, 7-yrs, and 5-yrs old respectively) in Kenya were investigated. Emphasis was made on the recruitment of 'new' mangrove species into the monospecific reforested stands, invasion of the stands by macrobenthos (crabs and soil-infauna) and the shift in environmental gradients following reforestation. The pre-restoration conditions of the reforested area were assessed by a naked system (denuded or open) while a natural system (relatively undisturbed) was used to evaluate the expected post-recovery conditions of the reforested area. See publication for additional information on techniques used. The results for this study were as follows: 1) salinity and temperature were lower ($p<0.05$), while organic matter content was higher ($p<0.05$) in the areas with mangrove cover; 2) the naked systems were more sandy, and areas with mangrove cover had higher proportions of clay and silt; 3) there was no floral recruitment into the naked areas, but the reforested stands of *S. alba, A. marina,* and *R. mucronata* had 5,400 recruits ha-1, 4,000 recruits ha-1 and 700 recruits ha-1 respectively; 4) macrobenthic density and soil-infauna taxa richness were higher in the reforested systems ($p<0.05$) compared to the naked systems.

Chen, R. and R. R. Twilley. 1998. A gap dynamic model of mangrove forest development along gradients of soil salinity and nutrient resources. *Journal of Ecology* 86:37-51.

Author Abstract. A gap dynamic model (FORMAN) was developed as a first synthesis of available data for three Caribbean mangrove species into an individual-based model that simulates the long-term dynamics of mangrove forest development. Field observations at three sites along the Shark River estuary were compared with simulation results, assuming development following Hurricane Donna in 1960. Total basal area simulated for each site was within plus or minus 10% of that observed, although species-specific basal area predictions were less accurate. A decrease in nutrient availability from marine to mesohaline sites modelled the reduced basal area of *Avicennia germinans* and *Laguncularia racemosa*. However, at the lower nutrient site a 83% reduction in maximum sapling recruitment of both *A. germinans* and *L. racemosa* was required to fit field results. Increased basal area of *A. germinans* and *L. racemosa* limited the development of *Rhizophora mangle* at higher nutrient downstream sites, apparently due to competition for light resources. Both observed and simulated results indicated that *R. mangle* had higher frequencies in the smaller size classes at all three sites, compared to a bell-shaped size-class distribution of *L. racemosa*, particularly at the higher nutrient sites. Succession was projected for the next 500 years at a site in the lower estuary. Long-term forest dynamics were sensitive to species-specific maximum sapling recruitment rates. In the absence of large-scale disturbance, initial dominance by *L. racemosa* was predicted to be replaced eventually by *A. germinans*, even when maximum sapling recruitment rate of *A. germinans* was set at half of *L. racemosa* and *R. mangle*. Response curves for each species along gradients of soil nutrient resource and salinity illustrated their relative competitive balance over time (up to 300 years). *Laguncularia racemosa* dominated in fertile soils with low salinity at early stages of recovery, but its abundance decreased over time while *A. germinans* increased. The dominance of *R. mangle* was limited to regions with low nutrient availability and low salinity. *Avicennia germinans* dominated at higher salinities, where the effect of nutrient availability was overwhelmed by the tolerance of individual species to salt stress.

Davis, S. E. III, D. L. Childers, J. W. Day, Jr., D. T. Rudnick and F. H. Sklar. 2001. Wetland-water column exchanges of carbon, nitrogen, and phosphorous in a southern Everglades dwarf mangrove. *Estuaries* 24:610-622.

Author Abstract. We used enclosures to quantify wetland-water column nutrient exchanges in a dwarf red mangrove (*Rhizophora mangle* L.) system near Taylor River, an important hydraulic linkage between the southern Everglades and eastern Florida Bay, Florida, USA. Circular enclosures were constructed around small (2.5-4 m diam) mangrove islands ($n = 3$) and sampled quarterly from August 1996 to May

1998 to quantify net exchanges of carbon, nitrogen, and phosphorus. The dwarf mangrove wetland was a net nitrifying environment, with consistent uptake of ammonium (6.6-31.4 mu mol m^{-2} h^{-1}) and release of nitrite + nitrate (7.1-139.5 mu mol m^{-2} h^{-1}) to the water column. Significant flux of soluble reactive phosphorus was rarely detected in this nutrient-poor, P-limited environment. We did observe recurrent uptake of total phosphorus and nitrogen (2.1-8.3 and 98-502 mu mol m^{-2} h^{-1}, respectively), as well as dissolved organic carbon (1.8-6.9 mu mol m^{-2} h^{-1}) from the water column. Total organic carbon flux shifted unexplainably from uptake, during Year 1, to export, during Year 2. The use of unvegetated (control) enclosures during the second year allowed us to distinguish the influence of mangrove vegetation from soil-water column processes on these fluxes. Nutrient fluxes in control chambers typically paralleled the direction (uptake or release) of mangrove enclosure fluxes, but not the magnitude. In several instances, nutrient fluxes were more than twofold greater in the absence of mangroves, suggesting an influence of the vegetation on wetland-water column processes. Our findings characterize wetland nutrient exchanges in a mangrove forest type that has received such little attention in the past, and serve as baseline data for a system undergoing hydrologic restoration.

Day, S., W. J. Streever and J. J. Watts. 1999. An experimental assessment of slag as a substrate for mangrove rehabilitation. *Restoration Ecology* 7:139-144.

Author Abstract. Rehabilitation of mangrove habitat has become common practice, but few studies have investigated the growth and survival of mangrove on artificial substrates. Managers attempting to plant mangrove in sites containing artificial substrates must remove substrates or risk poor performance of rehabilitation efforts. This study compared propagule retention, early survival, growth, flowering success, and nutrient concentrations of *Avicennia marina* (grey mangrove) grown on sand, naturally occurring substrate, and rock blast furnace slag over two growing seasons at an experimental site near Newcastle, Australia. Nutrient concentrations of experimental plants were also compared to those of naturally occurring plants. Experimental results showed significant differences ($p < 0.05$) in short-term survival, growth over the two growing seasons, and carbon and nitrogen concentrations between plants grown on different substrates. Comparison of plants grown in slag and plants from reference sites suggests, however, that slag does not lead to anomalies in nutrient concentrations of young mangroves. Although the results identified some differences between plants grown on river sand, naturally occurring substrate, and slag substrate, the absence of consistent differences suggests that mangroves planted in slag are under no greater risk of future failure than mangroves planted in naturally occurring substrate.

Elster, C. 2000. Reasons for reforestation success and failure with three mangrove species in Colombia. *Forest Ecology and Management* 131:201-214.

Author Abstract. As a result of human-induced changes in the hydrology of the lagoon system of the Cienaga Grande de Santa Marta, Caribbean coast of Colombia, 60% of the originally 51 000 ha of mangrove forest have died. The main reasons for this mass mortality were hypersalinization, increased sedimentation rates, and lowering of the water level. During the 1989-1998 period, efforts were made to reestablish the destroyed areas. The rehabilitation measures started with monitoring and the reopening of obstructed channels to introduce more freshwater into the area. Between 1994 and 1997, the first reforestation experiments with propagules, seedlings, and saplings were carried out at two sites with reestablished hydrology. The experiments with *Avicennia germinans, Laguncularia racemosa*, and *Rhizophora mangle* showed that the reforestation success depends mainly on site selection and preparation. Generally, all species developed best at sites with low salinities and a water level near the soil surface. Highest mortalities were found in set propagules and seedlings of *L. racemosa* and *A. germinans,* whereas the best survival rates occurred in R. mangle propagules as well as in *L. racemosa* saplings. Growth rates, especially of *L. racemosa*, were extremely high when the ecological factors were favorable, and flowering set in early.

Erftemeijer, P. L. A. and R. Nukul. 1999. Involving local communities in coastal wetland restoration: A case study of mangrove rehabilitation efforts in southern Thailand, 28 pp. In Limpsaichol, P., A. Edwards, and B. E. Brown (eds.), Proceedings of an International Workshop on the Rehabilitation of Degraded Coastal Systems, 19-24 January 1998. Phuket Marine Biological Center.

Author Abstract. Intensive logging and conversion for shrimp aquaculture have caused a rapid loss of large areas of productive mangrove forests and other coastal wetlands in Thailand over the past three decades. Although detailed information on the techniques for mangrove reforestation is available, and the government as well as private sector appear to be willing to invest huge amounts of money into mangrove rehabilitation, the success of these efforts are often limited, in terms of time and area. Besides technical and financial constraints, the success of coastal restoration efforts may be hampered by issues relating to land ownership, land-use conflicts, and the lack of follow-up and attention after initial planting. An increasing number of projects and initiatives have emerged throughout Thailand that are involving local communities in the planning and implementation of mangrove reforestation efforts. Recognition of the user-rights of these communities in sharing the benefits of the rehabilitation (e.g., extraction of non-timber products) through the granting of community forest status, can provide an important incentive for their active involvement in replanting and follow-up, to ensure high rates of survival and success. This paper examines three case studies of community participation in mangrove rehabilitation in Trang, Songkhla and Pattani provinces, Southern Thailand. The three examples differ in approach and in stage of progress (timescale), ranging from a low-key long-term grassroots initiatives with NGO support emphasising community, capacity building for self-reliance, to ICZM style projects with major technical, academic and financial inputs from outside. All three examples clearly demonstrate the benefits of community participation in mangrove rehabilitation. The building of confidence and understanding within the community may be time-consuming and hamper immediately measurable progress in replanting. This investment, however, will pay off in the long term because it builds a strong sense of ownership and commitment within the community and therefore ensures the long-term sustainability of the rehabilitation. By combining the rehabilitation with environmental awareness building and socio-economic development activities, this approach will not only ensure successful reforestation of mangroves but also contribute to the prevention of further degradation.

Erftemeijer, P. L. A. 2002. A new technique for rapid assessment of mangrove degradation: A case study of shrimp farm encroachment in Thailand. *Trees* 16:204-208 University of Dar es Salaam, Department of Botany, Dar es Salaam, Tanzania. Contact information: Paul Erftemijer, epaul@science.udsm.ac.tz.

Author Abstract. A new technique (Aerial Video Manta Analysis) was developed for the rapid assessment of mangrove degradation due to logging and conversion for shrimp aquaculture. Video recordings were made of mangroves along the Andaman Sea coastline, Thailand, during a 2-day aerial survey (16–17 September 1997) in a small Cessna 206 aircraft at an altitude of 800–1,000 feet and flying speed of 100 knots/h. The video recordings were analyzed following a modified Manta-Tow technique, originally developed for coral reef surveys. The percentage cover of good mangrove stands, mangrove areas degraded by logging, and mangrove areas converted into shrimp farms, was estimated for each consecutive 1-min interval of video playing time. The analysis revealed that 9.9–2.2% of the mangroves along the Andaman coastline were severely degraded by logging and 23.3–1.9% had been converted for shrimp farming (a total of 3,255–370 shrimp ponds were counted). The encroachment for shrimp farming was most severe (34%) in Krabi Province, while Phang-nga Province had the most (75%) good mangroves. These results demonstrate that illegal development of new shrimp farms along the Andaman Sea coast has been substantial in recent years. The results obtained by four independent observers using this new method were remarkably close (SD ± 25% of mean). The new method allowed cheap, rapid and accurate evaluation of the status of the mangrove resources over a long stretch of coastline within a time-span of a few days. Aerial Video Manta Analysis is a valuable tool to support coastal conservation and management efforts.

Field, C. D. 1998. Rehabilitation of mangrove ecosystems: An overview. *Marine Pollution Bulletin* 37:383-392.

This paper discusses considerations to be made when monitoring and rehabilitating mangrove ecosystems. These include site selection for mangrove planting and planting approaches. For example mangroves develop best on low energy muddy shorelines with suitable intertidal zone, and an abundant supply of fine grain sediment. The soil should be stable and non-eroding and of sufficient depth to support planting. Topography of the site should slope gently to permit proper drainage. The condition of adjacent sites should also be considered. If areas adjacent to site are degraded it may influence mangrove restoration success.

Planting methods include natural regeneration and artificial regeneration. Natural regeneration involves the use of natural occurring propagules or seeds. The advantages of natural regeneration is that it is cheap to establish, less labor required, less soil disturbance and seedlings establish vigorously and the mangrove forest is likely to resemble the original mangrove vegetation. When using this technique there should be adequate supply of seeds or propagules. Artificial regeneration includes the planting of seeds, propagules or seedlings in areas where there is not sufficient natural regeneration. This includes transplanting seedlings to a new location or to collect ripe seeds or propagules and planting them directly into the site. Seedlings may also be raised, or small trees, under nursery conditions and then to transplant them to the field.

Finn, M., P. Kangas and W. Adey. 1999. Mangrove ecosystem development in Biosphere 2. *Ecological Engineering* 13:173-178.

Ecological Engineering Abstract. Southwest Florida mangrove forest vegetation has been divided into a mesocosm within Biosphere 2. There were similar characteristics for dense stands of mangroves with Florida mangrove forests developed from the small seedlings and saplings initially installed in the mesocosm. The mangrove overstory was evaluated by leaf area index which ranged from 2.16 to 4.02 m^2/m^2. The mangrove understory decrease was monitored as the mangrove overstory developed. The Biosphere 2 mesocosm was compared with a similarly planted mesocosm at the Smithsonian

Institution in Washington, DC. Based on these studies mesocosms performance was used to evaluate existing theories on natural mangrove forest species composition. See publication for additional information on techniques used.

Haller, R. 1993. Experimental results of planting of mangrove trees in the Bamburi cement quarries and fisheries experiments. 33 pp. National workshop for improved management and conservation of the Kenyan mangroves.

Author Abstract. The paper describes the rehabilitation of the strip-mined quarries for cement manufacture by the Bamburi Portland Cement Company (BPCC) in Mombasa, Kenya. The management of BPCC felt that it was their moral obligations to rehabilitate quarries. They embarked on a rehabilitation project in 1971. The rehabilitation project has proved very successful and part of the initial trials is now enclosed in the Bamburi Quarry Nature Trial. The species which grew best were *Casuarina equisetifolia* and *Conocarpus lancifolius*. The leaf fall from these trees was broken down to form a layer of organic matter on top of the limestone. This nutrient rich layer allowed plants which could not survive the same harsh conditions as the first tree species to grow. Birds, animals, insects, and fish were introduced and this in turn attracted more wildlife; a new ecosystem was created. At the very beginning of the quarry rehabilitation project, the need to test alternatives to casuarinas, which may survive and thrive under conditions of rising ground water salinities was considered important. About fifteen years into the quarry reafforestation, it became obvious that the Casuarinas planted in swampy areas, where excavation had gone a bit too low, were much more prone to windfall. Casuarinas planted in areas where excavation had stopped at the usual level of 50 cm above ground water, were not as easily uprooted by strong winds and also produced more massive stems. For better economic use of the lower-flying, swampy sites, an alternative to Casuarinas had to be found and new trials with mangroves started. *Rhizophora mucronata, Heritiera littoralis, Xylocarpus granatum* and *Avicennia marina* were planted at different sites in the rehabilitation scheme. Later, *Bruquiera qymnorrhiza* and *Ceriops tagal* were also included. All these species were propagated from seeds. *Heritiera* and *Xylocarpus* seeds had been collected as drift seeds, *Rhizophora, Bruquiera, Ceriops* and *Avicennia* seeds were collected directly from seeding mother trees. The conclusions that can be drawn are: at least *Rhizophora mucronata, Heritiera littoralis, Xylocarpus granatum*, and *Avicennia marina* can grow and thrive in water of minimum salinities (1–3 ppt), with minimum tidal fluctuations (plus or minus 30 cm during spring tides, almost nil during neap tides). *Heritiera littoralis, Xylocarpus granatum*, and *Avicennia marina* grow well in shade, while *Rhizophora mucronata* seems to perform better with more light available. The four mangrove species tested all rooted and thrived on rocky underground. *Rhizophora mucronata* seems to respond favorably to high nutrient availability.

Imbert, D., A. Rousteau and S. Pierre. 2000. Ecology of mangrove growth and recovery in the Lesser Antilles: State of knowledge and basis for restoration projects. *Restoration Ecology* 8:230-236.

Author Abstract. Whereas the increasing knowledge on tropical coastal wetlands highlights the ecological and economical importance of such ecosystems, anthropogenic activities within the coastal zone have caused substantial, irreversible losses of mangrove areas in the Lesser Antilles during the last decades. Such a paradox gives strength to compensatory policy efforts toward mangrove restoration. We review the available knowledge on the ecology of mangrove growth and recovery in the Lesser Antilles as a contribution to possible restoration projects in such islands. Distribution of species follows a general pattern of seaward/landward zonation according to their respective tolerance to flooding and to pore-water salinity. An experimental study of seedling growth following simulated oil spill has documented the tolerance of *Rhizophora mangle* and *Avicennia germinans* seedlings to oil concentration in soils and the effects of natural biotic and abiotic factors on seedlings growth and survival. Monitoring mangrove recovery following hurricane Hugo has given information on growth patterns, from seedling to sapling stages, according to species and site conditions. Forest recovery was mostly due to pre-established seedlings. For the large *Rhizophora* propagules, buoyancy appears to be a quite inefficient way of dispersal far inland from the seashore or riversides. Causes of recovery failure are discussed. From these results we attempt to answer the questions when, where, how to plant mangroves, and what species to use.

Kairo, J. G. 1993. Mangrove re-afforestation: A Kenyan experience. National Workshop For Improved Management and Conservation of the Kenyan Mangroves. Kenya Marine and Fisheries Research Institute, Mombasa, Kenya. 25 pp. Contact information: jkairo@recoscix.org.

Author Abstract. The mangrove areas in Kenya are estimated to cover about 50,000 to 60,000 ha. However, non-sustainable utilization, over-exploitation of resources and conversion to other land uses principally for fish ponds, salt pans, human settlement and infrastructure development are drastically removing this resource base at an alarming rate. This has unfavorable effect on fisheries, fuel, coastal erosion, etc. Conservation alone is not enough. Mangrove afforestation will be essential for the areas where forests have decreased or been destroyed. In addition, the paper discusses part of a pilot study for practical afforestation. A reafforestation project to rehabilitate degraded areas, restock denuded mudflats, and transform disturbed forests into uniform stands of higher productivity was launched in October 1991 at Gazi Bay. Basically three artificial regeneration techniques were employed: use of seeds, use of saplings (less than 1.0 m height), use of 'small trees' (up to 2.0 m height). More than 7000 saplings and 'small trees' of *Sonneratia alba* (Milana), *Avicennia marina* (Mchu), *Xylocarpus granatum* (Mkomaafi), *Heritiera littolalis* (Msikundazi), *Rhizophora mucronata* (Mkoko), *Ceriops tagal* (Mkandaa) and *Bruguiera gymnorrhiza* (Muia) were transplanted or planted at different heights along inter-tidal complex, growth was monitored at 14 days, 1 month, or 2 month intervals depending on the experiment. The rate of the planted propagule and saplings after 12 months varied between 10% in areas heavily exposed to wave action and more than 85% in well protected areas. *Sonnertia alba* growing at the most seaward plots, showed the highest growth rate among all the transplanted saplings with a maximum diameter increment of 1.9 cm and height increment of 1.18 m. Besides field and nursery experiments, air-layering of Milana, Mkomafi and *Lumnitzera racemosa* (kikandaa) is also mentioned as promising technique of providing stock plants for transplanting without removing mangroves from source area. Rooting success was highest in Milana followed by Kikanda and Mkomafi. The paper presents a strong argument that research should increasingly be developed to study disturbed and manipulated mangrove areas, if positive contributions to management practices are to be achieved.

Kairo, J. G. 1995. Mangrove Restoration and Management: Monitoring of the Artificial Regeneration Plots in Gazi Bay, Kenya. 116 pp. Master thesis Botany, University of Nairobi, Nairobi, Kenya. http://www.specola.unifi.it/mangroves/human/restoration1.htm

A development project entitled "*Community Participatory Forestry for the Rehabilitation of Degraded Mangrove Forests at Gazi bay, Kenya*" was implemented in 1993/95 to monitor mangrove rehabilitation success. Assessment were made of the Gazi plantation site, to see whether it was suitable for re-afforestation with *Rhizophora mucronata, Ceriops tagal, Bruguiera gymnorrhiza, Avicennia marina, Xylocarpus granatum, Heritiera littoralis* and *Sonneratia alba.* Seeds and propagules were collected between March and June, corresponding with lengthy rain period. Mature propagules were collected from the parent tree or litter under trees. Local people were trained to identify and select mature and healthy propagules. After field collection, propagules were packed in plastic bags and transported to the planting site. Quality control was performed to remove damaged, infected or malformed propagules. Propagules were planted similarly to the natural distribution or zonation pattern. The propagules were then stored for two to three days under natural shed, and kept wet by sprinkling water throughout the period. Species of *Rhizophora* and *Sonneratia* that can withstand high inundation and deep mud were planted near to the water. Others including *Ceriops* and *Avicennia* were planted further off from the creeks.

Data was collected on growth performance and survival/mortality fortnightly, monthly, two, four, six, eight, nine and twelve months after planting/transplanting. Results show that the survival of the transplanted saplings or propagules was significantly better (80 - 100% of 70,000 after twenty-four months) than for sapling (< 5% after twelve months); planting of nursery saplings gave a higher survival rate (80-100% after twenty-four months) compared to transplanting of wildings; for most observed parameters, *C. tagal* showed the lowest growth rates of less than 0.5 m/year; and the maximum growth rate of 1.18 m/year was achieved by *Sonneratia alba* that were planted on the seaward denuded areas.

Kaly, U. L., G. Eugelink and A. I. Robertson. 1997. Soil conditions in damaged North Queensland mangroves. *Estuaries* 20:291-300.

Author Abstract. Selected physical, chemical, and biological characteristics of soils in mechanically damaged North Queensland mangrove forests were examined and compared with undisturbed controls. The soils in nine of the selected forests were tested in a factorial sampling program that was designed to examine effects of severity of mechanical damage to forests (severely damaged: trees removed and soils disrupted by bulldozing; versus damaged: trees felled no bulldozing; versus controls: trees and soils undisturbed); soil depth; forests (10s-100s km apart); and sites within forests (10s-100s m apart). The characteristics examined were soil compaction, grain size, pH, percent by weight of total carbon, nitrogen, phosphorus, potassium, sulfur, and iron and the density of crab burrows. Three of the ten variables examined included: total N, total P, and density of crab holes, decreased with mechanical damage to forests. Researchers stated that the loss of potentially-limiting nutrients and of an important bioturbator at severely damaged sites suggests the need for further experimental investigation of soil characteristics in relation to natural regeneration and efforts of mangrove restoration. See publication for additional information.

Kaly, U. L. and G. P. Jones. 1998. Mangrove restoration: A potential tool for coastal management in tropical developing countries. *Ambio* 27:656-661.

Author Abstract. This paper discusses mangrove restoration as a potential tool for the management and conservation of coastal ecosystems. Researchers examined the connections between mangroves and fisheries, and outlined an ecosystem approach to evaluate mangrove restoration initiatives. The goal of mangrove restoration projects is said to actively promote a return to the natural assemblage structure and function (within the bounds of natural variation) that is self-sustaining. This goal requires: (i) identifying the natural state, including key organisms in maintaining the physical substratum, community structure and food webs maintaining fish stocks; (ii) developing biotechnology for restoring key organisms; and (iii) assessing the long-term success of the project. See publication for more information on techniques used for successful mangrove restoration efforts.

Kent, C. P. S. and J. Lin. 1999. A comparison of Riley encased methodology and traditional techniques for planting red mangroves (*Rhizophora mangle*). *Mangroves and Salt Marshes* 3:215-225.

Author Abstract. The effectiveness of encasement and traditional techniques for planting red mangroves (*Rhizophora mangle*) in moderate to high wave energy environments was evaluated. The three encasement types were half-length PVC pipes, full-length PVC pipes, and bamboo pipes. In August, 1997, plantings were conducted at two locations in the Indian River Lagoon, Florida: Sebastian and Rocky Point. Furthermore, plantings were also conducted in November 1997 using full-length encasements and conventional planting. See publication for additional information on techniques used. Results showed that seedlings planted within full-length PVC encasements had the highest survivorship and growth because of their protection from waves and currents. Failure of seedlings within bamboo encasements appeared to be caused by low light exposure. Based on observations made for the two locations, there was a significantly greater growth at the Sebastian location than at the Rocky Point location for the planting conducted in November, but not for those planted in August. However, there was no significant difference observed in seedling survival between those planted in August and November. There was however a significantly greater growth in mangroves planted in August.

Kitheka, J. U., E. N. Okemwa and J. M. Kazungu (eds.). 1999. Monitoring of nutrient levels, turbidity and sediment transport at Port-Reitz Creek (Kilindini Creek) in Kenya. Kenya Marine and Fisheries Research Institute, Mombasa, Kenya, Contact information: jkitheka@recoscix.com.

Author Abstract. A significant gradient in the spatial distribution of suspended particulate matter (SPM) concentrations, salinity and temperature exists at Port-Reitz. Stations located in the upper backwater zones fringing the mangroves experience high SPM concentrations as well as lowest and highest salinities in wet and dry respectively. SPM concentration varied from 0.019 g/l to 0.900 g/l with a mean of 0.162 g/l in the upper zones and ranged from 0.010 g/l to 0.08 g/l with a mean of 0.033 g/l in central zone. In the lower region, the concentration varied from 0.011 g/l to 0.073 g/l with a mean SPM concentration of 0.022 g/l. There is no significant re-suspension of the bottom sediments when currents are < 0.4 m/s, but for currents > 0.5 m/s tidal driven re-suspension occurs and SPM concentrations rises from almost 0.0 g/l to 0.17 g/l. At higher current speeds > 0.5 m/s, the SPM concentration increases dramatically from 0.2 g/l to 1.0 g/l. Greater re-suspension occur during flood tide despite the ebb tide dominance. A comprehensive turbidity-monitoring program is recommended. As for nutrients distribution, the highest nutrients levels were recorded during the wet season signifying the relative importance of riverine contribution into Kilindini Creek. Nitrate-nitrogen concentrations during wet season were as high as 22 ± M at the upper backwater zone and decreased gradually to 4 mu M at the open water end. During dry period nitrate concentrations oscillated around 2 ± M throughout the creek system. As for phosphates concentration varied between 2.5 ± M and 0.8 ± M at the two extreme stations during the wet seasons. Dry season concentrations were mostly < 0.6 ± M. The highest ammonium concentration (ca. 14 ± M) was observed at station 1 immediately after the heavy rains of May/June. However, during this period, all the other two stations recorded almost nil concentrations.

Koch, M. S. and C. J. Madden. 2001. Patterns of primary production and nutrient availability in a Bahamas lagoon with fringing mangroves. *Marine Ecology Progress Series* 219:109-119.

Author Abstract. This study investigated the role of submerged autotrophs in the productivity of tropical lagoons and the potential influence of fringing mangroves by characterizing primary productivity and nutrient patterns in a Bahamas lagoon. At 5 sites along a transect from a fringe mangrove to tidal channel site, sediment, water, and seagrass tissue nutrient content was determined. The mangrove prop-root algal community was measured along the transect using benthic chambers, while phytoplankton and epiphyte production was quantified via light-dark bottle experiments. See publication for more details of techniques used in this study. Results showed that sediment phosphorus and nitrogen decreased from 0.24 ± 0.04 to 0.09 ± 0.01 and 3.23 ± 1.01 to 1.44 ± 0.69 mg/g dry wt from the mangrove to seagrass channel site. The nutrient levels in the water column and plant tissues followed a similar spatial trend. Leaf, root, and rhizome C:P molar ratios at the mangrove site (641 ± 30, 1208 ± 385, and 595 ± 71) were low compared to those of the lagoon (761 ± 70, 2220 ± 463, and 1137 ± 289) and channel (953 ± 42, 2177 ± 349, and 2003 ± 293) sites. These results indicated that seagrass beds adjacent to fringe mangroves have higher nutrient availability. Based on the results for sediment, water column nutrient patterns and tissue stoichiometry, seagrasses in close proximity to the mangrove fringe had the greatest nutrient availability among sites. The fringe mangrove zone supported high algal production rates, contributing to total ecosystem primary production. Based on the results, mangroves are valuable resources for other species within this ecosystem.

Lewis, R. R. III. 2003. Ecological engineering for successful management and restoration of mangrove forests. Lewis Environmental Services, Inc., Salt Springs, FL. Contact information: LESrrl3@aol.com.

Author Abstract. Great potential exists to reverse the loss of mangrove forests worldwide through the application of basic principles of ecological restoration using ecological engineering approaches, including careful cost evaluations prior to design and construction. Previous documented attempts to restore mangroves, where successful, have largely concentrated on creation of plantations of mangroves consisting of just a few species, and targeted for harvesting as wood products, or temporarily used to collect eroded soil and raise intertidal areas to usable terrestrial agricultural uses. Documented are the importance of assessing the existing hydrology of the natural extent of mangrove systems, and applying this knowledge to achieve successful and cost-effective mangrove forest ecological restoration. Previous research has documented the general principle that mangrove forests worldwide exist largely in raised and sloped platform above mean sea level, and inundated at approximately 30% or less of the time by tidal waters. More frequent flooding causes stress and death of these tree species. Prevention of such damage requires application of the same understanding of mangrove hydrology.

Lin, R., M. Lin, J. Teng, and W. Zhangi. 1994. Remote sensing survey and mapping of mangroves in western Xiamen Harbour. *Journal of Oceanography in Taiwan Strait/ Taiwan Haixia* 13:297-302.

Author Abstract. Satellite remote sensing technology was used for monitoring mangrove distribution in the western Xiamen Harbor because it provides a macroscopic, rapid and precise method for mangrove resources monitoring and plotting, and it is cheaper and less time-consuming than traditional artificial investigation methods. The Landsat TM image-CCT digital image magnetic tape has been used as an information source. With a computer the image pre- processing is carried out, such as image geometric rectification, pseudo- color composition, linear scale image enhancement and histogram linearization. Then, supervised classification was used to class the mangroves according to training samples, and the mangrove area was calculated by integrating the pixels. Finally, researchers made a 1:50,000 pseudo-color composed imagery map of mangrove distribution. The mangrove area calculated by computer was 73.89 hectares, compared to the 75.40 hectares by grid statistic method, the accuracy being 98%. This research provides a convenient method and model for mangrove resources dynamic monitoring and remote sensing survey and mapping.

McKee, K. L. and P. L. Faulkner. 2000. Restoration of biogeochemical function in mangrove forests. *Restoration Ecology* 8:247-259.

Author Abstract. Forest structure of mangrove restoration sites (6 and 14 years old) at two locations (Henderson Creek [HC] and Windstar [WS]) in southwest Florida differed from that of mixed-basin forests (>50 years old) with which they were once contiguous. However, the younger site (HC) was typical of natural, developing forests, whereas the older site (WS) was less well developed with low structural complexity. More stressful physicochemical conditions resulting from incomplete tidal flushing (elevated salinity) and variable topography (waterlogging) apparently affected plant survival and growth at the WS restoration site. Lower leaf fall and root production rates at the WS restoration site, compared with that at HC were partly attributable to differences in hydroedaphic conditions and structural development. However, leaf and root inputs at each restoration site were not significantly different from that in reference forests within the same physiographic setting. Macrofaunal consumption of tethered leaves also did not differ with site history, but was dramatically higher at HC compared with WS, reflecting local variation in leaf litter processing rates, primarily by snails (*Melampus coffeus*). Degradation of leaves and roots in mesh bags was slow overall at restoration sites, however, particularly at WS where aerobic decomposition may have been more limited. These findings indicate that local or regional factors such as salinity regime act together with site history to control primary production and turnover rates of organic matter in restoration sites. Species differences in senescent leaf nitrogen content and degradation rates further suggest that restoration sites dominated by *Laguncularia racemosa* and *Rhizophora mangle* should exhibit slower recycling of nutrients compared with natural basin forests where *Avicennia germinans* is more abundant. Structural development and biogeochemical functioning of restored mangrove forests thus depend on a number of factors, but site-specific as well as regional or local differences in hydrology and concomitant factors such as salinity and soil waterlogging will have a strong influence over the outcome of restoration projects.

Nagelkerken, I., S. Kleijnen, T. Klop, R. A. C. J. Van den Brand, E. C. De la Moriniere and G. Van der Velde. 2001. Dependence of Caribbean reef fishes on mangroves and seagrass beds as nursery habitats: A comparison of fish faunas between bays with and without mangroves/seagrass beds. *Marine Ecology Progress Series* 214:225-235.

Author Abstract. Mangroves and seagrass beds are considered important nursery habitats for coral reef fish species in the Caribbean, but it is not known to what degree the fish depend on these habitats. The fish fauna of eleven different inland bays of the Caribbean island of Curacao were compared; the bays contain 4 different habitat types: seagrass beds in bays containing mangroves, seagrass beds in bays lacking mangroves, mud flats in bays containing mangroves and seagrass beds, and mud flats in bays completely lacking mangroves and seagrass beds. Principal component analysis showed a high similarity of fish fauna among bays belonging to each of the four habitat types, despite some differences in habitat variables and human influence between bays. Juveniles of nursery species-fish species using mangroves and seagrass beds as juvenile nurseries before taking up residence on reefs-showed highest abundance and species richness on the seagrass beds, and on the mud flats near mangroves and seagrass beds, but were almost absent from bays containing only mud flats. The high abundance and species richness on the mud flats near nursery habitats can be explained by fishes migrating from the adjacent mangroves/seagrass beds to the mud flats. Seagrass beds near to mangroves showed a higher richness of nursery species than did seagrass beds alone, suggesting an interaction with the mangroves resulting in an enhancement of species richness. Comparison of fish densities from the four different habitat types indicates that for the nursery species the degree of dependence on a combination of mangroves and seagrass beds as nurseries for juvenile fish is high for *Ocyurus chrysurus* and *Scarus iserti*, the dependence on seagrass beds is high for *Haemulon parrai, H. sciurus, Lutjanus apodus, L. griseus, Sparisoma chrysopterum* and *Sphyraena* barracuda, and the dependence on mud flats near mangroves/seagrass beds is high for *L. analis*. The dependence on mangroves and/or seagrass beds is low for *Chaetodon capistratus, Gerres cinereus, H. flavolineatum* and *L. mahogon*i, which can also use alternative nursery habitats.

Nayak, S. and A. Bahuguna. 2001. Application of remote sensing data to monitor mangroves and other coastal vegetation of India. *Indian Journal of Marine Sciences* 30:195-213.

Author Abstract. Researchers in this study used remote sensing data, because of its repetitive, synoptic and multi-spectral nature, in monitoring of coastal vegetation. Indian Remote Sensing Satellite (IRS) data have been used to map mangroves and other coastal vegetation across the country's coastline. Large database on spatial extent of mangroves and their condition were created on 1:250,000, 1:50,000 and 1:25,000 scale using IRS data (the database provides information for the first time on the mangrove areas of the entire Indian coast). Researchers conducted studies on the Marine National Park, in the Gulf of Kachchh, where mangrove areas were monitored for 25 years. The degradation of mangroves continued up to 1985 and the condition significantly improved due to the adoption of conservation measures. IRS data were used in identifying dominant plant communities in many mangrove areas such as Bhitarkanika, Coringa, Mandovi estuary in Goa and the Gulf of Kachchh, etc. This approach provides spatial information at plant community level and can be seen as a first step towards bio-diversity assessment. See publication for more details on techniques used. This technique allows reasonable accuracy for mapping mangroves. Results suggest that remote sensing-based information contributes to preparation efficiency of management action plans.

Osunkoya, O. O. and R. G. Creese. 1997. Population structure, spatial pattern and seedling establishment of the grey mangrove, *Avicennia marina* var. *australasica*, in New Zealand. *Australian Journal of Botany* 45:707-725.

Author Abstract. In the North Island of New Zealand *Avicennia marina* (Forsk.) Vierh. var. *australasica* (Walp.) Moldenke occurs as monospecific stands. Researchers used 5 m wide strip transects, to map out *A. marina* adult plants and seedlings in eight distinctive mangrove forests. In most instances, seedling density increased with increasing distance from the seaward edge of the mangrove forests. See publication for additional information of techniques used. There was no consistent pattern for mean plant size and density with respect to tidal position. Plant size showed some correlation with latitudinal gradient, with taller trees in relatively warmer regions and shorter, stunted, dwarf-like types in colder areas. The survival and growth of naturally occurring seedlings in and out of tree-fall gaps and at various distances from the seaward edge of the forest; and transplanted seedlings of different sizes (small, medium and large propagules: less than or equal to 10 cm, 10-20 cm and 21-40 cm tall, respectively) and densities (2, 5, and 9 seedlings m^{-2}) in three delineated (low, mid and high) intertidal positions were monitored for more than 18-month periods. Both natural and transplanted seedlings grown varied significantly between locations, under canopy light conditions, intertidal levels and seedling sizes. Overall seedling survival and growth were better in gaps than under closed canopy, irrespective of tidal position. Intertidal level significantly affected survival of transplanted seedlings, but did so only marginally for the natural ones, with survival being greatest in the high intertidal zone. Conversely, increases in plant height and leaf production were best promoted in the low intertidal position of the forest floor. Survival of the transplanted seedlings ranged from large greater than small greater than or equal to medium-sized. However, the small seedlings grew best in height and accumulation of new leaves. Overall patterns of survival and growth were consistent across intertidal position and seedling density.

Ramirez-Garcia, P., J. Lopez-Blanco and D. Ocana. 1998. Mangrove vegetation assessment in the Santiago River mouth Mexico, by means of supervised classification using Landsat^{TM} imagery. *Forest Ecology and Management* 105:217-229.

Author Abstract. This paper presents a mangrove vegetation assessment from 1970 to 1993 of the Santiago River mouth, Nayarit, West of Mexico. Their goals were to describe the plant composition and structure of mangrove in the study area, and to evaluate the deforestation level and its amplitude by means of a retrospective analysis of the cover and distribution area of mangrove species using a Landsat^{TM} image, aerial photographs and oblique video. See publication for more details on techniques used for this study. The mangroves in the study area were dominated by *Laguncularia racemosa* with the average importance value of 158.18 and 400 ha of plant cover, followed by *Avicennia germinans*, with an average importance value of 138.52 and 324 ha of plant cover. *L. racemosa* was the dominant species in six of the eight compass lines. The highest absolute frequencies for both dominant species were found in the second height class frequency, and the first diametric class frequency. Cover area and distribution of mangrove in the study area were mapped using a Landsat^{TM5} image (April 1993). Researchers applied a supervised classification using the maximum likelihood algorithm. The classification was evaluated by obtaining a classification error matrix and by assessing its accuracy. The results of the mangrove vegetation area reported before were overestimated in 56% regarding the value obtained in our photointerpretation (1065 ha). However within the latter mangrove area, the current cover was 724 ha, indicating a decrease of 32% in a 23-yr period.

Ramachandran, S., S. Sundaramoorthy, R. Krishnamoorthy, J. Devasenapathy and M. Thanikachalam. 1998. Application of remote sensing and GIS to coastal wetland ecology of Tamil Nadu and Andaman and Nicobar group of islands with special reference to mangroves. *Current Science* 75:236-244.

Author Abstract. Sustainable use is a current theme of prime importance for better utilization of natural resources, through rational and responsible multiple-use management. Synoptic and repetitive coverage provided by orbiting satellites have opened up immense possibilities in terms of resource mapping, monitoring and management. The present study deals with the application of Remote Sensing and Geographic Information System (GIS) technologies in the study of coastal ecology with special reference to mangroves. The coastal wetland ecology of Muthupet and Pichavaram has been studied by considering the changes in wetlands. Wetland maps were prepared on 1:25,000 scale using high resolution SPOT (for the year 1989) and IRS LISS II data (for the years 1990 and 1996). Changes in coastal wetland ecology were studied by integrating remote sensing data with GIS. In Muthupet, about 86.77 m^2 of the mangrove forest have been reduced over a period of seven years (1989 to 1996). Digital analysis of 1986 Landsat TM and 1993 IRS LISS II data showed that 0.36 km^2 area of mangrove in Pichavaram was lost over a period of seven years. Ground-based spectral measurements of different mangrove species using field spectroradimeter showed highest spectral radiance between 0.7 and 1.1 μm using radiometer of MSS bands and highest spectral reflectance in 0.69-0.86 μm regions of IRS and TM band which could be used in identifying mangrove forest from other vegetation. In Andaman and Nicobar islands the total mangrove area is about 762 km^2 and degradation occurred only in very small pockets (up to 2.379 km^2).

Steyer, G. D., C. E. Sasser, J. M. Visser, E. M. Swenson, J. A. Nyman and R. C. Raynie. 2003. A proposed coast-wide reference monitoring system for evaluating wetland restoration trajectories. *Journal of Environmental Monitoring and Assessment* 81:107-117.

Author Abstract. Wetland restoration efforts conducted in Louisiana under the Coastal Wetlands Planning, Protection and Restoration Act require monitoring the effectiveness of individual projects as well as monitoring the cumulative effects of all projects in restoring, creating, enhancing, and protecting the coastal landscape. The effectiveness of the traditional paired-reference monitoring approach in Louisiana has been limited because of difficulty in finding comparable reference sites. A multiple reference approach is proposed that uses aspects of hydrogeomorphic functional assessments and probabilistic sampling. This approach includes a suite of sites that encompass the range of ecological condition for each stratum, with projects placed on a continuum of conditions found for that stratum. Trajectories in reference sites through time are then compared with project trajectories through time. Plant community zonation complicated selection of indicators, strata, and sample size. The approach proposed could serve as a model for evaluating wetland ecosystems.

Toledo, G., A. Rojas and Y. Bashan. 2001. Monitoring of black mangrove restoration with nursery-reared seedlings on an arid coastal lagoon. *Hydrobiologia* 444:101-109.

Author Abstract. This study monitored black mangroves restoration efforts with the use of nursery reared seedlings on arid lagoons. Black mangrove (*Avicennia germinans*) seedlings (n=555) were grown from field-collected propagules for three months in a terrestrial nursery. They were grown in clusters of five plants, and transplanted to a clear-cut zone in a lagoon fringed by a mangrove forest at Laguna de Balandra, Baja California Sur, Mexico. Plant survival and development of the transplants were monitored every six-months for two years. See publication for additional information on techniques used. Within one month, the survival of seedlings was 96%. Based on observations and evaluations made within twenty-four months, 74% of the plants were still living. The best cluster, showing maximum growth under mangrove swamp conditions in this arid zone, was a two-plant cluster. The lagoon has a low natural regeneration rate of 48 plants per 350 m^2 per 6 years of monitoring. Overall results indicated that restoring destroyed arid coast lagoons with black mangroves can be easily done.

Twilley, R. R., V. H. Rivera-Monroy, R. Chen and L. Botero. 1998. Adapting an ecological mangrove model to simulate trajectories in restoration ecology. *Marine Pollution Bulletin* 37:404-419.

Author Abstract. We used an ecological model to simulate the trajectories of mangrove attributes according to different restoration criteria at geographically specific conditions and at decadal time scales. This model may contribute to the design and implementation of restoration projects, and can be used to verify key mechanisms controlling ecosystem attributes during the recovery period. Presently a gap model of mangrove wetlands, FORMAN, was used to simulate restoration trajectories in one of the largest estuary rehabilitation projects (128,000 ha) in South America, Cienaga Grande de Santa Marta, Colombia (CGSM). Based on simulations of basal area following reductions of salinity to 40 g/kg within two-year or ten-year time periods, recovery of a disturbed mangrove forest in both cases suggests dominance would reach about 75% of that in the reference site (80 m^2/ha) in 40 years. Both forests are > 80% dominated by *Avicennia*, and *Laguncularia* has greater basal area than *Rhizophora* in the remaining structure. Simulations of forest recovery with a 25-year target for salinity reduction showed approximately 50% of the basal area in the reference site was recovered after 40 years. After 40 years of recovery, both the two and ten-year salinity targets displayed higher basal area and different patterns of community composition (*Laguncularia* becomes the dominant species) under enhanced recruitment (planting program) than seen under more natural recruitment. Researchers mention that ecological models can be useful improving engineering designs, project operation, and more clearly define monitoring programs and natural resource valuation. Also modeling techniques can be useful for identifying the spatial and temporal scale problems affiliated with mangrove restoration projects.

Twilley, R. R., R. Chen and V. Rivera-Monroy. 1999. Formulating a model of mangrove succession in the Caribbean and Gulf of Mexico with emphasis on factors associated with global climate change. *Wetland Biogeochemistry* 3:118-141.

Author Abstract. The structure of mangrove forests is influenced by a combination of geomorphological, climate, and ecological factors, each with specific time and spatial scales, that determine complex patterns of zonation. And these geomorphological, geophysical, and ecological forcings respond differently to projections of global climate change such as sea level rise, fresh water discharge, frequency of frost, or tropical cyclones. We describe an individual-based gap model (FORMAN) to simulate the effects of ecological forcings on mangrove forest dynamics in response to global climate change. Physiological processes that can control the species specific responses of mangrove growth to global climate change include salinity, sulfide concentrations, nutrient resources, and flooding. The relative ability of mangrove species to adapt to these edaphic conditions influence the growth of distribution of mangroves with rise in sea level, changes in upland fresh water input, and frequency of disturbance. In addition, cold temperatures and frequency of frost can influence the relative competition of mangrove species within the intertidal zone at the global limits of mangrove distribution. We also discuss how the time step of the gap dynamic models are not effective in simulation physiological responses that operate at much shorter time scales. Thus, the influence of diurnal temperature changes, humidity, and carbon dioxide concentrations on productivity and water use efficiency in mangroves are not presently included in the FORMAN model. In addition, the allocation of carbon in mangrove trees is important to in situ soil formation, which is significant to evaluating the response of mangroves to rise in sea level. The scale of these changes in specific forests stands in response to ecological forcings must be linked to the regional scale changes in geomorphology and geophysical energies in response to climate change. Gap models such as FORMAN, when linked to more spatially explicit models of soil characteristics of the intertidal zone in response to climate and change, can provide a clearer evaluation of climate change impacts on coastal wetlands of the tropics.

APPENDIX II: MANGROVES
REVIEW OF TECHNICAL METHODS MANUALS

This Review of Technical Methods Manuals includes a variety of sampling manuals, Quality Assurance/Quality Control (QA/QC) documents, standardized protocols, or other technical resources that may provide practitioners with the level of detail needed when developing a monitoring plan for a coastal restoration project. Examples from both peer reviewed and grey literature are presented. Entries were selected through extensive literature and Internet searches as well as input from reviewers. As with the Annotated Bibliography, these entries are not, however, a complete list. Entries are arranged alphabetically by author. Wherever possible, web addresses or other contact information are included in the reference to assist readers in more easily obtaining the original resource. Summaries preceded by the terms '*Author Abstract*' or '*Publisher Introduction*' or similar descriptors were taken directly from their original source. Summaries without such descriptors were written by the authors of the associated chapters.

Cintron-Molero, G. and Y. S. Novelli. 1984. Methods for studying mangrove structure, pp. 90-113. In Snedaker, S. and J. G. Snedaker (eds.), The Mangrove Ecosystem: Research Methods. United Nations Educational Scientific and Cultural Organizations. The Chaucer Press Ltd., UK.

This manual provides research methods that are used to study mangrove ecosystems. Chapter six presents methods for studying mangrove structure and growth. Described are parameters that are measured in relation to their response to change in environmental conditions over time. The structural parameters that are described and measured in mangroves are tree diameter, basal area, density, tree height and leaf area index. Some of the methods that are described in this manual to evaluate mangrove structure include: (1) point sampling to estimate stand basal area without direct measurement of plot or tree diameter; (2) point sampling by measuring its diameter (density); (3) angle gauge which is used for horizontal sampling; (4) point-centered quadrat method in which points to be sampled are located randomly along a transect line; (5) allometric techniques in which sets of trees of a given species be clear-cut and separated into compartments and weighed; and (6) multiplying the biomass of the stem of mean basal area by stand density to determine stand biomass estimates. Additional information on research methods for mangrove ecosystems is described in this manual.

Davis, G. E., K. R. Faulkner and W. L. Halvorson. 1994. Ecological Monitoring in Channel Islands National Park, California, pp. 465-482. In Halvorson, W. L. and G. J. Maender (eds.), The 4th California Islands Symposium: Update on the Status of Resources.

Author Abstract. Natural resource managers need to understand the natural functioning of and threats to ecosystems under their management. They need a long-term monitoring program to gather information on ecosystem health, establish empirical limits of variation, diagnose abnormal conditions, and identify potential agents of change. The approach used to design such a program at Channel Islands National Park, California, may be applied to other ecosystems worldwide. The design of the monitoring program began with a conceptual model of the park ecosystem. Indicator species from each ecosystem component were selected using a Delphi approach. Scientists identified parameters of population dynamics to measure, such as abundance, distribution, age structure, reproductive effort, and growth rate. Short-term design studies were conducted to develop monitoring protocols for pinnipeds, seabirds, rocky intertidal communities, kelp forest communities, terrestrial vertebrates, land birds, terrestrial vegetation, fishery harvest, visitors, weather, sand beach and coastal lagoon, and terrestrial invertebrates (indicated in priority order set by park staff). Monitoring information provides park and natural resource managers with useful products for planning, program evaluation, and critical issue identification. It also provides the scientific community with an ecosystem-wide framework of population information.

Everitt, J. H. and F. W. Judd. 1989. Using remote sensing techniques to distinguish and monitor black mangrove (*Avicennia germinans). Journal of Coastal Research* 5:737-745.

Author Abstract. In this study color-infrared (CIR) aerial photography was used to determine the current distribution of black mangrove *(Avicennia germinans)* that underwent freezing in December 1983. Ground reflectance measurements were made on black mangrove and associated plant species and soil to assist in interpreting CIR photographs. Ground surveys were conducted to verify aerial photos. Black mangrove had a distinct red to dark red CIR image response that made it easily distinguishable from other vegetation and soil. The ground reflectance measurements showed that black mangrove had lower visible red (0.63-0.69 μm) reflectance than associated plant species and soil, which contributed greatly to its image response. See publication for additional information on techniques used. The results showed that the dark green leaves of the black mangroves displayed low visible reflectance. Mangroves near Port Isabel-South Bay and Port Aransas on the lower and mid Texas coast respectively, had largely recovered from the freeze and were actively growing, producing flowers and seed. Major populations near Port O'Connor on the upper Texas coast were killed by the 1983 freeze, but a number of young plants grown from seeds or that survived the freeze due to the protection provided by taller plants produced flowers and seed. Computer-based image analyses of CIR film positive transparencies showed that black mangrove populations could be quantified accurately. The advantage of this technique is that it can permit 'percent area' which can be useful for monitoring changes in vegetation distribution over time. Based on results the researchers stated that remote sensing techniques can be a useful tool for distinguishing black mangrove and determine its extent along the Texas Gulf coast.

Gordon, D. M., A. R. Bougher, M .I. LeProvost and J. S. Bradley. 1995. Use of models for detecting and monitoring change in a mangrove ecosystem in northwestern Australia. *Water Modelling* 21:605-618.

Author Abstract. This publication describes a monitoring program used to detect effects of solar salt ponds on mangroves in Northwestern Australia. Researchers established sites in different mangrove communities at five locations, two that were modified by salt ponds and the other three used as references. A conceptual model was developed to identify potential changes to the mangrove ecosystem next to ponds, to identify responses to change and to formulate a null hypothesis to test that ponds have no effect on vegetation structure. A simulation model was developed to evaluate power of tests of the null hypothesis for nominated levels of change in mangrove stem density and leaf area index (LAI). See publication for more details on techniques used in this study. Changes in groundwater salinity and LAI monitored at the five locations between 1992 and 1995 are shown to demonstrate the similarity in behavior of these attributes at modified and unmodified locations. The results in this study for monitoring a localized disturbance to the mangrove system next to one pond demonstrates how the disturbance was successfully tracked through monitoring and how the mangrove responses to that disturbance coincided with those predicted in the conceptual model.

Halse, S. A., D. J. Cale, E. J. Jasinska and R. J. Shiel. 2002. Monitoring change in aquatic invertebrate biodiversity: Sample size, faunal elements and analytical methods. *Aquatic Ecology* 36:395-410.

Author Abstract. Replication is usually regarded as an integral part of biological sampling, yet the cost of extensive within-wetland replication prohibits its use in broad-scale monitoring of trends in aquatic invertebrate biodiversity. In this paper, we report results of testing an alternative protocol, whereby only two samples are collected from a wetland per monitoring event and then analyzed using ordination to detect any changes in invertebrate biodiversity over time. Simulated data suggested ordination of combined data from the two samples would detect 20% species turnover and be a cost-effective method of monitoring changes in biodiversity, whereas power analyses showed about 10 samples were required to detect 20% change in species richness using ANOVA. Errors will be higher if years with extreme climatic events (e.g., drought), which often have dramatic short-term effects on invertebrate communities, are included in analyses. We also suggest that protocols for monitoring aquatic invertebrate biodiversity should include microinvertebrates. Almost half the species collected from the wetlands in this study were microinvertebrates and their biodiversity was poorly predicted by macroinvertebrate data.

Lewis, R. R. and B. Streever. 2000. Restoration of Mangrove Habitat. WRP Technical Notes Collection (ERDC TN-WRP-VN-RS-3.2), U. S. Army Engineer Research and Development Center. Vicksburg, MS. http://www.wes.army.mil/el/wrp

This document provides general guidelines for restoring mangrove habitats. Highlighted in the document are costs for performing mangrove restoration efforts which may vary depending on the condition of each potential restoration site; and restoration techniques such as natural recruitment or planting seedlings. The authors described the steps to follow in order to achieve mangrove restoration success. The steps includes: understanding mangrove species ecology at the site (e.g., patterns of reproduction and propagule distribution); understanding hydrologic patterns that control distribution and successful establishment and growth of targeted mangrove species; assessing changes of the original mangrove environment that presently prevents secondary succession; designing the restoration program; and procedures for planting propagules, collecting seedlings, or cultivate seedlings whenever it has been verified that natural recruitment will not successfully establish seedlings, rate of stabilization, or rate of sapling growth and establishment. For additional information pertaining to guidelines for mangrove restoration please see document referenced above.

Miller, T., C. Bertolotto, J. Martin and L. Storm. 1996. Monitoring Wetlands: A Manual for Training Volunteers. 106 pp. Adopt-a-Beach, Seattle, WA. Contact information: Phone # (206) 624-6013 and Fax # (206) 682-0722.

This manual provides quantitative and qualitative methods for monitoring structural and functional characteristics in natural and created wetlands. Volunteers identify major vegetation communities, locate photo points, identify surrounding land uses, and establish locations of transects. Data collected serves as a baseline for future monitoring. The manual presents protocols for monitoring hydrology; wetland buffer condition; soil types; vegetation; topography (determining elevations); and wildlife.

Methods described in this manual include plant survival counts, vegetation assessment, and percent cover surveys. Plants surveys are designed for use in wetlands or wetland mitigation sites. Data collected can be used to evaluate planting success, mark areas for replanting, and identify species that should not be replanted in an area, given their low survival rates. Vegetation assessment surveys provide qualitative information on the wetland vegetation characteristics. Plots used are circular, with the radius depending on the predominant type of vegetation in the plot (10 meters for forested, 5 meters for scrub-shrub, and 1 meter for herbaceous). For each plot, volunteers record three to five of the most dominant species in each vegetation layer (tree, shrub, and herb). Data collected can be associated with other data (for example, hydrology or soil types) in order to understand wetland functions and how it should be managed and protected. Percent cover vegetation surveys uses similar plot sizes in vegetation assessment survey but the plots are placed every 50 feet along five transects over the wetland. In each plot, volunteers identify all species and estimate the area in which they covered.

Olin, T. J., J. C. Fischenich, M. R. Palermo and D. F. Hayes. 2000. Wetlands Engineering Handbook: Monitoring. U. S. Army Engineer Research and Development Center, Vicksburg, MS. Technical Report ERDC/EL TR-WRP-RE-21.

The wetlands engineering handbook presents methods for monitoring and evaluating success. Authors emphasize that local expertise and databases for particular wetland types must be used together with the guide to ensure monitoring plans for a specific project are effectively developed. Chapter eight of this report provides a guide for developing evaluation criteria and monitoring projects for wetland restoration and creation. Also presented is guidance for monitoring and success evaluation on basic monitoring concepts, assessing wetland hydrology, evaluating soils and vegetation, and fauna usage. The authors also outline an approach to determining project goals and evaluation criteria, basic considerations related to monitoring, provide detailed information on how to assess wetland structure and function regarding hydrology, soils, vegetation, and fauna (e.g., macroinvertebrates, birds and fish). Additional information needed on assessment, monitoring, and evaluating success are described within this report.

Raposa, K. B. and C. T. Roman. 2001. Monitoring nekton in shallow estuarine habitats. A Protocol of the Long Term Monitoring Program at Cape Cod National Seashore. 39 pp. Narragansett Bay National Estuarine Research Reserve Prudence Island, RI 02872 and National Park Service, Graduate School of Oceanography, University of Rhode Island, Narragansett, RI. Contact information: Kenny@gso.uri.edu http://www.nature.nps.gov/im/monitor/protocoldb.cfm

Author Abstract. Long term monitoring of estuarine nekton has many practical and ecological benefits but efforts are hampered by a lack of standardized sampling procedures. This study develops a protocol for monitoring nekton in shallow (< 1 m) estuarine habitats for use in the Long term Coastal Monitoring

Program at Cape Cod National Seashore. Sampling in seagrass and salt marsh habitats is emphasized due to the susceptibility of each habitat to anthropogenic stress and to the abundant and rich nekton assemblages that each habitat supports. Extensive sampling with quantitative enclosure traps that estimate nekton density is suggested. These gears have a high capture efficiency in most habitats and are small enough (typically 1 m^2) to permit sampling in specific microhabitats. Other aspects of nekton monitoring are discussed, including seasonal sampling considerations, sample allocation, station selection, sample size estimation, parameter selection, and associated environmental data sampling. Developing and initiating long term nekton monitoring programs will help track natural and human-induced changes in estuarine nekton over time and advance our understanding of the interactions between nekton and the dynamic estuarine environments.

Sasich, J. 1998. Monitoring Effectiveness of Forest Practices and Management Systems: Study Design Guidelines, Procedures and Methods. Northwest Indian Fisheries Commission, Spokane, WA. Contact information: Phone # (360) 438-1180. http://www.nwifc.wa.gov/TFW/documents/mws.html

The purpose of this document is to provide the framework, under the Timber Fish Wildlife (TFW) Monitoring Program Plan, for evaluating the control of fine and coarse sediment delivered to the aquatic resource from mass wasting. This document provides guidance for developing a monitoring plan, procedures for conducting evaluations, and methods of evaluation. The document is organized into two parts. Part I discusses considerations in designing a monitoring project such as general considerations for monitoring, consideration in mass wasting processes, site scale evaluation, evaluation of multiple practices and management, and quality assurance. Part II outlines the procedure and methods necessary to conduct a TFW monitoring project such as scale versus watershed scale monitoring, monitoring approaches and monitoring report. See report for additional information on monitoring planning and methods used.

Shafer, D. J. and D. J. Yozzo. 1998. National Guidebook for Application of Hydrogeomorphic Assessment of Tidal Fringe Wetlands. U.S. Army Engineer, Waterways Experiment Station, Vicksburg, Mississippi. Technical Report WRP-DE-16.

Authors described in the regional guidebook the hydrogeomorphic (HGM) approach used for assessing tidal wetlands. The procedures used to assess wetland functions in relation to regulatory, planning or management programs are described. The Application Phase includes characterization, assessment analysis, and application components. Characterization describes the wetland ecosystem and the surrounding landscape, describes the planned project and potential impacts, and identifies wetland areas to be assessed. Assessment and analysis involves collecting field data that is needed to run the assessment models and calculating the functional indices for the wetland assessment areas under the existing conditions.

The Tidal Wetland HGM Approach Application Phase involves determining the wetland assessment area (WAA) and the indirect wetland assessment area (IWAA) and, determining wetland type. The boundaries of the area and the type of tidal wetland to be assessed are identified. The WAA is the wetland area impacted by a proposed project. The WAA defines specific boundaries where many of the model variables are ascertained and directly contributes to calculations for other variables (e.g., maximum aquatic and upland edge).

Methods for determining WAA are discussed in detail in the procedural manual of the HGM Approach. The IWAA is any adjacent portions of hydrologic unit that may not be affected by the project directly but indirectly affected through hydrologic flow alterations. Wetland types are determined by comparing the hydroperiod, salinity regime, and vegetation community structure with those described in the wetland type profiles for each region. Plant communities react to change in the environment (e.g., salinity and hydrologic alterations) so are considered good indicators of a wetland type. Descriptions of the vegetation present, salinity levels, and hydrological conditions for each wetland type are presented in each regional wetland type profile. To determine the salinity regime of an area, one can refer to available references on salinity and or wetland distribution. Data collected on average salinity or the range of salinity helps to sort each site into one of the four categories of the Cowardin system.

Shafer, D. J., B. Herczeg, D. W. Moulton, A. Sipocz, K. Jaynes, L. P. Rozas, C. P. Onuf and W. Miller. 2002. Regional Guidebook for Applying the Hydrogeomorphic Approach to Assessing Wetland Functions of Northwest Gulf of Mexico Tidal Fringe Wetlands, U.S. Army Engineer Research and Development Center, Vicksburg, MS. Technical Report ERDC/EL TR-02-5.

This manual is designed to provide practitioners with guidelines for monitoring and assessing wetland functions. The manual outlines protocols used for collecting and analyzing data needed to assess wetland functions in the context of a 404 permit review or comparable assessment setting. When assessing tidal fringe wetlands in the northwestern Gulf of Mexico the researcher must define the assessment objectives by stating the purpose (e.g., assessment determines how the project impacts wetland functions); characterize the project area by providing a description of the structural characteristics of the project area (e.g., tidal flooding regime, soil type, vegetation and geomorphic setting); use screen for redflags; define the wetland assessment area; collect field data using a 30-m measuring tape, quadrats and color infrared aerial photography; analyze field data; and apply assessment results. This document provides additional detail information on criteria selection and methods used for assessing tidal fringe wetlands.

Twilley, R. R. and V. H. Rivera-Monroy. 2003. Developing Performance Criteria Using Simulation Models of Mangrove Ecosystem Restoration: A Case Study of the Florida Coastal Everglades. Center for Ecology and Environmental Technology, University of Louisiana at Lafayette, Lafayette, LA. Contact information: rtwilley@louisiana.edu.

Author Abstract. The design and goals mangrove restoration projects should account for three major functions of mangroves: hydrology, biogeochemistry, and community ecology. There are global, regional and local factors that can explain patterns of regulator gradients, and hydroperiod that account for the diversity of these functions across a variety of environmental settings. Simulation models of these functions that can account for this diversity have been developed to evaluate the restoration of mangroves in the Florida coastal Everglades. These restoration measures; and monitoring these criteria can help in adaptive management and assessment programs by testing hypotheses of system degradation. Hydrologic performance criteria include soil regulators, particularly soil salinity, surface topography of mangrove landscape, and hydroperiod, including both the frequency and duration of flooding. In the estuary, performance criteria should include salinity of the bay, tidal amplitude, and conditions of freshwater discharge (included in the salinity value). The most important performance measures of the biogeochemistry function of mangroves should include soil resources (bulk density, total nitrogen and phosphorus), and soil accretion. Community ecology should include performance criteria for both the mangrove and the estuary. Mangrove criteria include forest dimension analysis (transects and/or plots), sapling recruitment, leaf area index, and faunal relationships. In the estuary the habitat function of mangroves can be evaluated with growth rate of key species, habitat suitability analysis, isotope abundance of indicator species and bird census. There are several other performance criteria described for each of the three functions, but require more intensive investment of time and resources. The list of criteria can be modified depending of what characteristics of the models presented that describe the restoration goals during the restoration planning process.

U.S. EPA. 1992. Monitoring Guidance for the National Estuary Program. United States Environmental Protection Agency, Office of Water, Office of Wetlands, Washington D.C. EPA Report 842-B-92-004.

This document provides guidance on the design, implementation, and evaluation of the required monitoring programs. It also identifies steps to be taken when developing and implementing estuarine monitoring programs and provides technical basis for discussions on the development of monitoring program objectives, the selection of monitoring program components, and the allocation of sampling effort.

Some of the criteria listed for developing a monitoring program and described in this document include: monitoring program objectives, performance criteria, establish testable hypotheses, selection of statistical methods, alternative sampling designs, use of existing monitoring programs, and evaluate monitoring program performance. Additional information on guidelines for developing a monitoring program is described in this document.

U.S. EPA.. 1993. Volunteer Estuary Monitoring: A Methods Manual. 176 pp. In Ohrel, R. L., Jr., and K. M. Register (eds.), a Methods Manual. U.S. Environmental Protection Agency, Washington, D.C., Office of Water. EPA Report- 842-B-93-004. http://www.epa.gov/owow/estuaries/monitor/.

This document presents information and methodologies specific to estuarine water quality. Information presented in the first eight chapters include: understanding estuaries and what makes them unique; impacts to estuarine habitats and human's role in solving the problems; guidance on how to establish and maintain a volunteer monitoring program; guidance for working with volunteers and ensuring that they are well-positioned to collect water quality data safely and effectively; ensuring that the program consistently produces high quality data; and managing the data and making it readily available to data users. Also presented are water quality measures that determine the condition of the estuary: physical (e.g., substrate texture), chemical (e.g., dissolved oxygen) and biological parameters (e.g., plant and animal presence and abundance). The importance of each parameter and methods used to monitor the conditions are described in a gradual process. Proper quality assurance and quality control techniques must also be described in detail to ensure that the data are beneficial to state agencies and other data users.

Wenner, E. L. and M. Geist. 2001. The National Estuarine Research Reserves Program to Monitor and Preserve Estuarine Waters. *Coastal Management* 29:1-17.

The National Estuarine Research Reserve (NERR) sites in 1992 coordinated a program that would attempt to identify and track short-term variability and long-term changes in representative estuarine ecosystems and coastal watersheds. Water quality parameters that were monitored include: pH, conductivity, temperature, dissolved oxygen, turbidity, and water level. Standardized protocols were also used at each site so that sampling, processing, and data management techniques were consistent among sites. Statistical techniques are being used to identify periodicity in water quality variables. Periodic regression analysis indicated that diel periodicity in dissolved oxygen is a larger source of variation than tidal periodicity at sites with less tidal amplitude. Authors of this document stress how understanding the functions of estuaries and how they change over time will help predict how these systems respond to change in climate and anthropogenic sources.

APPENDIX III: LIST OF MANGROVE EXPERTS

The experts listed below have provided their contact information so practitioners may contact them with questions pertaining to the restoration or restoration monitoring of this habitat. Contact information is up-to-date as of the printing of this volume. The list below includes only those experts who were 1) contacted by the authors and 2) agreed to submit their contact information. Some of those listed also reviewed the associated habitat chapter. In addition to these resources, practitioners are encouraged to seek out the advice of local experts as well faculty members and researchers at colleges and universities. Engineering, planning, and landscape architecture firms also have experts on staff or contract out the services of botanists, biologists, ecologists, and other experts whose skills are needed in restoration monitoring. These people are in the business of providing assistance in restoration and restoration monitoring and are often extremely knowledgeable in local habitats and how to implement projects on the ground. Finally local, state, and Federal environmental agencies also house many experts who monitor and manage coastal habitats. In addition to the National Oceanic and Atmospheric Administration (NOAA), the Environmental Protection Agency (EPA), the Army Corps of Engineers (ACE), Fish and Wildlife Service (FWS), and the United States Geologic Survey (USGS) are important Federal agencies to contact for assistance in designing restoration and monitoring projects as well as potential sources of funding and permits to conduct work in coastal waterways.

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CHAPTER 12: RESTORATION MONITORING OF DEEPWATER SWAMPS

David Merkey, NOAA Great Lakes Environmental Research Laboratory[1]

INTRODUCTION

Deepwater swamps are forested wetlands that develop along edges of lakes, on alluvial river floodplains, in slow-flowing strands, and in large, coastal-wetland complexes. Deepwater swamps are commonly referred to as cypress swamps and in Cowardin et al. (1979) these forests are referred to as 'estuarine forested wetlands'. They can be found along the coasts of the Atlantic Ocean and Gulf of Mexico and throughout the Mississippi River valley from southern Illinois to Louisiana. Dominant species commonly include:

Baldcypress (*Taxodium distichum)*
Water tupelo (*Nyssa aquatica)*, and
Swamp tupelo (*N. sylvatica* var. *biflora*) (Wharton et al. 1982).

The dominant vegetation in deepwater swamps is distinguished from other forested swamps in that it is significantly more tolerant of flooding than other tree species (Figure 1 - Conner and Day 1992b; Allen et al. 1996). Adult baldcypress and tupelo can survive permanent inundation although seedlings require exposed sediments to germinate and become successfully established (Schneider and Sharitz 1988; Keeland et al. 1997; Middleton 2000). The soils of cypress swamps range from mineral to accumulated peat depending on the hydrodynamics and topography of the specific system (Giese et al. 2000; Mitsch and Gosselink 2000).

Essential to the health and functioning of downstream water bodies, deepwater swamps in alluvial forests allow floodwaters to spread out and deposit suspended sediment loads. Deepwater swamps, in these and other settings, filter flood- and surface water, absorb and transform nutrients, thus helping to prevent the eutrophication of downstream areas. Recent studies also indicate that some deepwater swamps may be useful in storing carbon, helping to offset the impact of global climate change (Bondavalli et al. 2000).

Figure 1. Adult baldcypress trees, shown here, can tolerate constantly flooded conditions. Photo from NOAA photo library.

Figure 2. Crayfish. Photo by Mary Hollinger, NOAA/ National Oceanographic Data Center, NOAA photo library. http://www.photolib.noaa.gov/coastline/line2281.htm

[1]2205 Commonwealth Blvd., Ann Arbor, MI 48105.

Figure 3. More light reaches the forest floor in areas with open canopies, this coupled with exposed soils, allows understory herbs and shrubs to grow. Photo from NOAA photo library.

DEEPWATER SWAMP INHABITANTS

Deepwater swamps support a diversity of wildlife. Macroinvertebrates such as crayfish (Figure 2) shrimp, insects, clams, snails, and worms are commonly found in deepwater swamps (Sklar 1985; Thorp et al. 1985). Fish can be temporary or permanent residents of deepwater swamps. While flooded, deepwater swamps provide spawning, nursery, and foraging areas for fish. Fish are able to survive periods of low water by concentrating in river channels, backwater areas, and deep holes (Hoover and Killgore 1998). Reptiles and amphibians are also common residents of deepwater swamps (Mitsch and Gosselink 2000). Due to the near-constant flooding, only a few mammal species are common to deepwater swamps. Of these, nutria, an exotic rodent, is a major obstacle to successful reforestation efforts. Nutria and white-tailed deer graze heavily on the roots and shoots of newly planted and germinating trees. In areas where these animals are particularly abundant, special management practices need to be implemented to ensure the success of restoration/reforestation efforts (Llewellyn and Shaffer 1993; Myers et al. 1995).

The presence and abundance of understory vegetation depends upon the amount of light that penetrates the canopy and the local flooding regime (Figure 3). Some areas with open canopies and moderate flooding may have a diverse shrub and herbaceous ground flora including such species as:

Buttonbush (*Cephalanthus occidentalis*)
Fetterbush (*Lyonia lucida*), and
Wax myrtle (*Myrica cerifera*)

Other swamps, with closed canopies or longer flooding times, may be devoid of any ground layer vegetation. In some swamps, floating logs and tree stumps provide the only substrate for understory vegetation and regeneration of overstory species. In these cases, it is possible to develop entire floating mat communities[2]. Deepwater swamps that are continually flooded and have high nutrient concentrations may also develop thick mats of floating aquatics such as duckweed (*Lemna* spp. and *Spirodela* spp.)

[2] Floating mat communities are wetlands whose substrate is composed of a thick layer of organic material held together with roots from living vegetation. The entire mat rises and falls with the ambient water level. Thus the vegetation community is freed from any hydrologic fluctuation, sediment deposition, or surface water inflows. It is also somewhat immune from saltwater intrusion and supports a relatively stable plant community (Mitsch and Gosselink 2000).

and mosquito fern (*Azolla* spp. - Mitsch and Gosselink 2000).

HUMAN IMPACTS TO DEEPWATER SWAMPS

Although once common throughout the southeastern United States, only a small portion of the original deepwater swamps exists today. Historically, losses were due to extensive logging and conversion to agriculture. Current impacts to deepwater swamps include altered hydrology, herbivory from exotic nutria, saltwater intrusion, and sea level rise (Sklar 1985; Conner and Toliver 1990; Myers et al. 1995; Allen et al. 1996). Logging of cypress swamps began in the mid 1700s when the southeastern United States was first settled by Europeans in large numbers (Conner and Toliver 1990; Conner and Buford 1998). Baldcypress was the main cash crop for colonists of Louisiana until about 1790 and remained a staple of the lumber industry until the early 1900's because of its tremendous durability and ease of workability. These early logging efforts were limited to periods of high water when the logs could be floated out.

In the 1890's, however, the use of the pull boat[3], overhead skidder, and the expansion of the rail system industrialized logging operations. Logging could now be conducted year round and throughout a greater extent of swampland than before. As early as 1915, people noted that cutover swamps were not regenerating on their own but there was no interest in reforestation efforts at that time. By the 1930's, baldcypress logging operations were already past their peak. The last major baldcypress logging operation closed in 1956 although some smaller operations still continue to harvest baldcypress (Conner and Toliver 1990).

Because of its long history of logging, there are no good estimates of precisely how much deepwater swamp habitat has been lost since European settlement began. Estimates of loss are further complicated by the various methods used to classify forests over time[4]. A general trend indicates that between 1934 and 1985 the area of oak/gum/baldcypress swamp decreased from 3 million ha to 1.6 million ha. A 50% decrease in 50 years.

Two early restoration projects were attempted in 1949-1950, one by the Rathborne Lumber Company, another by a private landowner (Bull 1949, Rathborne 1951, and Peters and Holcombe 1951 cited in Conner and Toliver 1990). In each case, initial monitoring a few months after seedlings were planted, indicated a high survival rate (~90%). It was later found, however, that many of the trees planted by Rathborne had eventually been killed by animals and the project had been abandoned (Brown and Montz 1986, cited in Conner and Toliver 1990). There was no additional monitoring of the other project so long-term results are unknown.

[3] Pull boats and skidders also contributed greatly to the degradation of deepwater habitats. By dragging large logs through the marsh, deep, wide ditches were created. In some cases, these ditches altered local hydrology by draining some swamps, further reducing the ability of cypress forests to regenerate (Conner and Buford 1998, Conner and Toliver 1990).

[4] See Conner and Toliver (1990) for a complete listing of various methods to measure area of deepwater (cypress) habitats over time.

STRUCTURAL CHARACTERISTICS OF DEEPWATER SWAMPS

When planning a restoration and monitoring project, practitioners should be mindful that it may take several decades before a deepwater swamp is able to fully perform all ecological functions. Therefore, it is important to state early on in the restoration planning process what the particular goals of the restoration project are and how the project will be monitored over time to determine if those goals are being achieved. For example, if the goal of a restoration project is to restore a natural flood regime to a floodplain allowing fish to access the area for feeding or breeding purposes, these results might be seen within a year or two. If the goal of the project is to restore a diversity of plant species to an area that is similar to a reference condition[5], that might be achieved in a relatively short time period such as five to ten years. If planting of sapling trees is undertaken with the goal of restoring native bird species that require standing deadwood for nesting, monitoring may take a human life-time or more as this function requires large trees that take a long time to grow. Understanding project goals and how they will be tracked through monitoring also helps determine what management actions may be required later to ensure that goals are achieved.

As with many of the other habitats described in Volume Two, the monitoring of restoration efforts in deepwater swamps should focus first on the primary structural characteristics of the habitat and then shift toward functional characteristics over time. The primary structural characteristics of deepwater swamps have been broken down into four categories:

Biological
- Habitat created by plants

Physical
- Sediment/Soil
  - Grain size
  - Organic matter
- Topography/Bathymetry

Hydrological
- Hydroperiod
- Water source
- Current velocity

Chemical
- Salinity

These structural characteristics were identified as being fundamental to the development of a healthy deepwater swamp habitat. Each of these dictates whether or not a forest can develop in an area, which particular tree species will become established, and the degree to which the habitat can perform characteristic biological and physical functions.

BIOLOGICAL

Habitat Created by Plants

Deepwater swamps are dominated by mixed or pure stands of baldcypress, water tupelo, and swamp tupelo, as these are the only species truly adapted to almost permanently flooded conditions. A variety of other species, however, are commonly associated with deepwater habitats at higher (i.e., dryer) elevations. These may include:

Red maple (*Acer rubrum*)
Black willow (*Salix nigra* a common successor to bald cypress after clear cutting)
Swamp cottonwood (*Populus heterophylla*)
Green and pumpkin ash (*Fraxinus pennsylvanica* and *F. profunda)*
Pond pine (*Pinus serotina*)
Waterlocust (*Gledistia aquatica*)
Water-elm (*Planera aquatica*)
Overcup oak (*Q. lyrata*)
Water oak (*Q. nigra*)
Water hickory (*Carya aquatica*)

[5] See Chapter 15 for a discussion of methods to select proper reference conditions for restoration monitoring.

Redbay (*Persea borbonia*), and
Loblolly pine (*Pinus taeda*) (Conner and Buford 1998)

Devall (1998) accumulated lists of understory species commonly associated with deepwater swamps. In areas where light gaps occur or where canopies have not closed to prevent understory growth, a variety of trees, shrubs, and herbaceous vegetation may be found (Conner and Buford 1998). These include:

Swamp-privet (*Forestiera acuminata*)
Carolina ash (*F. caroliniana*)
Poison sumac (*Toxicodendron vernix*)
Dahoon (*Ilex cassine*)
Buttonbush (*Cephalanthus occidentalis*)
Poison ivy (*T. radicans*)
Muscadine grape (*Vitis rotundifolia*)
Spanish moss (*Tillandsia usneioides*)
Cattail (*Typha latifolia*)
Lizardtail (*Saururus cernuus*)
Holly (*Ilex* spp.)
Viburnums (*Viburnum* spp.)
Lyonias (*Lyonia* spp.)
Sedges (family Cyperaceae)
Grasses (family Poaceae), and
Ferns (Johnson 1990; Wilhite and Toliver 1990)

Due to the flooding regime and low light conditions below a dense forest canopy, understory vegetation is typically sparse, if present at all in mature deepwater swamps. Recently, invasive exotic species such as Chinese tallow (*Sapium sebiferum*) and Brazilian pepper (*Schinus terebinthifolia*) have invaded deepwater swamps and are changing species composition in these forests (Devall 1998).

Sampling

The types of measurements used to monitor the restoration of a forested site change as the site matures. If plantings are part of the restoration project, the first few years are typically spent monitoring damage from herbivores, seedling survival, density, and growth rate as measured by plant height (Conner 1989; Kolka et al. 1998; Conner et al. 2000). As sites mature (e.g., starting around 10 years after planting), the monitoring of canopy closure becomes important as this factor is strongly related to light availability and understory vegetation (Fletcher et al. 2000). Growth rate can still be measured but the method changes from using seedling height to diameter at breast height (DBH).

Numerous field guides for the identification of plant species are available for different areas of the country. Practitioners should select a book (or books) from as close a region as possible to their study area. Most field guides, however, are not comprehensive and only cover the most common species one is likely to find. When knowing the exact species is absolutely necessary, such as when study results are to be published, then more detailed and comprehensive identification guides should be consulted. A few examples of these sorts of texts include:

- Godfrey and Wooten's *Aquatic and Wetland Plants of Southeastern United States: Dicotyledons* or their second volume *Aquatic and Wetland Plants of Northeastern North America: Angiosperms: Monocotyledons (Volume II)*
- Crow, Hellquist's, and Fassett's *Aquatic and Wetland Plants of Northeastern North America: Pteridophytes, Gymnosperms and Angiosperms: Dicotyledons and Aquatic and Wetland Plants of Northeastern North America: Angiosperms: Monocotyledons (Volume II)*, and
- Voss' three-volume *Michigan Flora*

PHYSICAL

Sediment/Soil

Grain size

The soils of deepwater swamps range from mineral to accumulated peat, depending on the hydrodynamics and topography of the specific system (Conner and Buford 1998; Giese et al. 2000). Deepwater swamp soils are typically nutrient rich and have high percentages of both clay and organic matter resulting in high concentrations of phosphorus and nitrogen (Conner and Buford 1998). These conditions lead to extremely high primary productivities (see *Primary Production* below). The soils of these habitats also tend to be moderately to strongly acidic and have an impervious subsoil (Conner and Buford 1998).

Organic matter

Soil organic matter is an important component of forest soils. It is composed of leaf litter, woody debris, plant roots, and microbes (Barton et al. 2000). Wigginton et al. (2000) measured forest floor organic matter, soil carbon content, and soil structure at restoration sites of different ages at the Savannah River Site in South Carolina. They found that forest floor organic matter increased in the first few years after restoration (657 g/m^2 maximum) but then dropped off as the system continued to mature (338 g/m^2). This was accompanied by a change in the type of forest floor litter as well. Originally organic matter of herbaceous origin dominated the forest floor litter. As the restoration sites aged and developed, organic matter from woody species (predominately leaves) became more abundant. Carbon content of the soil continually increased as restoration sites aged. It was, however, estimated that it would take over 50 years for soil carbon levels to reach 75% of those in reference sites. Additionally, soil structure had been severely altered by the original disturbance at the site. Soil structure too was changing in the restoration sites at a slow but measurable pace (Wigginton et al. 2000).

Giese et al. (2000) also measured soil carbon content, biomass production, and intra-site variability at the same restored locations. They found that soil carbon accumulation, soil carbon content in wetter areas increased faster than in dryer settings. Differing concentrations of carbon in the soil did not seem to have any measurable affects on above ground biomass productivity, however. Giese et al. (2000) reached a similar conclusion as Wigginton et al. (2000), that restored sites were slowly developing soil characteristics similar to mature reference forests.

Sampling and Monitoring Methods

The Soil Science Society of America publishes a 4-volume *Methods of Soil Analysis*. These volumes, revised in Appendix II, cover a variety of standard methods to sample the physical, mineralogical, microbiological, biochemical, and chemical properties of soils. This would be a valuable resource to anyone seriously considering soil sampling over the long-term. Most university libraries should also carry these as well.

Topography/Bathymetry

Deepwater swamps are found in a variety of settings such as along the edges of lakes, on alluvial river floodplains, in slow-flowing strands[6], and in large, coastal wetland complexes. Well-known examples of some of these systems include the Maurepas Swamp in Louisiana, the Big Cypress Swamp in Florida, the Okefenokee Swamp in Georgia, and the Great Dismal Swamp in Virginia. Areas where deepwater swamps occur typically have low topographic relief with subtle changes in elevation (a few cm) leading to a variety of hydrologic conditions, soil types, and vegetative communities (Conner and Buford 1998). Common geomorphic features of deepwater swamps include meandering river channels that help form backwater swamps, oxbow lakes, sloughs, and meander scrolls[7] (Figure 4 - Conner and Buford 1998).

Sampling

Topographic maps available from the United States Geologic Survey can provide a rough estimate of elevations in the study area. In most

[6] Shallow elongated depressions, often the remnants of old river channels.
[7] Ridges and swales created as the river channel moves back and forth across the floodplain.

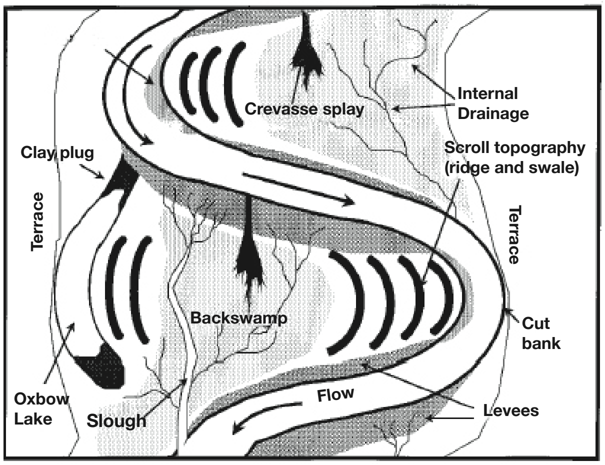

Figure 4. Some of the common geomorphic features of alluvial floodplains where deepwater swamps can often be found. Taken from Hupp 2000.

cases, however, a detailed survey or the area to be restored will need to be conducted. The surface elevations and topographic diversity of the area must be measured in relation to existing or projected water level changes as differences of only a few inches may determine whether or not planted material survives.

HYDROLOGICAL

Hydroperiod, Water Source, and Current Velocity

Regardless of the specific geomorphic setting, all deepwater swamps are freshwater ecosystems and their hydrodynamics are dominated by surface water runoff from adjacent uplands and/or overbank flooding from rivers (Mitsch and Gosselink 2000). Although deepwater swamps are typically flooded most of the year, seasonal water level fluctuations do occur (Figure 5). High water levels occur in winter and spring as a result of increased rainfall and snowmelt in headwater areas. Low levels occur in late summer and early fall, resulting from low precipitation levels and increased evapotranspiration (Conner and Buford 1998). During severe droughts, deepwater swamps may lack surface water completely (Conner and Buford 1998). These water level fluctuations and periodic drydowns are essential for the long-term maintenance of baldcypress, the dominant tree species of

Figure 5. Battle Creek Cypress Swamp in late spring/early summer when water levels are receding. Photo by Max Davis, Edgewater, MD.

deepwater swamps. Of all the trees found in these areas, baldcypress is the most tolerant of prolonged flooding (Conner et al. 1997). Seedlings, however, need to become established under non-flooded conditions in order to survive (Schneider and Sharitz 1988; Allen et al. 1996; Keeland et al. 1997; Middleton 2000). Once established they may be just as flood tolerant as adult trees as long as they are not completely submerged by floodwater (Keeland and Conner 1999).

Factors important to the growth and health of deepwater swamp forest trees include the depth, duration, and timing of inundation (collectively referred to as the 'hydroperiod'). While Young et al. (1995) and Keeland et al. (1997) both noted that growth rate of baldcypress, as measured by changes in diameter at breast height (DBH), initially increased with lengthened periods of flooding, this effect eventually subsided and tree growth diminished with permanent inundation over a period of several years (Young et al. 1995; Allen et al. 1996). Brinson et al. (1981) noted that the amount and frequency of water moving through a wetland was one of the predominant factors in determining wetland primary productivity. If reference sites are used as part of the monitoring program, it is critical that the restored sites and reference sites are subject to similar hydrologic conditions (water source, depth, timing, duration of flooding, and velocity) for accurate comparisons to be made.

Sampling

The United States Geological Survey operates a series of gauging stations throughout the country. Historical and real-time data on hydroperiod and characteristics of the watershed for many of these sites are available at http://water.usgs.gov/waterwatch/. Smaller, coastal rivers or more isolated areas may not have a gauging station, however, requiring that restoration practitioners implement other methods to collect this information. A variety of manual gauges are commercially available in different lengths and measurement intervals. These can be attached to metal poles driven into the substrate. Electronic gauges are also available that can be set up and left in place to continually record water level fluctuation. Thus recording data that might otherwise be missed by manual sampling alone.

CHEMICAL

Salinity

Increases in salinity due to rising sea levels or large storm surges can impact the growth rate of baldcypress (Conner 1993; Allen et al. 1996; Conner and Day 1998). As salinity increases, seedling height, diameter, leaf biomass, and survival all decrease (Kraus et al. 1998). Although some local varieties of baldcypress have been shown to be adapted to slightly higher salinities, intrusion of salt water will kill adult trees (Allen et al. 1996; Allen et al. 1997; Kraus et al. 1998). In areas where storm surges are common or where surface elevations are actively subsiding, selection of more salt tolerant genotypes is recommended for restoration success (Allen et al. 1996).

Measuring and Monitoring Methods

A variety of electronic probes are commercially available for measuring salinity in the water column and in the sediment. If salinity levels are unknown, then a probe with a wide measurement range is recommended as use of a probe outside of its operational range may damage the instrument. Data loggers[8] can also be left in place to record data frequently (e.g., hourly or daily) if it is suspected that salinity levels change fairly often. In areas were salinity levels are more stable, a less expensive manual probe can be used to measure salinity during site visits.

[8]Instruments left in place to record data frequently over time.

FUNCTIONAL CHARACTERISTICS OF DEEPWATER SWAMPS

Deepwater swamps provide a variety of biological and hydrological functions. Some of these functions, such as feeding and breeding grounds for fish and nutrient cycling are socially and economically important. The list of functions commonly attributed to deepwater swamps presented below has been broken into three categories Biological, Hydrological, and Chemical.

Biological

- Contributes to primary production
- Supports biomass production
- Produces wood
- Provides breeding grounds
- Provides nursery areas
- Provides feeding grounds
- Supports a complex trophic structure

Physical

- Affects transport of suspended and dissolved material
- Alters turbidity
- Reduces erosion potential
- Modifies water temperature
- Provides temporary floodwater storage

Chemical

- Supports nutrient cycling
- Modifies chemical water quality

BIOLOGICAL FUNCTIONS

Contributes to Primary and Biomass Production and Produces Wood

Deepwater swamps exhibit primary productivities among the highest recorded for forested ecosystems. Aboveground biomass production often exceeds 8,900 lbs/acre (10 t/ha/yr) and can be as high as 17,800 lbs/acre (20 t/ha/yr) in some cases (Conner and Buford 1998)[9]. As stated previously, hydrology has a large impact on primary productivity, too much or too little water can lower forest productivity. Poor drainage or stagnant water contributes to anoxic soil conditions which in turn lead to lower nutrient turnover rates, nitrogen limitations, low pH (Conner and Buford 1998), accumulation of biological waste products, and an increase in the solubility of certain heavy metals in the soil (Sharitz and Mitsch 1993). Swamps, such as the Okefenokee, with permanent standing water have lower decomposition rates, lower rates of nutrient cycling, and low nutrient inputs leading to very low rates of primary production (Devall 1998) compared to other systems with flowing water.

Swamps that have been drained can also exhibit reduced productivity (Conner and Buford 1998). Carter et al. (1973, cited in Conner and Buford 1998) found that drainage of a deepwater swamp in Florida resulted in a thinning of the canopy, and a reduction in productivity as measured by tree growth, litterfall, and herbaceous plants. The productivity of the drained swamp was 3,453 lbs/acre (3.87 t/ha/yr) compared to 7,656 lbs/acre (8.58 t/ha/yr) for an undrained swamp.

Sampling and Monitoring Methods

Some common methods to measure primary productivity include collection of leaf litter and calculation of growth rate from repeated measurements of diameter at breast height (DBH) or height of seedlings (Brown 1981; Conner and Day 1992a; Conner et al. 1997; Keeland et al. 1997). Although not much is known about belowground productivity, some evidence indicates that it is similar in scale to litterfall (Symbula and Day 1988). Methods for measuring belowground biomass production include taking a series of soil cores or placing

[9] Mickler et al (2002) estimated net primary productivity for all forest types in the southern U.S. to average 12,900 lbs/acre in 1992. Mickler, R. A., T. S. Earnhardt and J. A. Moore. 2002. Regional estimation of current and future forest biomass. *Environmental Pollution* 116:S7-S16.

soil-filled nylon bags in the substrate allowing roots to grow into them (Symbula and Day 1988; Powell and Day 1991). The bags are then retrieved after a specified amount of time and the root content analyzed. Neither of these methods is particularly effective at sampling roots greater than 5 cm in diameter, however, and may actually underestimate total underground productivity. Litterfall can account for approximately 39% of the above ground primary production and can be easily collected (Brown 1981; Conner and Buford 1998). Seedling height is also easily obtained although requires repeated (e.g., weekly) site visits if knowledge of seasonal differences in growth rate is desired. Annual measurements may, however, be acceptable for many restoration monitoring projects. Keeland et al. (1997) provide methods and equations for calculating growth rate from repeated measurements of DBH.

Provides Breeding, Nursery, Feeding Grounds, and Supports Trophic Structure

Macroinvertebrates

Macroinvertebrates such as crawfish, shrimp, insects, clams, snails, and worms are commonly found in deepwater swamps (Sklar 1985; Thorp et al. 1985). The types and abundance of invertebrates depend on several factors including water depth, flood duration, velocity, substrate, food source, and oxygen level (Sklar 1985; Thorp et al. 1985; Conner and Buford 1998).

Sklar (1985) compared backwater cypress swamp invertebrate communities on the substrate and in floating vegetation (*Lemna* spp.). He found that floating vegetation had greater numbers of individuals and higher density (individuals/m^2) than benthic areas, but benthic areas had greater biomass production. Overall, backwater swamps had some of the highest recorded invertebrate densities and biomass of any freshwater or estuarine soft bottom habitat. Due to frequent anoxic conditions and desiccation to which few invertebrate species are adapted, however, species diversity of backwater swamps was somewhat low. Sklar (1985) also found that density, biomass, and diversity changed throughout the year, peaked in spring and fall, and were related to seasonal flooding and water temperature. Restoration monitoring programs of deepwater or backwater areas that plan to incorporate invertebrate sampling should take these patterns into account.

As with other habitat functions of deepwater areas, complete restoration of a typical deepwater invertebrate community is dependent on the recovery of the vegetation community and may take several decades or longer. In areas that have had their canopy trees removed, exposing the water to full sunlight, submergent and emergent vegetation may have become established. These vegetation types provide significantly different habitat structure and will therefore have different invertebrate communities than areas with a closed forest canopy. Although Thorp et al. (1985) found that invertebrates will quickly colonize woody debris in the water, it may take decades (or longer) for planted seedlings to grow large enough to contribute such debris in significant quantities to alter aquatic invertebrate communities. Lakly and McArthur (2000) studied the invertebrate communities in the thermally impacted Savannah River of South Carolina. All canopy trees had been killed by thermal pollution from an upstream power plant. Impacted areas were being studied to assess both natural recovery and restoration efforts compared to un-impacted areas. They found that although the general abundance and diversity of organisms had recovered since thermal flows ceased in 1988, invertebrate communities in the once impacted streams with open canopies remained structurally and functionally distinct from reference areas with closed canopies. This may be the case for the early stages of many restoration efforts.

Fish, amphibians, reptiles, and birds

Conner and Buford (1998), Mitsch and Gosselink (2000), and Wharton et al. (1982) provide lists and examples of fish, amphibian, reptile, and bird species commonly associated with deepwater habitats. The presence or abundance of fish, amphibian, reptile, and bird species can be used to monitor the success of restoration efforts, particularly where wildlife were absent prior to the restoration effort. Many of the species listed in these sources, however, are dependent upon extensive tracts of mature deepwater forests and may not be able to utilize habitats provided by forests of seedlings or saplings. Hooded mergansers (*Lophodytes cucullatus*) and prothonotary warblers (*Protonotaria citrea*), both of which nest in tree cavities, are good examples of birds unable to use a restored deepwater forest for decades after initial planting. The re-establishment of species dependent on mature forests may take several decades and is likely dependent on the availability of migration corridors to and from existing populations and the restored area. If no suitable populations for natural migration into the restored area are available, trap and release activities may be required once suitable habitat has become established. This should not deter restoration practitioners from using wildlife to monitor restoration efforts but serves as a reminder to set realistic goals for restoration efforts within the time frame of monitoring activities.

Mammals

Nutria, an exotic rodent introduced to Louisiana in the 1930s from South America (Figure 6 - Conner and Buford 1998), is now a common pest in deepwater swamps of the southern United States and is one of the major obstacles to successful reforestation efforts. Nutria, as well as rabbits and white-tailed deer, can heavily graze the roots and shoots of newly planted or germinating trees.

Figure 6. The invasive, exotic nutria. Photo from the Louisiana Department of Wildlife and Fisheries.

Newly planted trees should be monitored for damage. In areas where nutria and other herbivorous mammals are particularly abundant or troublesome, special management practices need to be implemented to ensure the success of restoration/reforestation efforts. Without extra precautions to safe guard seedlings from herbivory, restoration and reforestation efforts are likely to fail. Methods of controlling herbivory of baldcypress seedlings using a variety of shelter types are described in Myers et al. (1995), Conner et al. (2000), and Conner and Ozalp (2002) .

PHYSICAL

The main physical functions performed by deepwater swamps are the transport of suspended/dissolved material, alteration of turbidity, modification of water temperature, and temporary floodwater storage. These have been described with the associated structural characteristics above.

CHEMICAL

Supports Nutrient cycling and Modifies Water Quality

As noted earlier, deepwater swamps are essential to the long-term health and sustainability of downstream waters. This function is carried out by the deposition of suspended sediments on alluvial floodplains and the absorption and transformation[10] of nutrients such as nitrogen and phosphorus. These processes are closely linked to hydrologic processes. The depth, duration, timing, and flow rate of flooding control the soil and water oxygen content and affect the microbial processes that determine whether a particular swamp acts as a nutrient sink, source, or transformer. Deepwater swamps with seasonal or annual water level fluctuations and/or moving, as opposed to stagnant, water typically have higher oxygen concentrations, faster rates of nutrient cycling, and higher growth rates of trees (Conner and Buford 1998). In addition, the deposition, uptake, and transformation of sediments and nutrients within deepwater swamps prevent these materials from being deposited in downstream water bodies where they may lead to eutrophication.

Soil type and oxygen concentration also have direct affects on the biogeochemistry of deepwater swamps and affect downstream water quality. Soil type and oxygen concentration impact the processes of nutrient cycling and transformation and storage of metals and toxics. Soils with high clay content such as those of deepwater swamps tend to be poorly aerated even when flooding subsides (Conner and Buford 1998). This leads to increases in the solubility of minerals such as phosphorus, nitrogen, magnesium, sulfur, iron, manganese, boron, copper, and zinc making them readily available for uptake by plants (Mitsch and Gosselink 2000). Extremely low oxygen levels over prolonged periods of time may, however, can cause toxic chemicals to accumulate in the soil (Sharitz and Mitsch 1993). These may harm plants and animals, limit the nutrient cycling ability of the swamp, and impact its ability to contribute to downstream water quality.

Sampling

The American Public Health Association's *Standard Methods for the Examination of Water & Wastewater* provides detailed field and laboratory procedures for analyzing any water quality parameter selected for use in restoration monitoring.

[10]Also referred to as biogeochemical cycling.

PARAMETERS FOR MONITORING STRUCTURAL/FUNCTIONAL CHARACTERISTICS

The matrices of structural and functional parameters for restoration monitoring provided below were developed through extensive review of restoration and ecological monitoring literature. Additional input was received from recognized experts in the field of deepwater swamp ecology. This listing of parameters is not exhaustive, it is merely intended as a starting point to help restoration practitioners develop monitoring plans for this habitat. Additional parameters not in this list, such as human dimensions parameters, may also be appropriate for restoration monitoring efforts. Parameters with a closed circle (●) are those that, at the minimum, should be considered in monitoring restoration progress. Parameters with an open circle (❍) may also be monitored depending on specific restoration goals. Information on why these parameters are important for monitoring and how they relate to structural and functional characteristics as well as to one another is found throughout the text above. Literature directing readers toward additional information on the ecology of deepwater swamps and restoration case studies can be found in the Annotated Bibliography of Deepwater Swamps. Information on sampling strategies and techniques can be found in the associated Review of Technical Methods Manuals.

Parameters to Monitor the Structural Characteristics of Deepwater Swamps

Parameters to Monitor	**Biological**	Habitat created by plants	**Physical**	Sediment grain size	Topography/Bathymetry	**Hydrological**	Tides/Hydroperiod	Water sources	Current velocity	**Chemical**	pH, salinity, toxics, redox, DO[11]
Geographical											
Acreage of habitat types		●									
Biological											
Plants											
Species, composition, and % cover of:											
Herbaceous vascular		❍									
Woody		●									
Basal area		❍									
Canopy aerial extent and structure		❍									
Plant height		❍									
Seedling survival		●									
Stem density		●									
Woody debris (root masses, stumps, logs, etc.)		❍			❍						
Hydrological											
Physical											
Sheet flow									●		
Temperature							❍	❍			
Upstream land use								●			
Water level fluctuation over time							●	●			
Chemical											
Salinity (in tidal areas)							❍	❍			❍
Toxics											❍
Soil/Sediment											
Physical											
Basin elevations					❍						
Depth of mottling							❍				
Geomorphology (slope, basin cross section)					●		●				
Moisture levels and drainage							❍				
Organic content				❍			❍				
Percent sand, silt, and clay				❍							
Sedimentation rate and quality				❍	❍		❍		❍		
Chemical											
Pore water salinity (in tidal areas)											❍
Redox potential											❍

[11] Dissolved oxygen.

Parameters to Monitor the Functional Characteristics of Deepwater Swamps

Parameters to Monitor	**Biological**							**Physical**					**Chemical**	
	Contributes primary production	Supports biomass production	Produces wood	Provides breeding grounds	Provides nursery areas	Provides feeding grounds	Supports a complex trophic structure	Affects transport of suspended and dissolved material	Alters turbidity	Reduces erosion potential	Modifies water temperature	Provides temporary floodwater storage	Supports nutrient cycling	Modifies chemical water quality
Geographical														
Acreage of habitat types	●	●	●	●	●	●	●	●	●	●	●	●	●	●
Biological														
Plants														
Species, composition, and % cover of:														
Herbaceous vascular	❍	❍		❍	❍	❍	❍	❍	❍	❍	❍		❍	❍
Invasives				❍	❍	❍	❍							
Woody	●	●	●	●	●	●	●	●	●	●	●	●	●	
Basal area	❍	❍	❍											
Canopy aerial extent and structure			❍	❍	❍	❍					❍			
Interspersion of habitat types		❍		❍	❍	❍	❍	❍	❍	❍	❍	❍		
Litter fall	❍	❍				❍	❍		❍				❍	
Plant health (herbivory damage, disease)						❍								
Plant height	❍	❍												
Rate of canopy closure	❍	❍	❍								❍			
Seedling survival[12]			●							●				
Stem density			❍					❍	❍	❍	❍			
Woody debris (root masses, stumps, logs, etc.)			❍	❍	❍	❍	❍			❍	❍			

[12]If the whole community is destroyed by disease or lack of seedling survival, all vegetation-related functions will be impaired

Parameters to Monitor the Functional Characteristics of Deepwater Swamps (cont.)

Parameters to Monitor	Biological: Contributes primary production	Supports biomass production	Produces wood	Provides breeding grounds	Provides nursery areas	Provides feeding grounds	Supports a complex trophic structure	Physical: Affects transport of suspended and dissolved material	Alters turbidity	Reduces erosion potential	Modifies water temperature	Provides temporary floodwater storage	Chemical: Supports nutrient cycling	Modifies chemical water quality
Biological (cont.)														
Animals														
Species, composition, and abundance of:														
Birds		○		○	○	○	○							
Fish		○		○	○	○	○							
Invasives		○						○	○					
Invertebrates		○		○	○	○	○							
Mammals		○		○	○	○	○							
Reptiles		○		○	○	○	○							
Hydrological														
Physical														
Fetch								○	○	○				
PAR[13]	○	○						○	○					
Seiche disc depth	○	○						○	○					
Shear force at sediment surface								○	○	○				
Sheet flow								○	○	○		○	○	○
Temperature				○	○						○			○
Trash								○	○					
Upstream land use								●	●		●			●
Water column current velocity								○	○	○			○	○
Water level fluctuation over time	●	●		●	●	●	●	●	●	●		●	●	●

[13]Photosynthetically active radiation. Methods to calculate PAR underwater can be found in Chapter 2 'Restoration Monitoring of the Water Column' and Chapter 9, 'Restoration Monitoring of Submerged Aquatic Vegegation'.

Parameters to Monitor the Functional Characteristics of Deepwater Swamps (cont.)

Parameters to Monitor	Biological: Contributes primary production	Supports biomass production	Produces wood	Provides breeding grounds	Provides nursery areas	Provides feeding grounds	Supports a complex trophic structure	Physical: Affects transport of suspended and dissolved material	Alters turbidity	Reduces erosion potential	Modifies water temperature	Provides temporary floodwater storage	Chemical: Supports nutrient cycling	Modifies chemical water quality
Hydrological (cont.)														
Chemical														
Nitrogen and phosphorus	❍	❍							❍				❍	❍
Salinity (in tidal areas)														❍
Toxics				❍	❍	❍								❍
Soil/Sediment														
Physical														
Basin elevations				❍	❍	❍		❍	❍		❍	❍		
Bulk density										❍			❍	
Geomorphology (slope, basin cross section)				●	●	●		●	●	●	●	●	●	●
Moisture levels and drainage												❍	❍	❍
Sediment grain size (OM[14]/sand/silt/clay/gravel/cobble)		❍						❍	❍	❍			❍	❍
Sedimentation rate and quality								❍	❍	❍				❍
Chemical														
Organic content in sediment		❍				❍	❍	❍	❍				❍	❍
Pore water nitrogen and phosphorus		❍											❍	❍
Pore water salinity (in tidal areas)		❍	❍											
Redox potential													❍	❍

[14]Organic matter.

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APPENDIX I: DEEPWATER SWAMPS ANNOTATED BIBLIOGRAPHY

This annotated bibliography contains summaries of restoration case studies and basic ecological literature. It is designed to provide restoration practitioners with examples of previous restoration projects as well as overviews of papers from the ecological literature that offer more detail than that covered in the associated chapter. Entries are presented from both peer reviewed and grey literature. They were selected through extensive literature and Internet searches as well as input from reviewers. They are not, however, a complete listing of all of the available literature. Entries are arranged alphabetically by author. Wherever possible, web addresses or other contact information have been included in the reference to assist readers in obtaining the original resource. Summaries preceded by the terms '*Author Abstract'* or *'Publisher Introduction*', or similar descriptors were taken directly from the original source. Summaries without such descriptors were written by the author of the associated chapter.

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Author Abstract. Three methods of clearing forested wetland vegetation (*Nyssa aquatica – Taxodium distichum*) were done to test their impact on the regeneration of natural vegetation in southwestern Alabama in 1986: clearcutting with helicopter log removal (HELI), HELI followed by rubber-tired skidder traffic simulation (SKID), and HELI followed by glyphosphate application for 2 growing seasons to remove all vegetation (GLYPH). It was believed that woody plant regeneration would be least affected in the HELI-treated areas. However, monitoring measurements taken after seven years showed that the SKID treatment actually had greater total above-ground biomass (65, 979 kg/ha) than the HELI treated area (46,748 kg/ha) and that SKID plots also had a higher proportion of the most desirable timber species (*Nyssa aquatica*). GLYPH areas became freshwater marshes with some invasion of *Salix nigra*. Each of the treatment areas had significant herbaceous vegetation that increased sediment accumulation 70 – 175% relative to an undisturbed reference area. The regrowth of vegetation in treated areas has lowered the water table during the growing season but had minimal impact on soil redox potential and pH. Researchers concluded that, in each case, wetlands were rapidly recovering from logging disturbance seven years ago, although successional trajectories appeared to be quite different.

Barton, C., E. A. Nelson, R. K. Kolka, K. W. McLeod, W. H. Conner, M. Lakly, D. Martin, J. Wigginton, C. C. Trettin and J. Wisniewski. 2000. Restoration of a severely impacted riparian wetland system — The Pen Branch Project. *Ecological Engineering* 15:S3-S15.

The Savannah River Swamp is a 3020 ha forested wetland in the floodplain of the Savannah River. It is located on the Department of Energy's Savannah River Site (SRS) in South Carolina and was severely degraded by high temperatures (~65°C) and high volume discharges of cooling water from nuclear reactors and a coal-fired power plant beginning in the 1950s. Historically, the forest cover of the swamp consisted of approximately 50% bald cypress-water tupelo, 40% mixed bottomland hardwoods, and 10% shrub, marsh, and open water. The increases in water volume and temperature resulted in the overflow of the original stream banks, creation of additional floodplain area, erosion of the original stream corridor, and deposition of a deep silt layer on the newly formed delta. These impacts caused the complete elimination of the original floodplain vegetation. In the years since pumping was reduced (1988), natural regeneration and restoration efforts have occurred in the affected areas. Herbs, grasses, and shrubs dominate and a few hardwood or bald cypress seedlings have been found in regenerating areas. Different methods to reintroduce tree species characteristic of mature forested wetlands were tested.

The following parameters were monitored to assess the impact of the restoration efforts: stream hydrology, seedling survival and competition, aquatic insect community dynamics, revegetation techniques, fish ecology and stream habitat, autotrophic and macroinvertebrate characterization, organic matter decomposition and nutrient mineralization, and terrestrial vertebrate distribution. In most cases, measurements were made in both the restored system and in one or more reference systems. Some studies also included control systems, which experienced a thermal impact similar to that of Pen Branch, but where the hydrology had been restored at an earlier date. Results indicated the return of some forested wetland functions to varying degrees. Some factors, such as plant species diversity were similar to reference sites. Other factors and functions such as canopy closure, contribution of woody debris to streams, or soil organic matter content appeared to be moving in the direction of a mature forested wetland but it would several decades before restored areas fully functioned as mature forests. Other results are presented in individual papers in this annotated bibliography.

Clewell, A. F. and R. Lea. 1990. Creation and restoration of forested wetland vegetation in the southeastern United States, pp. 195-231. In Kusler, J. A. and M. E. Kentula (eds.), Wetland Creation and Restoration: the Status of the Science. Island Press, Washington, D.C.

Author Abstract. This chapter describes forested wetland creation and restoration project experience and establishment methods in the region from Virginia to Arkansas south to Florida and Louisiana. In contrast to marshes, forest replacement is more complex and requires a much longer development period. A wide variety of forest establishment techniques have been employed, some with initial success but none of them proven. Most projects pertain to bottomland hardwood and cypress replacement. The two most significant trends in project activity have been the direct seeding of oaks on abandoned croplands and the replacement of all trees and sometimes the undergrowth at reclaimed surface mines. Although some young projects appear promising in terms of species composition and structure, it is still too early to assess functional equivalency.

Project success depends largely on judicious planning and careful execution. The most critical factor for all projects is to achieve adequate hydrological conditions. Other important factors may include substrate stability, availability of adequate soil rooting volume and fertility, and the control of herbivores and competitive weeds. A checklist of these and other important issues is appended for the benefit of personnel who prepare project plans and review permit applications.

Success criteria for evaluating extant projects throughout the southeast are either inadequately conceived or usually lacking. Emphasis needs to be placed upon the presence of preferred species (i.e., indigenous trees and undergrowth characteristic of mature stands of the community being replaced) and on the attainment of a threshold density of trees that are at least 2 meters tall. Once such a stand of trees is attained, survival is virtually assured and little else could be done that would further expedite project success. At that point, release from regulatory liability should be seriously considered.

Several critical information gaps are also identified.

Conner, W. H. 1989. Growth and survival of baldcypress (*Taxodium distichum* [L.] Rich.) planted across a flooding gradient in a Louisiana bottomland forest. *Wetlands* 9:207-217.

Author Abstract. One-year-old baldcypress (*Taxodium distichum* [L.] Rich.) seedlings were planted across a flooding gradient in a Louisiana bottomland forest in March and September 1985. One half of the seedlings were protected with a chickenwire fence. Survival and height growth were monitored from 1985 through 1987. First year survival was high in all areas for both plantings, except for the unprotected March-planted seedlings, which were destroyed by animals. After three growing seasons, survival of March-planted seedlings in the flooded and intermittently flooded plots was still over 70%. Natural mortality of March-planted seedlings in the unflooded plot was high, with only 40% of the seedlings surviving to the end of the study. Survival of the September-planted seedlings was also best in the flooded and intermittently flooded plots and least in the unflooded plot. Height growth, like survival, was best for seedlings in the flooded and intermittently flooded plots. It seems that baldcypress seedlings can be planted in a swamp and grow well if animal damage is controlled.

Conner, W. H. 1995. Woody plant regeneration in three South Carolina *Taxodium/Nyssa* stands following Hurricane Hugo. *Ecological Engineering* 4:277-287.

Author Abstract. Long-term monitoring began in 1990 to follow community changes resulting from hurricane disturbance. In addition, one-year-old *Taxodium distichum* seedlings were planted to determine if planting was feasible in saltwater-flooded areas. The canopy of the least impacted swamp recovered rapidly, but there were few seedlings growing in the understory. Planted seedlings survived well, but they grew very little. Both lack of seedlings and poor growth of planted seedlings were probably due to intense shading and flooding. Two impacted areas contained a greater number of seedlings, most of which were found growing on raised microsites like *Taxodium* knees. The majority of the seedlings in all areas were shrub species. Planted seedlings grew well (30 cm/yr) where open canopy conditions allowed sunlight to reach the forest floor and no new saltwater has been introduced since the hurricane.

Conner, W. H., L. W. Inabinette and E. F. Brantley. 2000. The use of tree shelters in restoring forest species to a floodplain delta: 5-year results. *Ecological Engineering* 15: S47-S56.

Author Abstract. Without herbivory control, natural seed sources, and seasonal flood events, recovery of the Pen branch delta in South Carolina to former conditions (prior to thermal discharge) may take many years. To assess the recovery process, seedlings of baldcypress (*Taxodium distichum*), water tupelo (*Nyssa aquatica*), swamp blackgum (*Nyssa sylvatica* var. *biflora*), and green ash (*Fraxinus pennsylvanica*) were planted in four areas of the delta in 1994. One-half of the seedlings were protected using tree shelters 1.5 m tall. Heights of seedlings were taken after planting and at the end of each growing season from 1994 to 1998. Survival at the end of 5 years ranged from 67 to 100% for seedlings in tree shelters and 2–90% for those not in tree shelters. Survival of seedlings without tree shelters was generally low, and mortality was attributed mainly to beaver damage. Although water tupelo, swamp blackgum, and green ash seedlings tended to die once clipped by beaver, 85% of the clipped baldcypress resprouted after clipping, and new sprouts grew vigorously. During year 1, height growth of tree shelter seedlings was significantly greater than non-tree shelter seedlings for all species, but once the seedling emerged from the top of the shelter, growth differences declined dramatically. Differences in height growth among areas was highly variable from year to year, and no one species tended to grow better in one area over another throughout the period. Restoration of the Pen branch delta to a baldcypress–water tupelo forest similar to the surrounding forest is possible. Baldcypress and water tupelo seem ideally suited to growing in all areas of the delta equally well, but it may take 10–20 years before the seedlings are of sufficient size to not be affected by herbivory and old enough to produce sufficient quantities of seed to maintain the forest.

Conner, W. H. and M. Ozalp. 2002. Baldcypress restoration in a saltwater damaged area of South Carolina. pp. 356-369. In K. W. Outcalt, Eleventh biennial southern silvicultural research conference. U.S. Department of Agriculture, Forest Service, Southern Research Station, Asheville, NC.

Author Abstract. Bald cypress (*Taxodium distichum* (L.) Rich.) seed was collected in 1992 from nine different estuarine areas in the southeastern United States (Winyah Bay, SC, Ogeechee and Altmaga Rivers in GA, Loftin Creek, FL, Ochlockonee River, FL, Mobile Bay, AL, West Pearl River, LA, Bayou LaBranche, LA, and Lake Chicot, LA.) and planted in Clemson University's Hobcaw nursery in the spring of 1993. Germination ranged from a low of 16 percent for seed from FL to 58 percent for seed from NC. Seedlings were grown in the nursery for two growing seasons, lifted, and planted in an area killed by saltwater introduced by Hurricane Hugo's (1989) storm surge. Half of the seedlings were protected with tree shelters. Seedlings averaged 122 cm tall upon planting. Survival after 6 years was 99 percent. Height growth of seedlings in tree shelters was significantly higher than those not in tree shelters for each year except during year 3. Among the seed sources, seedlings from the Loftin Creek, FL source have shown greatest growth, with and without protection, for all growing seasons except the first year. After 6 years, average height of non-protected seedlings was 81 cm. Tree shelters increase early growth of seedlings, but once they emerged from the tree-shelter, growth differences between shelter and no-shelter treatments decreased and seems to be more related to the degree of deer herbivory experienced by unprotected seedlings.

Keeland, B. D. and W. H. Conner. 1999. Natural regeneration and growth of *Taxodium distichum* (L.) Rich. in Lake Chicot, Louisana after 44 years of flooding. *Wetlands* 19:149-155.

Author Abstract. Lake Chicot, in south central Louisiana, USA, was created in 1943 by the impoundment of Chicot Bayou. Extensive establishment of woody seedlings occurred in the lake during a 1.5 year period, including the growing seasons of both 1986 and 1987, when the reservoir was drained for repair work on the dam. Study plots were established in September 1986 to document woody vegetation establishment and to provide a baseline by which to monitor survival and growth after flooding resumed. *Taxodium distichum* seedlings were the dominant species after one growing season, with a maximum density of 50 seedlings/m2, an average of about 2/m2, and an average height of 75 cm. The lake was reflooded at the end of 1987, bringing water depths at the study plots up to about 1.4 m. Temporary drawdowns were again conducted during the fall of 1992 and

1996. In December 1992, the site was revisited, new plots established, and saplings counted and measured. There was an average of 2.1 *T. distichum* stems/m^2, and the average height was 315 cm. After the 1996 growing season, there was still an average of about 1.9 stems/m^2, and the average height had increased to 476 cm. Preservation of *T. distichum* forests in relatively shallow but continuously flooded areas such as Lake Chicot may be a simple matter of draining the lake after a good seed crop and maintaining the drawdown long enough for the seedlings to grow taller than the typical growing season water level. In the case of Lake Chicot, this period was two growing seasons. This action will mimic natural, drought-related drawdowns of the lake and will allow the seedlings to establish themselves and grow tall enough to survive normal lake water levels.

Kolka, R. K., E. A. Nelson and C. C. Trettin. 2000. Conceptual assessment framework for forested wetland restoration: the Pen Branch experience. *Ecological Engineering* 15:S17-S21.

Author Abstract. Development of an assessment framework and associated indicators that can be used to evaluate the effectiveness of a wetland restoration is critical to demonstrating the sustainability of restored sites. Current wetland restoration assessment techniques such as the index of biotic integrity (IBI) or the hydrogeomorphic method (HGM) generally focus on either the biotic or abiotic components of wetlands. In addition, current methods generally rely on qualitative or semi-quantitative rankings in the assessment. We propose a quantitative, ecosystem level assessment method similar to that developed by the US EPA's Wetland Research Program (WRP approach) that includes both biotic and abiotic metrics. Similar to the IBI and HGM approaches, biotic and abiotic parameters are compared to those of reference communities, however, the proposed comparisons are quantitative. In developing the assessment method, bottomland reference systems at various stages of succession were compared to a recently restored site in South Carolina (Pen Branch). Studies involving hydrology, soil organic matter and nutrient dynamics, vegetation communities, seedling establishment and competition, and avian, small mammal, herpetofauna, fish and macroinvertebrate communities were implemented. In this paper, we discuss the conceptual framework in which we developed our assessment technique.

Middleton, B. 2000. Hydrochory, seed banks, and regeneration dynamics along the landscape boundaries of a forested wetland. *Plant Ecology* 146:169-184.

Author Abstract. Following the environmental sieve concept, the setting in which the recruitment of *Taxodium distichum* occurs in, becomes increasingly restrictive from the seed to seedling stage in an impounded forested wetland. Although a wide elevational band of dispersing seed moves across the boundary of a swamp-field in the water sheet, the zone of germination is relegated to that portion of the forested wetland that draws down during the growing season. Seedling recruitment is further restricted to the uppermost zone of the winter water sheet. These patterns are likely applicable to other species of dominant swamp species, e.g., *Cephalanthus occidentalis* crossed the boundary of a forested wetland and abandonded field in winter flooding (November–December and November–March, respectively) in Buttonland Swamp. The elevation of the boundary was 101.3 m NGVD. While the seeds of at least 40 swamp species were dispersed across the boundary, few viable seeds were dispersed after the winter season. Kriged maps showed seeds of *T. distichum* and *C. occidentalis* dispersed in patches in the water depending on the position of the water sheet. Most species of both water-and gravity-dispersed species had a localized pattern of seed distribution (either spherical or exponential) and this indicated that seeds may not be dispersed for great distances in the swamp. Water-dispersed *T. distichum* and *C. occidentalis* had larger dispersal ranges (A_0 = 225 and 195 m, respectively) than *Bidens frondosa* and *B. discoidea* (A_0 = 14 and 16 m, respectively). Seed dispersal varied with season depending on the availability of seeds. In Buttonland Swamp, viable seeds typically were dispersed for *T. distichum* in November–June, and for *C. occidentalis* in November-July. Low water occurred in August 1993 and high in February 1994 (99.8 and 101.6 m NGVD, respectively). The seed banks along the landscape boundary varied in species composition according to elevation (r_2 0:996). While the similarity of species richness between water-dispersed seeds and the seed bank at elevations that flooded (during June 1993 through May 1995) was high (10–17%), it was low between water-dispersed seeds and the seed bank at elevations that did not flood (5%). *T. distichum* seeds had a short germination window in that seeds germinated within a year following their production in zones that were flooded in the winter followed by drawdown during the next growing season. After 1 year, less than 5% of the *T. distichum* seeds remained viable on the surface of the soil. Germination of *T. distichum* was confined to specific elevations (above 99.3 but below 101.6 m NGVD) during this study with 4.1% of the seedlings surviving for more than 2 years at a mean of 101.4 m NGVD. All seedlings below this elevation died. To maximize natural regeneration along the boundaries of swamps in abandoned farm fields targeted for restoration, this study suggests a flood pulse regime consisting of high water in the winter to maximize dispersal of live seeds followed by low water in the summer to facilitate seed germination and seedling recruitment. Hydrologic restoration could assist in the natural recovery of damaged wetlands if a seed source exists nearby.

Myers, R. S., G. P. Shaffer and D. W. Llewellyn. 1995. Bald cypress (*Taxodium distichum*) restoration in southeast Louisiana: the relative effects of herbivory, flooding, competition, and macronutrients. *Wetlands* 15:141-148.

Author Abstract. In the early 1900s, old-growth bald cypress (*Taxodium distichum*) was completely logged out of what is now the Manchac Wildlife Management Area, located in the Lake Pontchartrain Basin, Louisiana. Natural regeneration of the swamp did not occur; the area is currently dominated by bulltongue (*Sagittaria lancifolia*) marsh. This study was conducted to isolate the major factors prohibiting cypress restoration. Specifically, four hundred bald cypress seedlings were planted in a three-way factoral treatment arrangement that included nutrient augmentation (fertilized vs. unfertilized), management of entangling vegetation (managed vs. unmanaged), herbivore protection (Tubex tree shelters, PVC sleeves, Tanglefoot), and elevation (included as a covariable). Highly significant differences in diameter growth were found for all main effects. For the herbivore protection treatment, relatively inexpensive PVC sleeves were as effective as Tubex Tree Shelters; unprotected trees experienced 100% mortality. Seedlings that received Osmocote 18-6-12 fertilizer showed nearly a two-fold increase in diameter than unmanaged seedlings. However, seedlings that were unmanaged grew nearly two times greater in height than managed seedlings. This study indicates that biotic factors are primarily responsible for the lack of cypress regeneration in southeastern Louisiana, not the prevalent, but largely untested, hypothesis of saltwater intrusion. Moreover, it is likely that, with a combination of management techniques, it is possible to restore swamp habitat in this area. Though labor intensive in the short run (i.e., first few years), once established, these trees may survive for hundreds of years.

Nelson, E. A., N. C. Dulohery, R. K. Kolka and W. H. McKee, Jr. 2000. Operational restoration of the Pen Branch bottomland hardwood and swamp wetlands — the research setting. *Ecological Engineering* 15:S23–S33.

The Savannah River swamp is a 3020 ha forested wetland within the floodplain of the Savannah River. It is located on the Department of Energy's Savannah River site (SRS) near Aiken, South Carolina. The swamp once consisted of stands of approximately 50% bald cypress–water tupelo (*Taxodium distichum–Nyssa aquatica*), 40% mixed bottomland hardwood, and 10% shrub, marsh, and open water. The site was severely degraded by historic high temperature discharges from a nuclear reactor and a coal-fired power plant. These discharges have since ended and the site is in various stages of regeneration augmented with plantings. Plantings were monitored in the short-term using seedling density, abundance, and size. Results showed the most plantings were successful and the sites are on their way toward becoming mature forested wetlands.

Paller, M. H., M. J. M. Reichert, J. M. Dean and J. C. Seigle. 2000. Use of fish community data to evaluate restoration success of a riparian stream. *Ecological Engineering* 15: S171–S187.

Author Abstract. From 1985 to 1988, stream and riparian habitats in Pen Branch and Four Mile branch began recovering from deforestation caused by the previous release of hot water from nuclear reactors. The Pen Branch corridor was replanted with wetland trees in 1995 to expedite recovery and restore the Pen branch ecosystem. Pen branch, Four Mile branch, and two relatively undisturbed streams were electrofished in 1995:1996 to determine how fish assemblages differed between the previously disturbed and undisturbed streams and whether such difference could be used to measure restoration success in Pen branch. Fish assemblages were analyzed using nonparametric multivariate statistical methods and the index of biotic integrity (IBI), a bioassessment method based on measurement of ecologically sensitive characteristics of fish assemblages. Many aspects of fish assemblage structure (e.g. species richness, disease incidence, taxonomic composition at the family level) did not differ between disturbed and undisturbed streams; however, disturbed streams had higher densities of a number of species. These differences were successfully detected with the multivariate statistical methods; whereas, the IBI did not differ between most recovering and undisturbed sampling sites. Because fish assemblages are strongly influenced by instream habitat, and because instream habitat is strongly influenced by the riparian zone, fish assemblages can be used to measure restoration success. Nonparametric ordination methods may provide the most sensitive measure of progress towards restoration goals, although the IBI can be used during early stages of recovery to indicate when certain ecologically important aspects of structure and function in recovering streams have reached levels typical of undisturbed streams.

Sklar, F. H. 1985. Seasonality and community structure of the backswamp invertebrates in a Louisiana cypress-tupelo wetland. *Wetlands* 5:69-86.

Author Abstract. Core and floating "scoop" samples were taken monthly for two years in a Louisiana hardwood swamp for the characterization and identification of the benthic habitats far removed from waterways and bayous. Most backswamp macroinvertebrates have physiological and behavioral adaptations to withstand both desiccation and anoxia. The most ubiquitous taxa included amphipods, oligochaetes, diptera larvae, isopods, and fingernail clams. The biomass and density of backswamp benthic communities were some of the highest recorded for any “unpolluted” freshwater or estuarine soft bottom habitat. The average numbers of invertebrates living in the sediments (5,690/m^2) was significantly less than the numbers living in the floating mats of *Lemna* spp. (10,508/m^2). The biomass distribution was just the opposite. There was a significantly greater invertebrate biomass in the sediments (8.4 g AFDW/m^2) than in the floating vegetation (4.2 g AFDW/m^2). Diversity (H) was relatively low, averaging only 1.8 in the floating vegetation and 1.4 in the sediments. Seasonal changes in density, biomass, and diversity were bimodal with peaks occurring during spring and fall, and were a function of the seasonality of wetland flooding and temperature.

Souther, R. F. and G. P. Schaffer. 2000. The effects of **s**ubmergence and light on two age classes of bald cypress (*Taxodium distichum* (L.) Richard) seedlings. *Wetlands* 20:697-706.

In the early 1900s, baldcypress swamps were harvested *en masse* in coastal Louisiana, USA. In many areas, natural regeneration did not occur; instead, these areas converted to marsh or open water. One of the factors that may have been responsible for the lack of regeneration was shading of newly germinated seedlings by herbaceous vegetation. Alternatively, prolonged flooding or complete submergence may have suppressed germination or growth rates of young seedlings and even caused mortality. This study investigated the effects of complete submergence and variable light regime on two age classes of baldcypress seedlings. Newly germinated seedlings (under two weeks of age) subjected to complete submergence began to show clear signs of stress after approximately one month and substantial mortality following 45 days of submergence. In contrast, one-year-old seedlings submerged for as much as five months experienced up to 75% survival. In a four-way factorial experiment, two age classes of baldcypress seedlings were subjected to five light transmissions (100%, 80%, 50%, 30%, 20%), five flood durations (0 days, 14 days, 25 days, 35 days, 45 days), and two nutrient regimes (fertilized vs. not fertilized). At 100% light transmission, the newly germinated seedlings suffered complete mortality after 35 days of submergence, whereas the one-year-old seedlings were largely unaffected by prolonged flooding or light regime. Fertilized one-year-old seedlings that were submerged for an entire month had considerably greater growth in height and diameter than seedlings grown under mesic conditions without fertilizer. This is particularly important in coastal Louisiana because several re-introductions (i.e., diversions) of Mississippi River water into declining swamps are planned or underway, and these diversions will periodically increase nutrient and flood levels.

Weller, J. D. 1995. Restoration of a south Florida forested wetland. *Ecological Engineering* 5:143-151.

Author Abstract. A rewatering project conducted at Fern Forest Nature Center in Pompano Beach, Florida, USA, has rejuvenated and restored an area of south Florida forested wetland to its pre-drainage condition in three years. Through the removal of undesirable vegetation such as Brazilian pepper (*Schinus terebinthifolius*) and the re-introduction of water, the following have been accomplished: increase in surface water duration time; elevation of groundwater by 70 to 84 cm; rejuvenation of a depressed forested wetland, a deciduous hardwood swamp, and an emergent wetland; and enhancement of a wading bird habitat, a cypress dome, and 3.2 km of shallow stream bed (1.5 m deep or less). These accomplishments have assured the survival of the park’s 34 rare and endangered fern species and encouraged the natural return of 16 wetland bird species, 8 fish species, 6 species of turtles, 6 species of snakes, 5 snails, 2 frog species, and even the American alligator (*Alligator mississippiensis*).

This project demonstrates that when certain hydrological criteria are met and vegetation composition and animal resurgence demonstrated, restoration of valuable ecosystem functions can be inferred and may be grounds for declaring a project successful in as short a time as 5 years. This paper focuses on vegetation composition and animal resurgence and touches on the complex task of evaluating ecosystem functions.

Wharton, C. H., W. M. Kitchens, E. C. Pendleton and T. W. Snipe. 1982. The ecology of bottomland hardwood swamps of the Southeast: a community profile, 133 pp. FWS/OBS-81/37, U.S. Fish and Wildlife Service, Biological Services Program, Washington, DC.

Author Abstract. This report is one in a series of community profiles whose objective is to synthesize extant literature for specific wetland habitats into definitive, yet handy ecological references. To the extent possible, the geographic scope of this profile is focused on bottomland hardwood swamps occupying the riverine floodplains of the Southeast whose drainage originates in the Appalachian Mountains/ Piedmont or Coastal Plain. References are occasionally made to studies outside this area, primarily for comparative purposes or to highlight important points. The sections detailing the plant associations and soils in the study area are derived from field investigations conducted specifically for this project.

In order to explain the complexities of the ecological relationships that are operating in these bottomland hardwood ecosystems, this report details not only the biology of floodplains but also the geomorphology and hydrological components and processes that are operating on various scales. These factors, in concert with the biota, dictate both the ecological structure and function of the bottomland hardwood ecosystems. We have utilized the ecological zone concept developed by the National Wetlands Technical Council to organize and explain the structural complexity of the flora and fauna.

The information in this profile will be useful to environmental managers and planners, wetland ecologists, students, and interested laymen concerned with the fate and the ecological nature and value of these ecosystems. The format, style, and level of presentation should make this report adaptable to a variety of uses, ranging from preparation of environmental assessment reports to supplementary or topical reading material for college wetland ecology courses. The descriptive materials detailing the floristics of these swamps have been cross-referenced to specific site locations and give the report the utility of a field guide handbook for the interested reader.

APPENDIX II: DEEPWATER SWAMPS
REVIEW OF TECHNICAL METHODS MANUALS

This Review of Technical Methods Manuals includes a variety of sampling manuals, Quality Assurance/Quality Control (QA/QC) documents, standardized protocols, or other technical resources that may provide practitioners with the level of detail needed when developing a monitoring plan for a coastal restoration project. Examples from both peer reviewed and grey literature are presented. Entries were selected through extensive literature and Internet searches as well as input from reviewers. As with the Annotated Bibliographies, these entries are not, however, a complete list. Entries are arranged alphabetically by author. Wherever possible, web addresses or other contact information is included in the reference to assist readers in easily obtaining the original resource. Summaries preceded by the terms '*Author Abstract'* or *'Publisher Introduction*' or similar descriptors were taken directly from their original source. Summaries without such descriptors were written by the authors of the associated chapters.

Allen, J. A., B. D. Keeland and J. A. Stanturf. 2001. A guide to bottomland hardwood restoration, 132 pp. Information and Technology Report USGS/BRD/ITR-2000-0011 General Technical Report SRS-40, U.S. Geological Survey, Biological Resources Division U.S. Department of Agriculture, Forest Service, Southern Research Station, Asheville, NC. http://www.srs.fs.fed.us/pubs/viewpub.jsp?index=2813

This guidebook is an essential resource to anyone planning to restore an area of bottomland forest. It briefly introduces the ecology of bottomland forests, their extent, the degree of degradation, and need for restoration. It then guides readers through the entire restoration process from general planning issues such as where to obtain planted material through to post-restoration monitoring and management of existing forests. It instructs readers on how to evaluate sites for restoration, which factors biotic and abiotic need to be taken into consideration before the proper species can be selected and planting begin. It covers: site preparation, seed collection, handling, and storage, and also has chapters on planting seeds vs. seedlings, including the tools and methods used in each. The guidebook also touches on other methods of restoration other than direct planting. It covers the selection and planting of not only canopy species but understory plants as well, something that is otherwise not well documented in the literature. The guidebook also instructs readers on how to control undesirable species and protect the restoration site from animals, fire, and human impacts. Post-restoration monitoring is also covered in this document, what to measure, how to measure it, and what information it tells you is presented clearly and concisely. Lastly, management and rehabilitation of existing bottomland forests is covered for restoration of sites that haven't been completely denuded of trees. The guidebook also has a series of appendixes that include information on different forest cover types, common and scientific names of plant species common to bottomland forests, a partial list of seed and seedling suppliers, as well as species to site relationships for the Midsouth and Southern Atlantic Coastal Plain to aid restoration practitioners in selecting the proper plant materials for their site conditions.

Dane, J. H. and G. C. Topp. 2002. Methods of Soil Analysis: Part 4-Physical Methods, 1692 pp. Soil Society of America, Madison, WI.

Publisher's Description. Due to the rapid and numerous changes in measurement methods associated with soil physical and mineralogical properties, it was decided not to print a third edition of the highly popular Methods of Soil Analysis. Part 1—Physical and Mineralogical Methods. The decision was made to split the volume into two parts. The part containing soil physical measurements is now published as Methods of Soil Analysis: Part 4—Physical Methods. The approach in Part 4 differs substantially from that in Part 1 in that the new book uses a more hierarchical approach. As such it is divided into eight chapters, with each chapter covering a major aspect of soil physical properties. Following the table of contents, the reader can than refine the search until the specific topic or measurement of interest is indicated. Compared with Part 1, new methods have been added and some of the older methods have been updated or deleted.

de Vries, P. G. 1986. Sampling Theory for Forest Inventory: A Teach-Yourself Course. Springer-Verlag, Berlin.

de Vries has attempted to address many of the shortcomings of other statistical sampling texts by simplifying the process of learning advanced statistics and putting them to practical use in forestry sampling. His book covers a variety of sampling techniques including: random sampling, cluster and double sampling, use of points and circular plots, line intersect and list sampling, and a variety of others. de Vries has tried, where ever possible, to provide examples and take readers through the step by step process of how statistical analyses have been developed in order to gain a more thorough understanding of the theory and proper application of different procedures. Several appendices are also included that review many introductory statistical concepts, however, the text is not intended for the uninitiated. An existing background in calculus and introductory statistics is encouraged before using this resource. Upon completion of his book and a short period of time for the new material to sink in, de Vries confidently states that readers will 'experience the satisfaction of mastering some sampling methods widely used in forest inventory, that he will be able to read critically more professional literature than before, and that he will possess a sound basis on which to expand his knowledge of sampling.'

Hoover, J. J., K. J. Killgore and G. L. Young. 2000. Quantifying habitat benefits of restored backwaters, 10 pp. EMRRP Technical Notes Collection ERDC TN-EMRRP-EI-01, U.S. Army Engineer Research and Development Center, Vicksburg, MS. http://www.wes.army.mil/el/emrrp

Backwater areas act as important nursery and spawning habitats for fish. This technical report describes methods of quantifying and enhancing fish species that use backwater areas, areas subject to dewatering during low river flows. Brief lists or descriptions of fish species that use backwater habitats and methods to sample young-of-the-year populations are presented. The use of plexiglas light-traps to efficiently sample young-of-year is explained for a variety of circumstances. The development of Habitat Suitability Indexes (HSI) a statistical method useful in determining which species use particular habitats and therefore might benefit from a restoration is presented in greater detail. Example restoration projects where the HIS method was used (Lake Whittington, a Mississippi River oxbow lake and Lake George, a Mississippi delta backwater) are also provided. Contact information of the authors is also included.

Killgore, K. J. and J. J. Hoover. 1992. A guild for monitoring and evaluating fish communities in bottomland hardwood wetlands, 7 pp. WRP Technical Note WRP TN FW-EV-2.2, U.S. Army Engineer Waterways Experiment Station, Vicksburg, MS.

This technical note is a summary of the adult and larval fish communities of the Rex Hancock/Black Swamp Wildlife Management Area, Cache River system, Arkansas. Fish communities are classified according to habitat preference and reproductive strategy. Brief descriptions of three habitat categories are given: lentic-oxbow lakes, lentic-floodplain ponds, and lotic-channels. Four reproductive modes are also defined. Tables listing which bottomland forest fish species use which habitats at varying life stages is also presented. By knowing which communities of fish are capable of using each habitat, the classifications provided can be used to select and evaluate fish species for monitoring studies in southern bottomland forest wetlands.

Klute, A. 1986. Methods of Soil Analysis: Part 1-Physical and Mineralogical Methods, 1188 pp. Soil Science Society of America, Madison, WI.

Publisher's Description. Great strides have been made in the conception of physical and mineralogical characteristics of soils and how they relate to each other and to chemical properties. The methods of analyses included here provide a uniform set of procedures that can be used by the majority of soil scientists and engineers.

Kolka, R. K., C. C. Trettin and E. A. Nelson. 1998. Development of an assessment framework for restored forested wetlands. Proceedings of the Conference on Ecosystems Restoration & Creation. Tampa, Florida. May 14-15. http://www.srs.fs.fed.us/pubs/viewpub.jsp?index=1541

Author Abstract. Development of an assessment framework and associated indicators that can be used to evaluate the effectiveness of a wetland restoration is critical to demonstrating the sustainability of restored sites. An interdisciplinary approach was developed to assess how succession is proceeding on a restored bottomland site in South Carolina relative to an undisturbed reference and a naturally agrading site. Comparisons of populations and processes across successional gradients and treatments allows the effect of disturbance and restoration activities to be evaluated. Studies involving vegetation communities, organic matter and nutrient dynamics, seedling establishment and competition, and avian, herpetofauna, fish and macroinvertebrate communities have been implemented. Seedling establishment and competition studies suggest nonchemical and minimal mechanical site preparation techniques, tree shelters and root pruning should be considered as alternatives depending on restoration objectives and site conditions. The restored site contains many of the functional capabilities of a wetland with respect to fauna, however certain species tend to dominate populations in Pen Branch when compared to late successional wetlands. Fish populations show higher population densities in the restored site as compared to the reference site. A conceptual framework for integrating biotic and abiotic processes into a restoration response model will be used to synthesize ecosystem response and to identify indicators for restoration assessments.

McCobb, T. D. and P. K. Weiskel. 2002. Long-term hydrologic monitoring protocol for coastal ecosystems, 93 pp. Protocol, USGS Patuxent Wildlife Research Center, Coastal Research Field Station, University of Rhode Island, Narragnasett, RI. http://science.nature.nps.gov/im/monitor/protocols/caco_hydrologic.pdf

Author Abstract. Long-term monitoring of hydrologic change using a standard data-collection protocol is essential for the effective management of terrestrial, aquatic, and estuarine ecosystems in the coastal park environment.

This study develops a consistent protocol for monitoring changes in ground-water levels, pond levels, and stream discharge using methods and techniques established by the U.S. Geological Survey for use in the Long-term Coastal Monitoring Program at the Cape Cod National Seashore. The protocol establishes a hydrologic sampling network in the four ground-water-flow cells in the Seashore area, and provides justification for the measurement methods selected and for the spatial and temporal sampling frequency. Data collected during the first year of monitoring are included in this report; common hydrologic analyses such as hydrographs for ground-water and pond levels, and rating curves between stream stage and discharge for streamflow, are presented for selected sites. Long-term hydrologic monitoring at the Seashore will aid in interpretation of the findings of other monitoring programs. Developing and initiating long-term hydrologic monitoring programs will provide a better understanding of effects of natural and human-induced change at both the local and global scales on coastal water resources in park units.

Merritt, R. W. and K. W. Cummins, (eds.). 1996. An Introduction to the Aquatic Insects of North America. Third edition ed. Kendall/Hunt Publishing Company, Dubuque, IA, USA.

While the bulk of Merritt and Cummins is on identification of aquatic insects of North America, they include several chapters useful in project planning as well. Various experts in the field of aquatic insect collection and identification have submitted chapters on: the general morphology of aquatic insects, designing studies, collection equipment and techniques, aquatic insect respiration, habitat and life history, and the ecology and distribution of aquatic insects. The rest of the manual is devoted to identification keys for each family of aquatic insect found in North America with many detailed and useful pictures of identifying characteristics. Since this book is continental in scope, it is suggested that practitioners first look for identification keys prepared for their local or regional waterways. This will reduce much confusion in the identification process by eliminating species that are not found locally. Any local aquatics expert or science librarian should be able to locate these materials. If local materials are not available, then Merritt and Cummins will be useful, however, be sure to check the distribution of species identified whenever possible.

Ossinger, M. 1999. Success standards for wetland mitigation projects - a guideline, 31 pp. Washington State Department of Transportation, Environmental Affairs Office. http://pnw.sws.org/forum/success.PDF

This report offers guidance and examples on how to write specific success criteria for mitigation and restoration projects. Though it was designed to address mitigation projects in the Pacific Northwest, its information and approach make it useful throughout the United States. It outlines the steps necessary for planning the monitoring and management of a mitigation/restoration project. Guidance in writing the following program elements is provided: how to set project goals, how to select specific project objectives (i.e. what functions or values will the mitigation/restoration provide), how to select performance objectives (i.e. what structural characteristics need to be in place to provide desired functions), selection of success standards (measurable benchmarks used to determine success of performance objectives), monitoring method (how will the success standard be measured), contingency measure (what to do if the success standards are not met). Several examples are provided of each of these steps. These examples, while not all-inclusive, facilitate the application of this method to diverse areas and project types.

Ryan, T. J., T. Philippi, Y. A. Leiden, M. E. Dorcas, T. B. Wigley and J. W. Gibbons. 2001. Monitoring herpetofauna in a managed forest landscape: effects of habitat types and census techniques. *Forest Ecology and Management* 5739:1-8.

Author Abstract. We surveyed the herpetofaunal (amphibian and reptile) communities inhabiting five types of habitat on a managed landscape. We conducted monthly surveys during 1997 in four replicate plots of each habitat type using several different methods of collection. Communities of the two wetland habitats (bottomland wetlands and isolated upland wetlands) were clearly dissimilar from the three terrestrial communities (recent clearcut, pine plantation, and mixed pine–hardwood forest). Among the three terrestrial habitats, the total herpetofaunal communities were dissimilar ($P<0.10$), although neither faunal constituent group alone (amphibians and squamate reptiles) varied significantly with regard to habitat. Three survey techniques used in the terrestrial habitats were not equally effective in that they resulted in the collection of different subsets of the total herpetofauna. The drift fence technique revealed the presence of more species and individuals in every habitat and was the only one to detect species dissimilarity among habitats. Nonetheless, coverboards contributed to measures of abundance and revealed species not detected by other techniques. We suggest that a combination of census techniques be used when surveying and monitoring herpetofaunal communities in order to maximize the detection of species.

Shiver, B. D. and B. E. Borders. 1996. Sampling Techniques for Forest Resource Inventory. John Wiley and Sons, Inc., New York, NY.

Author Preface. The purpose for writing this book was to create a forest inventory textbook that clearly explains the sampling methods associated with the inventory of forest resources. There are several books available which do a good job of explaining the theory of the various sampling techniques used in forest inventory. However, the transition from theory to practice is not easily made without extensive course work in theoretical statistics and mathematics. This book provides thorough coverage of forest inventory topics for the practitioner rather than the theoretician and should be understandable to undergraduate forest resources students and professionals who must inventory forest resources.

Examples are used extensively throughout the book to illustrate various estimators and to demonstrate different uses for sampling methods. Problems are also included at the end of each chapter to help instructors and students.

Some of the topics discussed, such as point sampling and 3P sampling, were developed specifically for timber inventory. Other topics, such as mark-recapture methods were developed for inventory of mobile wildlife populations. Many of the topics, however, can be utilized to inventory virtually any of the resources in a forest (understory vegetation, soils, water, etc.)

As the book has developed over the last several years, we find that we are using it as a reference as well as a textbook. Some of the topics such as double sampling with point sampling and sampling with partial replacement have been available only in scattered journal articles or in more theoretically oriented textbooks. Inventory is a job which most forest resource managers will use repeatedly throughout their careers. This book should allow them to work confidently in forest inventory regardless of the specific inventory problem.

Sparks, D. L., A. L. Page, P. A. Helmke, R. H.Loeppert, P. N. Soltanpour, M. A. Tabatabai, C. T. Johnson and M. E. Sumner.

1996. Methods of Soil Analysis: Part 3-Chemical Methods. 1358 pp. Soil Science Society of America, Madison, WI.

Publisher's Description. This volume covers newer methods for characterizing soil chemical properties as well as several methods for characterizing soil chemical processes. This book will serve as the primary reference on analytical methods. Updated chapters are included on the principles of various instrumental methods and their applications to soil analysis. New chapters are included on Fourier transform infrared, Raman, electron spin resonance, x-ray photoelectron, and x-ray absorption fine structure spectroscopies.

Steyer, G. D., R. C. Raynie, D. L. Steller, D. Fuller and E. Swenson. 1995. Quality management plan for Coastal Wetlands Planning, Protection, and Restoration Act monitoring program, 82 pp. Open-File Report 95-01, Louisiana Department of Natural Resources, Coastal Restoration Division, Baton Rouge, LA. http://www.lacoast.gov/cwppra/reports/MonitoringPlan/index.htm

This document is a Quality Assurance Project Plan (QAPP) used for all restoration projects conducted under the Coastal Wetlands Planning, Protection, and Restoration Act (CWPPRA) and similar legislation for coastal Louisiana. Though it does not explain how to develop a QAPP for new wetland restoration monitoring projects, it can be used as a template by which monitoring plans can be developed. Detailed explanations of how to data is to be collected, acceptable error rates, and methods to ensure high quality data is collected, recorded, and analyzed are included. Quality assurance guidelines are provided for field data collection, remote sensing and airphoto interpretation, computer systems to be used, data entry procedures, data review, laboratory procedures, and documentation and reporting. Any restoration practitioner attempting to develop a monitoring plan or preparing a QAPP for their project may find this document a valuable example to follow.

Uranowski, C., Z. Lin, M. DelCharco, C. Huegel, J. Garcia, I. Bartsch, M. S. Flannery, S. J. Miller, J. Bacheler and W. Ainslie. 2003. A regional guidebook for applying the hydrogeomorphic approach to assessing wetland functions of low-gradient, blackwater riverine wetlands in peninsular Florida, 590 pp. ERDC/EL TR-03-3, U.S. Army Engineer Research and Development Center, Vicksburg, MS. http://www.wes.army.mil/el/wetlands/wlpubs.html

This manual was prepared for use in assessing the functional capacity of blackwater, forested wetlands on the western coast of Florida using the Hydrogeomorphic (HGM) method. It provides a brief overview of the general HGM method for classification and assessment and explains how the HGM process was implemented for this particular type of forested wetland system and why. Although the equations provided for assessing functions were calibrated using data from western Florida, they can be adapted and re-calibrated using data from other areas. Methods for determining a blackwater forest's ability to perform the functions of temporary surface water storage, maintenance of characteristic subsurface hydrology, cycling of nutrient, removal and sequester of elements and compounds, retention of particles, export of organic matter, maintenance of plant communities, and provision of wildlife habitat are provided in detail. References to additional literature as needed are also provided.

U.S. EPA. 1996. The volunteer monitor's guide to quality assurance project plans, 59 pp. EPA 841-B-96-003, U. S. Environmental Protection Agency, Washington, D.C. http://www.epa.gov/volunteer/qapp/vol_qapp.pdf

Author Abstract. The Quality Assurance Project Plan, or QAPP, is a written document that outlines the procedures a monitoring project will use to ensure that the samples participants collect and analyze, the data they store and manage, and the reports they write are of high enough quality to meet project needs.

U.S. Environmental Protection Agency-funded monitoring programs must have an EPA-approved QAPP before sample collection begins. However, even programs that do not receive EPA money should consider developing a QAPP, especially if data might be used by state, federal, or local resource managers. A QAPP helps the data user and monitoring project leaders ensure that the collected data meet their needs and that the quality control steps needed to verify this are built into the project from the beginning.

Volunteer monitoring programs have long recognized the importance of well-designed monitoring projects; written field, lab, and data management protocols; trained volunteers; and effective presentation of results. Relatively few programs, however, have tackled the task of preparing a comprehensive QAPP that documents these important
elements. This document is designed to help volunteer program coordinators develop such a QAPP.

U.S. EPA. 2002. Guidance for quality assurance project plans, 57 pp. EPA QA/G-5, U. S. Environmental Protection Agency, Washington, D. C. http://www.epa.gov/swerust1/cat/epaqag5.pdf

This document is designed to guide those involved with Quality Assurance Project Plan (QAPP) development for environmental monitoring and data analysis. It describes various issues to be addressed when preparing a QAPP, with an emphasis on systematic planning. The report is divided into three chapters. An introduction that describes the target audience and the importance of systematic sampling. A second chapter describes all of the pieces of a QAPP, focusing on environmental data collection and analysis. The third chapter describes methods for developing QAPPs for projects that use previously collected data.

The importance of having high quality, reliable data cannot be over estimated. Use of this document or the EPA's *Volunteer monitor's guide to quality assurance project plans*, will help restoration practitioners develop monitoring plans that will provide the high quality, reliable data necessary to monitor and manage restoration projects. The step-by-step approach of this document takes restoration practitioners through the entire planning, data collection, data analysis, and reporting process from start to finish. Ensuring that all aspects of the monitoring project are well thought out ahead of time and that contingency plans are in place.

Weaver, R. W., S. Angle, P. Bottomley, D. Bezdicek, S. Smith, A. Tabatabai and A. Wollum. 1994. Methods of Soil Analysis: Part 2-Microbiological and Biochemical Properties. 1121 pp. Soil Science Society of America, Madison, WI.

Publisher's Description. Laboratories outside of soil science will find it advantageous to use the methods contained in this book. They will be particularly relevant and useful to laboratories with interest in environmental microbiology or bioremediation. Analytical methods are essential to progress in science and the methods presented in this book are recognized as being among the best currently available.

APPENDIX III: LIST OF DEEPWATER SWAMP EXPERTS

The experts listed below have provided their contact information so practitioners may contact them with questions pertaining to the restoration or restoration monitoring of this habitat. Contact information is up-to-date as of the printing of this volume. The list below includes only those experts who were 1) contacted by the authors and 2) agreed to submit their contact information. Some of those listed also reviewed the associated habitat chapter. In addition to these resources, practitioners are encouraged to seek out the advice of local experts as well faculty members and researchers at colleges and universities. Engineering, planning, and landscape architecture firms also have experts on staff or contract out the services of botanists, biologists, ecologists, and other experts whose skills are needed in restoration monitoring. These people are in the business of providing assistance in restoration and restoration monitoring and are often extremely knowledgeable in local habitats and how to implement projects on the ground. Finally local, state, and Federal environmental agencies also house many experts who monitor and manage coastal habitats. In addition to the National Oceanic and Atmospheric Administration (NOAA), the Environmental Protection Agency (EPA), the Army Corps of Engineers (ACE), Fish and Wildlife Service (FWS), and the United States Geologic Survey (USGS) are important Federal agencies to contact for assistance in designing restoration and monitoring projects as well as potential sources of funding and permits to conduct work in coastal waterways.

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CHAPTER 13: RESTORATION MONITORING OF RIVERINE FORESTS

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Bobby Keeland, USGS National Wetlands Research Center[2]

INTRODUCTION

A riverine forest is a type of wetland dominated by trees and located along sluggish streams, drainage depressions, and in large alluvial floodplains. Although this habitat occurs throughout the United States, extensive areas of riverine forests are found on the Atlantic and Gulf coasts and throughout the Mississippi river valley from Louisiana to southern Illinois (Figure 1 - Mitsch and Gosselink 2000; Allen et al. 2001). Riverine forests are commonly referred to as bottomland hardwoods, floodplain forests, or riverine swamps. They are referred to as 'palustrine forests' by Cowardin et al. (1979).

Riverine forests are often subdivided into a variety of types or classes based on dominant tree species or the regional landform they are found in. Some examples include deepwater swamps, alluvial floodplains, pondcypress swamps, and wet flatwoods (Mitsch and Gosselink 2000; Allen et al. 2001). Riverine forests can be flooded by up to several feet of water in the winter and spring. By summer, water levels in most cases recede, exposing the soil. Some forests occasionally remain flooded throughout the year (Mitsch and Gosselink 2000; Allen et al. 2001), others have dry-downs early in the growing season nearly every year. All riverine forest habitats need occasional dry periods when the soils are exposed for tree seedlings to germinate. Soils of riverine forests are typically mineral although limited peat accumulation may occur in deeper depressions and wetter areas (Giese et al. 2000).

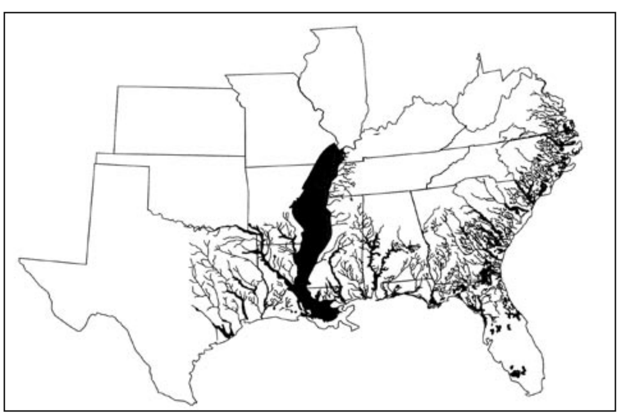

Figure 1. Distribution and extent of riverine forests along rivers and streams in the southeastern United States. Figure Courtesy of USGS, based on a figure modified from Putnam et al. 1960.

The dominant woody vegetation of riverine forests includes softwood as well as hardwood tree species. Some examples include:

Baldcypress (*Taxodium distichum*)
Water tupelo (*Nyssa aquatica*)
Red maple (*Acer rubrum*)
Silver maple (*A. saccharinum*)
Green ash (*Fraxinus pennsylvanica*)

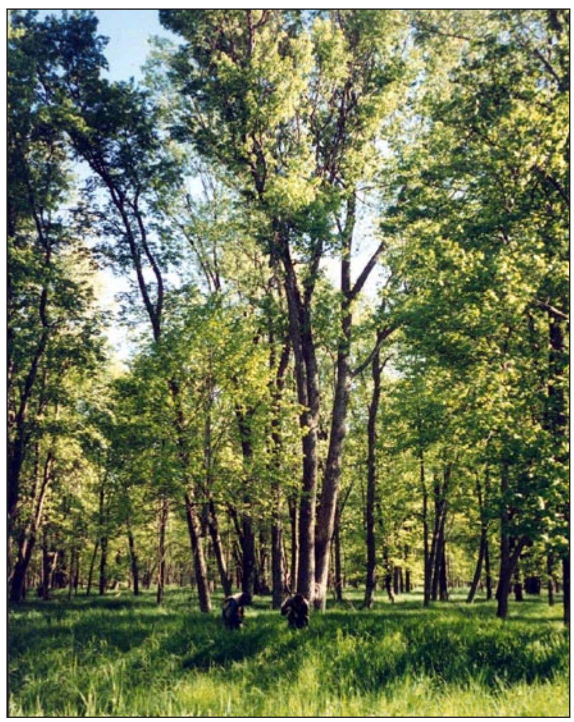

Figure 2. A silver maple dominated riverine forest in northern Lower Michigan. Photo courtesy of Matthew Baker, Smithsonian Institute.

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[2] 700 Cajundome Boulevard, Lafayette, LA 70506.

Sugarberry/hackberry (*Celtis laevigata*)
Elm (*Ulmus* spp.)
Cottonwood (*Populus deltoids*)
Swamp cottonwood (*P. herophylla*)
Willow (*Salix* spp.), and

a variety of oaks such as:

Overcup (*Quercus lyrata*)
Willow (*Q. phellos*)
Nuttall (*Q. texana*)
Water (*Q. nigra*), and
Cherrybark (*Q. pagoda*) (Putnam et al. 1960; Hosner and Minckler 1963; Barnes and Wagner 1981; Allen et al. 2001)

Pond cypress (*Taxodium distichum* var. *nutans*) and Atlantic white cedar (*Chamaecyparis thyoides*) also occur in isolated locations in the southeastern United States.

Riverine forests support a diversity of animal populations, including commercially important wildlife species. Many species of macroinvertebrates such as crayfish, shrimp, insects, clams, snails, and worms are also commonly found in riverine forests (Wharton et al. 1982). Fish make extensive use of flooded riverine forests for temporary feeding, spawning, and nursery areas. Deepwater, backwater, and main river channel areas provide refuge for fish when floodwaters subside (Wharton et al. 1982; Killgore and Hoover 1992). Forests that are inundated for longer periods of the growing season provide greater habitat benefits for invertebrates and fish than those that dry down in the summer (Bowers et al. 2000). The American alligator, cottonmouth snakes, and several species of frogs and salamanders all use riverine habitats for foraging, cover, and reproduction (Bowers et al. 2000). White-tailed deer, nutria, rabbits, beaver, mink, migrating songbirds, waterfowl, and wading birds are all typical residents of riverine forest habitats (Wharton et al. 1982; O’Neal et al. 1992; Guilfoyle 2001).

Riverine forests are essential to the health and function of downstream areas. Alluvial forests temporarily store floodwaters, reduce downstream flood peaks, and retain sediments that would otherwise be transported downstream. They absorb and transform nutrients, preventing eutrophication of downstream water bodies and export organic matter that can be used as food by fish (Conner and Day 1982; Giese et al. 2000; Stanturf et al. 2000). The floodplain forest of the Apalachicola River in the Florida panhandle, for example, is a primary mechanism influencing the chemistry and biology of Apalachicola Bay. River flow is influenced by local rainfall patterns, watershed drainage, flood water storage in the floodplain, and plant cover (Wharton et al. 1982). Thus the salinity level of the Bay (and its associated effects on plants and animals of the Bay) is partly under the influence of the riverine forests through which floodwaters flow. The productivity of the Bay also depends on the annual pulses of organic material and silt from riverine forests but also on longer-term (5 to 7 year) flood pulses originating in the mountains of Georgia. These larger flows flush accumulated organic material, nutrients, and sediments that have been stored within the riverine forest out to the Bay and have been linked to peaks in commercial fish catches nearshore. Similar processes have also been noted in the Chesapeake Bay and in Barataria Bay in Louisiana (Wharton et al. 1982).

HUMAN IMPACTS TO RIVERINE FORESTS

Although the total area of riverine forest cover prior to European settlement for the entire United States is not known, estimates for some areas do exist. The Mississippi Alluvial Valley had the largest extent of riverine forest (Figure 1) at 25 million acres (Hefner and Brown 1985), approximately 20% of that remains today (MacDonald et al. 1979). In Texas and Illinois, only 34% and 2% respectively of the original riverine forest remain (Frye 1987; Allen et al.

2001). Losses in these and other areas once dominated by riverine forests continue. The majority of losses have primarily been due to conversion to agriculture although flood control structures, reservoirs, drainage and conversion to pine forests, surface mining, petroleum extraction, and urban development have also impacted forest area (Allen et al. 2001). In addition, conversion to tree-farm monoculture for wood production, construction of impoundments, diversion canals, channelization, dredging, shortening of channels, and urban development also diminish the health and acreage of riverine forests (Wharton 1982). Highway construction projects impact riverine hardwood forests beyond the footprint of the highway because water often ponds or drains more slowly from the upstream or uphill side of the highway causing extensive mortality of species not capable of surviving the increased flooding or soil saturation. Although these alternative land uses contain obvious value, so too, do the functions provided by healthy, intact riverine forests.

Need for Restoration

Functions such as floodwater storage and nutrient cycling have only recently begun to be understood and valued by society. When floodplain ecosystems are connected to their associated rivers and allowed to flood, they filter nutrients, store sediments, retain floodwater and otherwise help preserve downstream water quality. In addition, riverine forests also provide important habitat for migratory and resident birds, fish, and a variety of other wildlife. As the public has become more aware of the environmental and economic benefits of riverine forests, the desire to preserve and restore them has increased. Conservation and preservation of remaining riverine forests is important but considering the extent of loses, restoration of these habitats is also required (Allen et al. 2001).

Originally when riverine forests were harvested for lumber, cutover areas were converted to agriculture and no reforestation or restoration was attempted. Eventually large-scale logging operations were developed in areas unsuitable for agricultural production. These required that bottomlands be managed for forest production over long periods of time. Early efforts at replanting cutover riverine forest areas were focused on planting pines or other fast growing tree species for repeated harvest. There was little concern or need for ecological monitoring in these situations. The only thought was to assess how fast the trees were growing and when they would be ready for harvest.

Ecosystem-based restoration of riverine forest ecosystems is a relatively new practice. Only since the early 1980s have any serious, large-scale, ecological restorations been attempted. Considering the amount of this habitat type that has been lost, the need for restoration is great. Unfortunately it is also expensive if it is to be done properly and/or on any large scale. Hydrologic restoration projects need to be carefully monitored to ensure that hydroperiods and water flows are developing as planned and that excessive erosion or flooding in unintended areas is not occurring. If planting is also part of the restoration project, monitoring of which planting schemes offer the best survivorship of planted material can increase the efficiency of future restoration efforts. Without monitoring, it will be impossible to determine if money spent on site acquisition, site preparation, and plant materials were well spent or wasted.

STRUCTURAL CHARACTERISTICS OF RIVERINE FORESTS

When planning a restoration and monitoring project, practitioners should be mindful that it may take several decades before a riverine forest is able to fully perform all ecological functions. Therefore, it is important to state early on in the restoration planning process what the particular goals of the restoration project are and how the project will be monitored over time to see if those goals have been achieved. A few examples to illustrate this point may be helpful:

- If the goal of a restoration project is to allow fish access to a forested floodplain for feeding and breeding purposes by removing a dike or levee, evidence of fish usage in the area might be seen within a year or two.
- If the goal of the project is to restore plant diversity to levels similar to a reference condition[3], this might be achieved in a relatively short time period as well (5 to 10 years).
- The goal of restoring native fish or bird species, on the other hand, may require the presence of woody debris in the stream channel for cover, a closed canopy to shade the water and keep day-time temperatures low, or old trees with cavities in which to build nests. If large trees to supply these habitat needs are not available, trees will need to be grown from seedlings or saplings. Thus monitoring may take a human lifetime or more as trees grow to the proper size.

Understanding project goals and how they are to be monitored also helps determine what management actions may be required later to ensure that goals are achieved.

As with many of the other habitats described in *Volume Two*, the monitoring of restoration efforts in riverine forests should focus first on the primary structural characteristics of the habitat and then shift toward functional characteristics over time. The primary structural characteristics of riverine forests have been broken down into four categories.

Biological

- Habitat created by plants

Physical

- Sediment grain size
- Topography/Bathymetry

Hydrological

- Hydroperiod and water source

These structural characteristics were identified as being fundamental to the development of a healthy riverine forest habitat. Each of these dictates whether or not a forest can develop in an area, which particular tree species will become established, and the degree to which the habitat can perform characteristic biological and physical functions. Much of the information presented here has been derived from studies in the southeastern United States, as this is where riverine forests are most extensively found[4]. The same general characteristics and parameters, however, may apply to riverine forests throughout the United States.

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[3] See Chapter 15 for a discussion of methods to select proper reference conditions for restoration monitoring.

[4] This document and its associates were created to address monitoring requirements of the Estuary Restoration Act of 2000 (ERA), Title I of the Estuaries and Clean Waters Act of 2000. The Act places a head of tide inland boundary on habitats to be addressed by these documents. Therefore, inland riverine forests, often called 'riparian forests', are not specifically described in this text. Two publicly available resources, however, provide extensive technical assistance toward the restoration and monitoring of these systems and can be found at: http://www.usda.gov/stream_restoration/ and http://www.npwrc.usgs.gov/resource/literatr/ripareco/ripareco.htm#contents

Figure 3. Small-scale changes in topography can also influence the abundance of understory vegetation. Lower, wetter areas (left) are often devoid of groundcover while slightly higher and dryer areas (right) have abundant vegetation. Photo courtesy of Matthew Baker, Smithsonian Institute.

BIOLOGICAL

Habitat Created by Plants

Riverine forests can be extremely diverse communities, exhibiting a variety of canopy/ground cover combinations (Eyre 1980). The presence and abundance of understory vegetation depends upon hydrology, soil type and pH, and to a large extent the amount of light that penetrates the canopy (Hosner and Minckler 1963; Dunn and Stearns 1987). Some areas with open canopies and moderate flooding may have a diverse shrub and herbaceous ground flora (Figure 3). Others, with closed canopies or longer flooding times may be devoid of any ground layer vegetation (Mitsch and Gosselink 2000). The relationship of these plant community characteristics to the physical, hydrological, and chemical structural characteristics of riverine forests are explained in the various sections below.

Most wildlife have particular ranges of attributes within which they are best adapted. Forestry attributes such as stem density, % canopy closure, tree height, diameter at breast height (DBH), amount of woody debris on the forest floor, forested area, presence of gaps, seed (mast) production, amount of litter fall, frequency of fire, and tree species composition can all have a positive or negative impact on wildlife habitat depending on the particular animal species or community in question. A comprehensive description of how riverine forests provide habitat is beyond the scope of this document. Although a few examples are used in the Functional Characteristics section below, practitioners requiring more detail on particular types of riverine forests or particular portions of the country are directed to documents in the annotated bibliography. Even these often can only provide broad generalizations. Practitioners may need to investigate the primary scientific literature if the goals of their project are very narrow in focus. Once a practitioner is familiar with the general literature, local and regional experts can be contacted for further information and assistance.

Sampling and Monitoring Methods

The types of measurements used to monitor the restoration of a forested site change as the site matures. If plantings are part of the restoration project, the first few years are typically spent monitoring damage from herbivores, seedling survival, density, and growth rate as measured by plant height (Conner 1989; Kolka et al. 1998; Conner et al. 2000). Small seedlings may, however, be difficult to find amongst taller, denser grasses. In addition, plants that have been clipped by herbivores may sprout back the following year. As sites mature (e.g., starting around 10 years after planting), the monitoring of canopy closure becomes important as this factor is strongly related to light availability and understory vegetation (Fletcher et al. 2000). Growth rate can still be measured but the method changes from using seedling height to diameter at breast height (DBH).

Numerous field and identification guides are available for different areas of the country.

Practitioners should select a book (or books) from as close a region as possible to their study area. Most field guides are not comprehensive and only cover the most common species one is most likely to find. When knowing the exact species is absolutely necessary, such as when study results are to be published, then more detailed and comprehensive identification guides should be consulted. A few examples of these sorts of texts include:

- Godfrey and Wooten's *Aquatic and Wetland Plants of Southeastern United States: Dicotyledons* or their second volume *Aquatic and Wetland Plants of Northeastern North America: Angiosperms: Monocotyledons (Volume II)*
- Crow, Hellquist's, and Fassett's *Aquatic and Wetland Plants of Northeastern North America: Pteridophytes, Gymnosperms and Angiosperms: Dicotyledons and Aquatic and Wetland Plants of Northeastern North America: Angiosperms: Monocotyledons (Volume II)*, and
- Voss' three-volume *Michigan Flora*

PHYSICAL

Sediment Grain Size

The soils of riverine forests are a product of the hydrologic process of the associated river. The alternating cycle of flooding and drydown controls the physical and chemical properties of floodplain soils such as sediment grain size, bulk density, pH, redox potential, and nutrient cycling which in turn strongly influence species composition (Dunn and Stearns 1987). The cycle of flooding and drawdown:

- Continually deposits and replenishes minerals and essential nutrients in floodplain soils
- Produces anaerobic conditions in the soil that affect biological and chemical processes
- Imports and exports particulate and dissolved organic matter, and
- Exports biological waste products (Wharton et al. 1982)

Healthy, intact riverine forest communities absorb and dissipate the physical energies of overbank flooding. When water enters the floodplain and has to work its way around and through dense stand of trees and shrubs, water velocity is slowed, suspended sediments are deposited, and erosion is held in check (Wharton et al. 1982). As a result, alluvial riverine soils generally have more clay and organic matter than upland soils and thus tend to have greater nutrient and moisture-holding capacity leading to high rates of productivity[5] (Allen et al. 2001). When suspended sediments are deposited in the floodplain instead of being carried further downstream, habitat and water quality in receiving bodies of water are protected from sedimentation or increased turbidity.

At lower elevations where standing water occurs for most of the year, significant accumulations of soil organic matter can develop. Percent soil organic matter ranges from <5% for alluvial river floodplains to 30-40 % for rivers draining acid bogs, tidal forests and floodplains along spring-fed rivers. Soils in low elevations have higher organic matter content within that range (Wharton et al. 1982). The distribution of organic matter is an important factor affecting water quality, habitat, and food webs (Giese et al. 2000). Organic matter binds nutrients and metals, provides an energy source for microbes that break down pesticides and transform nutrients into non-soluble forms, and forms the basis of detrital food chains (Lockaby and Walbridge 1998).

Sampling

The Soil Science Society of America publishes a 4-volume *Methods of Soil Analysis*. These volumes cover a variety of standard methods to sample the physical, mineralogical, microbiological, biochemical, and chemical properties of soils. This would be a valuable

[5] Productivity can also be decreased by stagnant water and associated anaerobic conditions in the soil.

resource to anyone seriously considering soil sampling over the long-term. Most university libraries should also carry these volumes as well.

Topography/Bathymetry[6]

The hydrologic processes of the river shape the topography of riverine forests. River flows form and maintain the floodplain by transporting and redistributing sediments within the system. Sediments are continually eroded and deposited through the processes of point bar deposition, overbank deposition, and sheet, gully or streambank erosion during major flood events as the river moves back and forth across the floodplain (Brown and Lugo 1982; Wharton et al. 1982). As the river meanders across the floodplain, outer banks are eroded away and carried downstream and sediment from upstream is deposited on the inner bank of the meander (Figure 4). During overbank flooding, water spreads out over the floodplain, losing much of its energy and subsequently dropping its load of suspended sediment. The heavier sediments, such as sand and silt, are deposited near the stream channel and form the natural levee. Fine sediments, such as clays, are typically carried further out onto the floodplain. This increases the elevation of the local floodplain while preventing down stream areas or instream habitats from being sedimented over. As river channels move back and forth across a floodplain, new gullies and banks are formed (Brown and Lugo 1982; Wharton et al. 1982; Hupp 2000).

This process of constant erosion and deposition of nutrient rich sediments of the forest floor results in topographic complexity and contributes to the high primary productivity and species richness (Brown and Lugo 1982; Wharton et al. 1982). Other aspects of hydrology are also related to high productivity of riverine forests. Riverine forests with flowing water or seasonal wet/dry cycles have higher productivities when compared to those that are either permanently ponded or drained (Brown and Lugo 1982; Wharton et al. 1982).

Forest zones

Riverine forests are typically subdivided into six zones following an elevational gradient

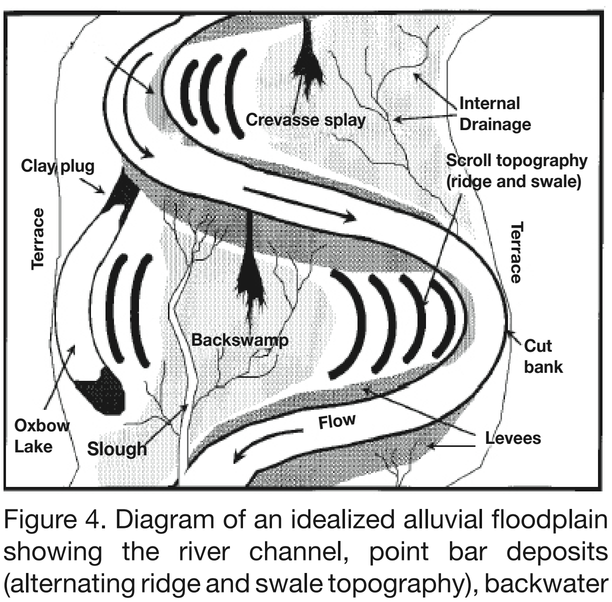

Figure 4. Diagram of an idealized alluvial floodplain showing the river channel, point bar deposits (alternating ridge and swale topography), backwater swamps, channel fill deposits (clay plug forming in an oxbow lake), natural levees around the channel, and sloughs. Taken from Hupp 2000.

Figure 4.1. A river channel in northern Lower Michigan, the picture shows a zone of erosion (left) and a zone of deposition (right). The height of the vegetation on the zone of deposition can be used to indicate the age of the area. Sandy deposits are relatively recent with herbs, shrubs, and trees growing on successively older deposits. Photo courtesy of Matthew Baker, Smithsonian Institute.

[6] Information for this section was taken liberally from these sources Wharton et al. 1982; Allen et al. 2001; Guilfoyle 2001. They are cited here instead of repeatedly throughout the text.

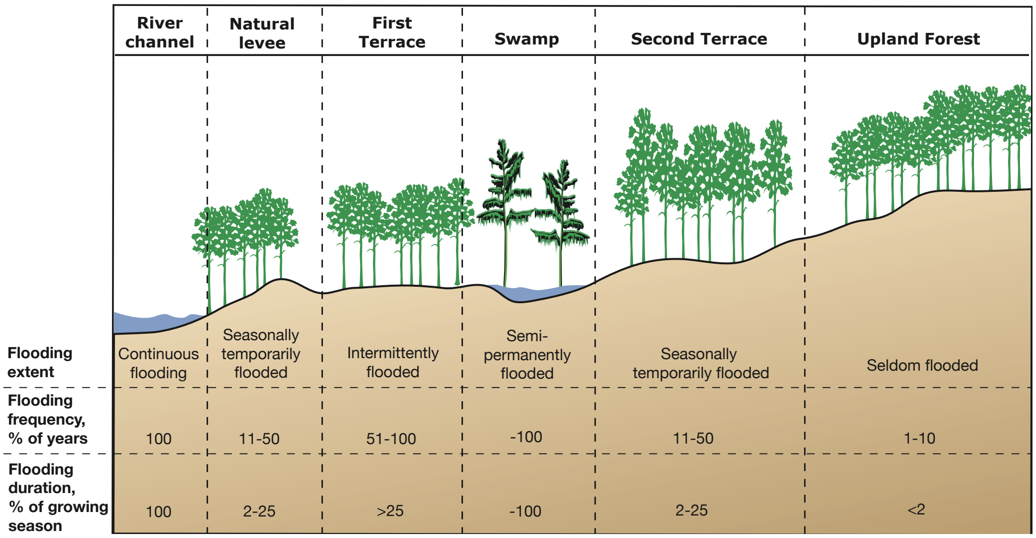

Figure 5. An idealized progression of riverine forest zones from the open water of a river to upland, along a water table gradient showing characteristic hydrologic conditions for each zone (modified from Mitsch and Gosselink 2000).

from open water in the river channel to upland forests. Although each zone may not be well represented in every location, nor follow the progression from open water to upland, a discussion of the different zones is useful in understanding the factors controlling vegetation community, wildlife habitat, and water quality functions (Figure 5).

Zone I is the main channel of the river and has a 100% probability of being flooded[7]. It provides habitat year round for fish and other aquatic organisms and may (depending on the extent of forest cover and water velocity) be dominated by submersed macrophytes in deeper water and emergent vegetation along the edge.

Zones II – V make up the active floodplain. Zone II is referred to as the Deepwater Swamp[8] and is dominated by baldcypress and tupelo in southern systems[9]. It also has a near 100% probability of being flooded and provides habitat for fish, alligators, and aquatic invertebrates. Occasional drawdown of this zone is necessary for forest regeneration.

Zone III is semi-permanently flooded with a 51-100% probability of prolonged annual flooding. This zone is often dominated by:

Willow (*Salix* spp.)
Red maple (*Acer rubrum* var *drummondii*)
Cottonwood, and
Overcup oak

In southern systems, other common overstory species include:

Water hickory (*Carya aquatica*)
Water elm (*Planera aquatica*)
Swamp tupelo (*Nyssa sylvatica* var *biflora*)
Black willow (*Salix nigra*)
Baldcypress, and
Water tupelo

Zone IV is seasonally flooded with a 51-100% probability of short-term annual (usually winter/spring) flooding. This area is typically dominated by:

Green ash
Willow oak
Water oak

---

[7] Percent refers to the probability of annual flooding, not the amount of time the area is flooded.
[8] The structural and functional characteristics of Deepwater Swamps useful in restoration monitoring are discussed in Chapter 12.
[9] Tree species presented as examples are drawn from southern systems, some of which may be found in northern areas as well. Practitioners should consult with regional experts and printed resources to determine which species are present in their area.

Nuttall's Oak
American elm (*Ulmus americana*)
Sweetgum (*Liquidambar styraciflua*)
Sycamore (*Platanus occidentalis*)
Cottonwood
Hackberry (*Celtis laevigata* or *C. occidentalis* in more northern areas), and
Diamondleaf oak (*Q. laurifolia*)

Zones II through IV provide seasonal spawning, nursery, and foraging habitat for fish when inundated.

Zone V is only temporarily flooded, with an 11-50% probability of annual flooding. Dominant tree species may include:

Red mulberry (*Morus rubra*)
Loblolly pine (*Pinus taeda*)
Water oak
Cherrybark oak
Shumard's oak (*Q. shumardii*), and
American beech (*Fagus grandifolia*)

Zone VI is the floodplain-upland transition ecosystem, it is only intermittently flooded, with a 1-10% probability of annual flooding.

The exact spatial location of each zone is more a function of elevation than of distance from the river channel. For example, a large levee adjacent to the active channel may have vegetation and functional characteristics of Zone IV because it is well drained due to elevation and the presence of coarse sediments. A deep swale or backwater some distance from the active channel may be dominated by Zone II-III vegetation.

Measuring and Monitoring Methods

Topographic maps available from the United States Geologic Survey can provide a rough estimate of elevations in the study area. In most cases, however, a detailed survey of the area to be restored will need to be conducted. The surface elevations and topographic diversity of the area must be measured in relation to existing or projected water level changes as differences of only a few centimeters may determine whether or not planted material survives.

HYDROLOGICAL

Hydroperiod and Water Source

The hydroperiod (depth, frequency, duration, seasonality, and source of flooding and/or soil saturation including the depth to the water table) of a riverine forest is an important factor in determining plant species distribution and composition (Allen et al. 2001). Seasonal climate differences and large storm events together with watershed slope, size, and soil drainage characteristics determine flooding and inundation patterns. Winter and spring are typically periods of high flow while low flows occur in late summer and fall, due to high evapotranspiration and low precipitation during those time periods. Larger catchments tend to have deeper, longer floods than do smaller ones (Brinson 1990).

Riverine forests can be broken down into four categories based on water source and hydrodynamics: alluvial, blackwater, spring-fed, and bog or bog-fed (Wharton et al. 1982).

Alluvial

Alluvial rivers are those with well-developed, broad, flat floodplains with sandy/gravelly sediments deposited by flowing water. The Mississippi River is a good example of an alluvial river with a well-developed and broad flood plain that extends nearly 620 miles from the confluence of the Mississippi and Ohio Rivers to the Gulf of Mexico. Other good examples can be found along the southeast coast.

The headwaters (source) of some large alluvial rivers in the southeast are in the Piedmont or Ridge and Valley area. As water flows down off the Piedmont and enters the topographically flat coastal plain, the water slows down, spreads

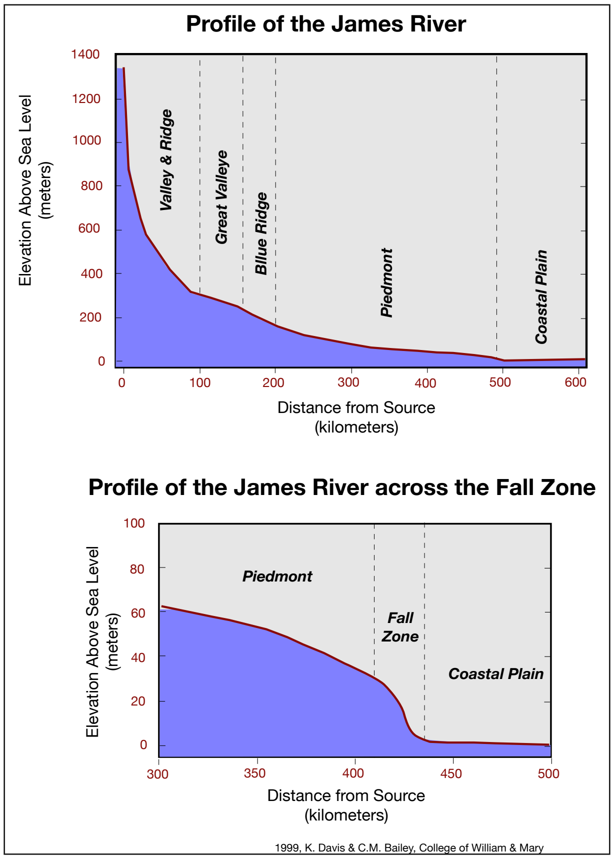

Figure 6. Elevation profile of the James River, Virginia as it flows from its headwaters in the Ridge and Valley to the Coastal Plain. Figure courtesy of C. Bailey, College of William and Mary.

out, and forms large swamps. The James River in Virginia is a good example of an alluvial river. The top graph in Figure 6 shows the elevation of the river as it makes its way from the Ridge and Valley area down to the coastal plain. The bottom graph is a close up of the Piedmont and coastal plain stretch of the river. Due to the slope of the Piedmont (and particularly the Fall Zone), water moving in the river has a lot of energy. When it hits the flat coastal plain, however, there is not enough slope to maintain fast flow toward the ocean and water spreads out horizontally across the landscape developing broad floodplains.

Blackwater

The headwaters of most blackwater rivers are in the coastal plain or other extremely flat areas. Blackwater rivers receive most of their discharge from local precipitation. Compared to rivers with headwaters in the mountains or the Piedmont, coastal plain headwater rivers have much less discharge, slower flows, clearer water, carry less sediment, and have less developed floodplains. The term blackwater refers to the dark, tea-like, color of the water due to organic substances characteristic of swamp drainage. Blackwater rivers may be tributaries to alluvial rivers as they make their way through the coastal plain to the Gulf of Mexico or Atlantic Ocean.

Spring- and Bog-fed Rivers

Spring-fed rivers are common where mineral rich groundwater discharges from highly permeable geologic formations. For many of these rivers, the source of water is predominantly groundwater, water levels are relatively stable, and they rarely experience overbank flooding. Bog and bog-fed rivers are found in areas less permeable geologic deposits. They are generally rare and quite small compared to the other river types. The sources of water to these rivers are some groundwater mixed with a larger portion of local precipitation. Unlike groundwater-fed systems, rivers with flow dependent upon precipitation patterns, can have dramatic, short-term water level fluctuations (Wharton et al. 1982).

Of these four river types, alluvial rivers have the greatest range and covered the largest acreage and therefore have greater opportunity for restoration than the others. Unless otherwise stated, all information in the following sections refers to alluvial rivers and their associated riverine forests.

Effects of Hydrology

Hydrology, soil type, and topography are the main structural characteristics that can be used to explain the variability between forest communities (Hosner and Minckler 1963; Wharton et al. 1982; King and Keeland 1999). The relationship of hydrology and topography to vegetation types introduced in Figure 5 can

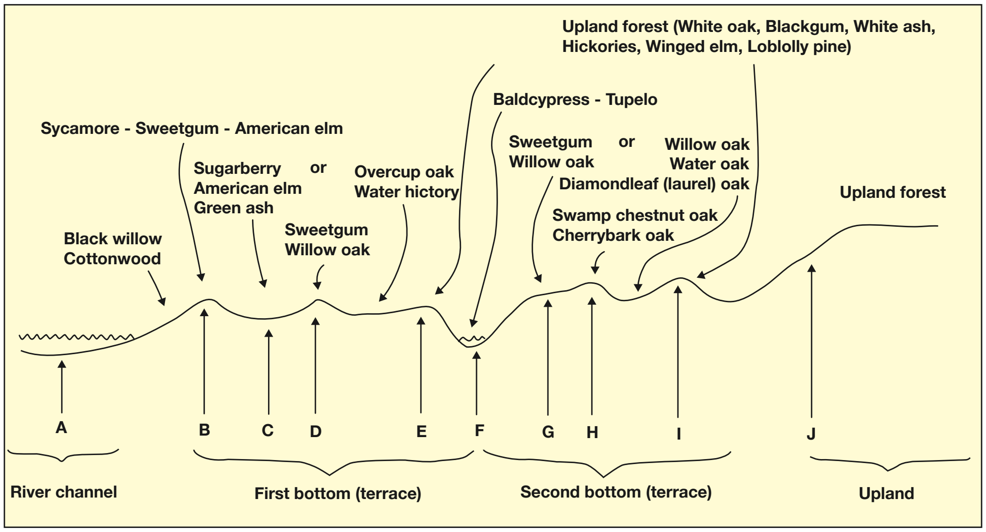

Figure 7. Dominant riverine vegetation by elevation along a southeastern alluvial floodplain. Adapted from Wharton et al. 1982.

be seen in more detail in Figure 7. Flooding can be very stressful on woody vegetation. Except for a few species, stresses associated with inundation can only be handled for short periods of time depending on the range of tolerance for the individual species (Wharton et al. 1982). Baldcypress and tupelo are better able to tolerate these stresses and tend to occupy the lowest, wettest elevations of the floodplain. Communities of sycamore-sweetgum-American elm or willow oak-water oak-diamond leaf oak, to name a few, segregate out across the floodplain depending on changes in elevation and associated depth and duration of flooding (Figure 7).

Differences in vegetation community related to drainage and soil characteristics can be seen in northern forests as well. Hosner and Minckler (1963) studied forest regeneration and succession in bottomland forests in Illinois. They found that sandy, well-drained alluvial deposits were colonized by cottonwood and willow and later dominated by:

Boxelder (*Acer negundo*)
Silver maple
Elms, and
Ash

Finer-textured, poorly drained areas were colonized by:

Buttonbush (*Cephalanthus occidentalis*)
Swamp cottonwood
Swamp privet (*Forestiera acuminata*)
Baldcypress
Tupelo
Willow, and
Ash

These areas were later succeeded by a variety of hardwood species such as:

Pin oak (*Quercus palustris*)
Bur oak (*Q. macrocarpa*)
Overcup oak
Honey locust (*Gleditsia triacanthos*),
Red maple, and eventually
Sweetgum (*Liquidambar styraciflua)*, and
Hickory (*Carya* spp.) in some cases

Given results such as these, restoration projects that carefully match species requirements to specific site conditions will increase the likelihood of success.

The structural characteristics of hydroperiod and water source are also part of a functional characteristic of riverine forests, floodwater storage. During high river flows, when water is allowed to spread out over the floodplain, water is stored in the forest and later released back to the stream channel (Winger 1986). Storage and slow release of floodwater reduces flood peaks and decreases the extent of damage downstream (Bedient and Huber 1992). By helping to moderate channel flows over time, floodwater storage in riverine forests also reduces stress on aquatic organisms within the stream channel. Although some wetland fish species such as bowfin (*Amia calva*) are able to survive a summer of desiccation by becoming dormant inside balls of dried mud (Hoover and Killgore 1998), riverine fish typically cannot do this (Moyle and Cech 1988). In addition to the direct effects little or no water has on fish, low water levels also increase temperature, turbidity, growth of aquatic plants, and decrease oxygen levels further stressing riverine fish (Moyle and Cech 1988).

Floodplain vegetation also influences hydrodynamics and water quality. As floodwaters spread out into the forest, water velocities decrease. Sediments and attached nutrients settle out onto the forest floor. High stem densities can increase this effect by further slowing water velocity (Bedient and Huber 1992). Herbaceous vegetation also increases moisture levels in upper soil layers by shading the surface and through capillary action along rhizomes bringing water up from deeper soil horizons (Kutschera and Lichtenegger 1982, cited in Tabacchi et al. 2000). Woody vegetation can increase the hydraulic conductivity of the soil through root development and decomposition (Thorne 1990). The effect floodplain vegetation has on hydrologic processes varies depending on the type, health, and patchiness of plant communities as well as how long the community has had a chance to alter soil characteristics. Tabacchi et al. (2000) provide an up-to-date and comprehensive review of the literature regarding the effect vegetation has on hydrologic processes and nutrient cycling. Readers interested in a thorough explanation of these interactions and related lphenomena are referred there.

A change in the hydrology of riverine forests in the southeastern United States has occurred since European settlement. Before settlement and subsequent alteration of riverine habitats, most of the inputs to alluvial streams came from subsurface flow with flood pulses in the winter and spring due to increased seasonal precipitation and snow melt. Today, however, due to decreases in forest cover and soil organic matter and changes in land use to agriculture and urban environments with lower soil permeability, surface water inputs have become an increasingly larger percent of river inputs and may dominate some streams (Wharton et al. 1982). A dominance of surface water in stream hydrology makes them flashier, with lower base flows in the summer and higher flood peaks throughout the year (Figure 8). This change in hydrology alters the depth, duration, and timing of flood events, and the patterns of sedimentation and erosion in riverine forests. In other areas, dams and flood control levees have completely cut the floodplain off from the river. Barnes (1997) found that areas downstream from dams had reduced rates of meandering and bank erosion and thus were less dynamic than free-flowing forest systems. This resulted in the

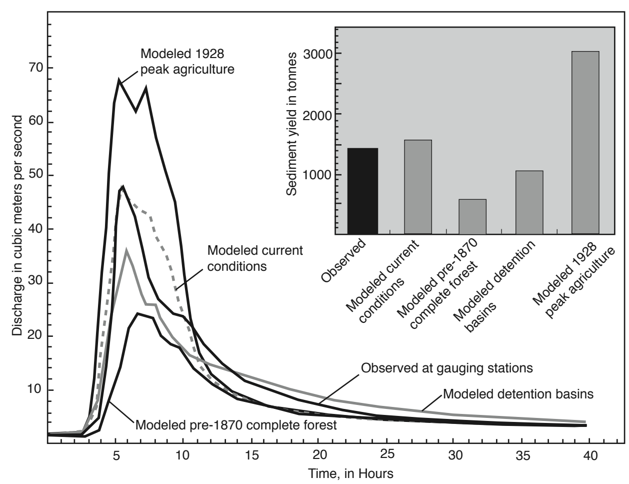

Figure 8. This series of historical hydrographs on the North Fish Creek near Moquah, WI shows how changes in land use have contributed to changes in peak flows. Higher peak flows, associated with agricultural land uses, mean that flooding is more severe than under forested conditions. Taken from Fitzpatrick et al. 1999.

Figure 9. Damage to a monitoring well by an animal chewing on the top of the well. Damage of this sort prevents water level measurements and water samples from being obtained until the top portion of the well can be cut off or a new well installed. Photo by David Merkey, NOAA/Great Lakes Environmental Research Laboratory.

dominance of a single species (silver maple) and generally lower tree species diversity compared to areas without dam. In addition to decreases in species diversity, many of the hydrologic and water quality functions a riverine forest can provide are also altered or eliminated by the presence of dams and levees.

Measuring and Monitoring Methods

The United States Geological Survey operates a series of gauging stations on rivers throughout the US. Historical and real-time data on hydroperiod and characteristics of the watershed for many of these sites are available at http://water.usgs.gov/waterwatch/. Smaller, coastal rivers may not have a gauging station, however, requiring that restoration practitioners implement other methods to collect this information. A variety of manual gauges are commercially available in different lengths and measurement intervals[10]. These can be attached to metal poles driven into the ground. Electronic gauges are also available that can be set up and left in place to continually record water level fluctuation. Thus recording data that might otherwise be missed by manual sampling alone. Monitoring wells can also be constructed for measuring the depth of water below the soil surface. Watermarks on surrounding trees should be used to estimate the depth of flooding events to ensure that the gauge will be visible and accurately measure water level no matter the depth. The gauge can also be surveyed in so that exact elevation and location can be determined. This will allow for maps to be made showing depth and duration of flooding across the floodplain.

Care should also be taken when selecting the placement of gauges and other equipment to be left in the field over extended periods of time because vandals and animals, too, can damage equipment (see Figure 9). Equipment should be placed where it is hidden from the general public to avoid random vandalism but where those taking measurements can still find them. Large animals such as deer may rub on equipment dislodging it and even smaller animals can chew on and damage plastic fixtures. If damage from animals is a persistent problem, monitoring equipment may need to be fenced off for protection.

Hydraulic models may also be useful in riverine forest restoration monitoring as they can be used to predict the timing and depth of flooding in a particular area. This information can be used to select tree species for planting at different elevations along the floodplain during the restoration planning process. It can also be used to predict changes in forest hydrodynamics as the forest matures and characteristics of flow through the system change. This sort of information would be particularly useful in

[10]Measurements are taken from the top of the well to avoid problems related to sedimentation and erosion around the well.

restoration projects that incorporate hydrologic modifications such as the breaching of dikes. The United States Army Corps of Engineers Hydrologic Engineering Center has a variety of software packages and publications available free on-line that may be of use to restoration practitioners. Additional information on the different types and applications of hydrologic modeling and downloading instructions can be found at http://www.hec.usace.army.mil/default.html.

FUNCTIONAL CHARACTERISTICS OF RIVERINE FORESTS

Riverine forests provide a variety of biological and hydrological functions. Many of these functions, such as feeding and breeding grounds for wildlife, temporary floodwater storage, and nutrient cycling are socially and eonomically important. The list of functions commonly attributed to riverine forests presented below has been broken into three categories, Biological, Physical, and Chemical functions. This list includes:

Biological

- Contributes to primary productivity
- Produces wood
- Provides breeding grounds
- Provides feeding grounds
- Provides nursery areas
- Supports a complex trophic structure
- Supports biomass production

Physical

- Affects transport/deposition of suspended/ dissolved material
- Alters turbidity
- Modifies water temperature
- Provides temporary flood water storage

Chemical

- Modifies chemical water quality
- Supports nutrient cycling

Many of the hydrological/physical functions performed by riverine forests are closely linked with primary structural characteristics were more appropriately explained therein. Biological and hydrological/chemical functions are explained below.

BIOLOGICAL

Riverine forests provide seasonal or year-round habitat for a large variety of species. Allen et al. (2001) compiled a list of 101 amphibian, reptile, bird, and mammal species that use early successional stages of southern riverine forests at some stage in their life cycle. As forested areas mature, the diversity of species increases for some time and then decreases as the vegetative associations mature. Some species are found only in early successional habitats while other can only use mature riverine forests (Buffington et al. 2000; Guilfoyle 2001). As noted earlier, a thorough description of all these interactions is beyond the scope of this document. A few examples are provided in the sections below to illustrate specific points but practitioners should make it their responsibility to learn as much as they can about the local resources they are attempting to restore.

Contributes to Primary and Biomass Production and Produces Wood

A variety of structural characteristics influence the primary productivity of riverine forests. Monitoring them will help explain trends observed in productivity measurements particularly when comparing results from a restored area to reference sites. The combination of particulate and dissolved organic matter, fluctuating water levels, and nutrient rich soils (predominantly clay and silt) leads to high primary productivity (as measured by litter fall or wood production) for many riverine forests. Stagnant water can lead to anaerobic soils and cause stress in trees, reducing productivity. Relatively high decomposition rates, except in permanently ponded areas, allows for the quick release of accumulated nutrients back to the soil where they are again available for plant uptake. Accumulated biological waste products and some of the released nutrients are periodically flushed from the area during floods. Ironically, it was this high rate of production that led to the large-scale destruction of riverine forests. Since European settlement, riverine forests have been repeatedly cut over, either selectively for commercially valuable species (e.g., baldcypress and oak) or clear cut so the area may be converted to agricultural production (typically cotton, rice, or soybeans) (Wharton et al. 1982).

Sampling

Some common methods to measure primary productivity include collection of leaf litter and calculation of growth rate from repeated measurements of seedling height or diameter at breast height (DBH) (Brown 1981; Conner and Day 1992; Conner et al. 1997; Keeland et al. 1997). Although not much is known about belowground productivity, some evidence indicates that it is similar in scale to litterfall (Symbula and Day 1988). Methods for measuring belowground biomass production include taking a series of soil cores or placing soil-filled nylon bags in the substrate allowing roots to grow into them (Symbula and Day 1988; Powell and Day 1991). The bags are then retrieved after a specified amount of time and the root content analyzed. Neither of these methods is particularly effective at sampling roots greater than 5 cm in diameter, however, and may actually underestimate total underground productivity. Litterfall, collected over several site visits, can account for approximately 39% of the above ground primary production and can be easily collected (Brown 1981; Conner and Buford 1998). Seedling height is also easily obtained although requires repeated (e.g., weekly) site visits if knowledge of seasonal differences in growth rate is desired. Annual measurements may, however, be acceptable for many restoration monitoring projects. Keeland et al. (1997) provide methods and equations for calculating growth rate from repeated measurements of DBH.

Provides Breeding, Nursery, and Feeding Grounds, and Supports Trophic Structure

Invertebrates

Macroinvertebrates tend to be most prevalent in Zone II and wetter portions of Zone III. Stoneflies (Order Plecoptera), amphipods such as *Hyallella azteca*, worms (Order Oligochaetae), and midges (Family Chironomidae) among other members of the detrital food chain can be extremely abundant in deepwater areas with sufficient accumulations of organic matter (Wharton et al. 1982). Lakly and McArthur (2000) used macroinvertebrates to monitor restoration progress on the Pen Branch Creek, a tributary of the Savannah River after thermal discharges from an upstream nuclear power plant that had severely degraded the riverine forest prior to 1988. Thermal discharges had killed off most of the canopy trees and opened up the stream to direct sunlight, allowing submerged aquatic vegetation (SAV) to grow. A structural shift in the available habitat occurred from one dominated by instream woody debris and allochthonous[11] material to a habitat dominated by SAV and autochthonous[12] production. This fundamental shift in available food sources and instream structure brought about a change in the invertebrate communities found in each portion of the stream. Ten years after thermal discharges had ceased, water temperatures had returned to normal but the overstory canopy in degraded areas had not closed. Along degraded sections, the stream was still exposed to direct sunlight and the differences in instream structure and food web remained unchanged. Differences in invertebrate community also remained unchanged. This highlights the need for monitoring forest restoration projects over an extensive period of time, depending on the particular goals of the project. It will likely take many decades for trees to grow large enough

[11] Allochthanous refers to sources of food that have come from outside of the stream, leaves falling from trees adjacent to the stream, for example.

[12] Autochthanous referes to sources of food that have come from within the stream itself, algae and submersed aquatic vegetation, for example.

to shade the water and provide enough woody debris to the stream to alter the structure of the invertebrate community.

Fish

As many as 53 species of fish such as bowfin (*Amia calva*), gar (*Lepisosteus* spp., Figure 10), and topminnows (*Gambusia* spp.) use riverine forest habitats during flooded conditions as spawning and nursery habitats, as migration routes to upstream spawning areas, or as year round residence. Roughly half of the fishes of the lower Mississippi River use floodplains as nurseries (Wharton et al. 1982). Access to a variety and abundance of new food sources is extremely important to fish, the longer the duration of inundation, the longer fish have to feed in these productive areas (Wharton et al. 1982). Fish depend on annual water level fluctuations of spring flooding and fall drydown to limit intra- and inter-specific competition for food, space, and spawning ground. Fish distribution and abundance are so closely tied to this wet/dry cycle that any change in hydrology (man made or natural) can directly impact the success of fish reproduction (Bruton and Jackson 1983; Hoover and Killgore 1998)

Since fish communities are closely correlated to instream habitat, which is in turn closely related to the riparian zone, fish can be used to monitor the success or failure of riverine forest restoration projects. Paller et al. (2000) compared fish communities in streams of undisturbed riverine forests and streams in areas recovering from thermal pollution (power plant discharges). They compared fish assemblages using nonparametric statistics[13] with an index of biotic integrity (IBI) that measured ecologically sensitive characteristics of fish assemblages. They found that the different techniques provided different information depending on the length of time sampling occurred after restoration of the floodplain. Whereas the IBI could be used in the early stages of recovery to indicate when important aspects of instream structure and function had returned, use of the IBI alone missed information concerning density of individuals (leading to inferences in biomass production) elicited with the nonparametric statistics. Killgore and Hoover (1992) also provide a list of fish species common to riverine forest communities with a breakdown of which life cycle stages are found in channel vs. floodplain habitats that may be of use in designing a sampling strategy.

Figure 10. A spotted gar. Photo from NOAA National Estuarine Research Reserve Collection.

Birds

Southern riverine forests provide habitat for a variety of bird species on a seasonal or year round basis (O'Neal et al. 1992; Guilfoyle 2001). Every fall, neotropical migratory birds forage in southern riverine forests before making the long flight across the Gulf of Mexico to wintering grounds in the Caribbean, Mexico, or Central and South America. When they return in the spring, riverine forests are their first stop to feed and replenish themselves after the long return flight. Nearctic birds use southern forests as a migration destination during the winter. Riverine forests also host a variety of year-round resident birds. During any given season, resident birds may comprise 35–55% of the population (Guilfoyle 2001). Within the mix of migratory and resident species are a number

[13]For description of statistical procedures, see Paller, M. H., M. J. M. Reichert, J. M. Dean and J. C. Seigle. 2000. Use of fish community data to evaluate restoration success of a riparian stream. *Ecological Engineering* 15:S171–S187.

of bird species (approximately 70) completely dependent upon southern riverine habitats to breed (Guilfoyle 2001).

Identification of specific bird species can be a useful means of developing restoration goals and monitoring progress. Particular tree species can be selected for planting that attract certain types of birds, provided the target species is currently found in the general area (i.e., planting to attract bird species that are extinct in an area is not likely to be particularly successful). Gabbe et al. (2002) found that certain tree species were preferred by insectivorous birds and that tree species composition is an important attribute to plan for and monitor if restoration of particular bird species is a project goal. They also found that most restoration projects were deficient in properly planning for this diversity and were often lacking in heavy-seeded tree species and/or commercially non-valuable species such as silver maple (*Acer saccharinum*, Figure 11) that are particularly valuable to birds.

There is, however, a weakness with using birds to monitor specific restoration projects. Birds must also use resources outside of a particular wetland area. They are, therefore, susceptible to negative impacts in the other habitats they use. Galatowistch et al. (1998-1999) found that bird-related metrics such as proportion of wetland birds, wetland bird richness, and proportion of insectivorous birds showed consistent relationships to land cover types regardless of the scale of assessment. They concluded that bird-related metrics are better suited to studies at the landscape-scale and if used to monitor a local restoration project, need to be used with caution.

When developing a restoration-monitoring plan, one should consider that the structural aspects of riverine forests influence how the forest as a whole is used by individual species. Specifically, since hydrology and elevation strongly influence the structural habitat (i.e., dominant vegetation) creating the different zones within these systems, hydrology, as well as seasonality, has an influence on what bird species are present within any given zone (Guilfoyle 2001). Any perceived changes in bird community could therefore be a result of seasonality or annual variations in climate, flood regime, vegetation zonation, and/or the success or failure of restoration efforts. In addition, it may take up to 60 years after restoration efforts have begun to measure any change in avian community, particularly for those species dependent on mature forested systems (Buffington et al. 2000; Guilfoyle 2001). This also applies to other wildlife such as fish, amphibians, and reptiles that are also dependent on mature riverine forest habitats (Bowers et al. 2000).

Figure 11. A leaf from a silver maple, a common riverine forest tree species that provides abundant seeds eaten by migratory birds and other wildlife. Photo by David Merkey, NOAA/Great Lakes Environmental Research Laboratory.

Mammals

Riverine forests are home to a variety of mammal species, many of which browse on or uproot seedlings and planted trees. The animals most likely to cause damage include white-tailed deer (*Odocoileus virginianus*), raccoons (*Procyon lotor*), beaver (*Castor canadensis*) and other small rodents, and hogs (*Sus scrota*) (Allen et al. 2001). Use of small, native mammals to monitor restoration activities at local scales (Pen Branch Creek of the Savannah River Site) has been tried and proven unsuccessful, possibly due to the large ranges some small animals are able to cover and the diversity of habitats they may traverse to get from one area to another (Wike et al. 2000). It is possible that on larger scales, native mammals may still be useful for restoration monitoring. However, sufficient research has not yet been conducted. It is advisable, at this point, to limit monitoring of mammals to presence/absence of particular species depending on the goals of the restoration effort and to assessing and minimizing herbivore damage to planted trees.

PHYSICAL

The main physical functions performed by riverine forests (i.e. transport of suspended/dissolved material, alteration of turbidity, modification of water temperature, and temporary flood water storage) have been described in the associated structural characteristics above.

CHEMICAL

Modifies Water Quality and Supports Nutrient Cycling

The alternating cycle of aerobic and anaerobic soil conditions brought about by seasonal flooding patterns allows several biochemical and nutrient cycling processes such as nitrification, denitrification, ammonification, methanogenesis, sulfate reduction, and general nutrient mineralization to take place in riverine forests that do not occur in upland forests (Wharton et al. 1982). These biochemical processes either increase nutrient availability for immediate uptake by plants within the forest or transform nutrients to biologically inactive forms. Downstream water quality is preserved in either case, as long as anthropogenic inputs do not overwhelm the system. Nitrate (NO_3) in the water column or soil, for example, can be taken up by plants, converted to nitrite (NO_2) by microbes, or bound to sediments (Walbridge 1993). These processes are also influenced by hydrology. The longer the residence time of water, the more time microbes and plants have to transform nutrients.

Riverine forests often act as sinks for phosphorus (P) (Winger 1986). When phosphorus enters the riverine forest with floodwater it is adsorbed to sediments or taken up by plants. Phosphorus is returned to the forest floor when leaves fall and quickly decomposed. Under aerobic conditions, phosphorus is bound to the sediments. Under anaerobic conditions, phosphorus is soluble and is again taken up by roots of other plants during the growing season or by green algae growing in floodplain pools during winter (Winger 1986; Walbridge 1993; Lockaby and Walbridge 1998). Although large flows may move some phosphorus downstream, it is generally believed that most phosphorus is held within the forested floodplain.

The ability of riverine forests to act as nutrient transformers and preserve downstream water quality, within limits, may be their most valuable function to society (Walbridge 1993). It is, however, only when floodwaters are able to flow out into the riverine forests that the nutrient transformation and sediment trapping function of these wetland systems can occur. When riverine forests are isolated from the river channel by a constructed levee system, the nutrient transformation function is disrupted and excess nutrients and sediments are carried downstream and eventually to the coast. Restoration of riverine forests could contribute greatly to the preservation and restoration of coastal water quality. It has been suggested that restoring riverine forests throughout the Mississippi alluvial valley and tributaries could be used to improve the water quality of the Gulf of Mexico, lessening the extent and severity of the hypoxic zone off the coast of Louisiana (Mitsch et al. 2001).

PARAMETERS FOR MONITORING STRUCTURAL/FUNCTIONAL CHARACTERISTICS

The matrices of structural and functional parameters for restoration monitoring featured on the following pages were developed through extensive review of restoration and ecological monitoring-related literature. Additional input was received from recognized experts in the field of riverine forest ecology. This listing of parameters is not exhaustive, it is merely intended as a starting point to help restoration practitioners develop monitoring plans for this habitat. Additional parameters not in this list may also be appropriate for restoration monitoring efforts. Parameters with a closed circle (●) are those that, at the minimum, should be considered in monitoring restoration progress. Parameters with an open circle (❍) may also be monitored depending on specific restoration goals. Information on why these parameters are important for monitoring and how they relate to structural and functional characteristics as well as to one another is found throughout the text. Literature directing readers toward additional information on the ecology of riverine forests, restoration case studies, and sampling strategies and techniques can be found in the *Annotated Bibliography of Riverine Forests* and the associated *Review of Technical Methods Manuals*.

Parameters to Monitor the Structural Characteristics of Riverine Forests

Parameters to Monitor	Biological	Physical		Hydrological	
	Habitat created by plants	Sediment grain size	Topography/Bathymetry	Tides/Hydroperiod	Water sources
Geographical					
Acreage of habitat types	●				
Biological					
Plants					
Species, composition, and % cover of:					
Herbaceous vascular	❍				
Woody	●				
Basal area	❍				
Canopy aerial extent and structure	❍				
Plant height	❍				
Seedling survival	●				
Stem density	●				
Woody debris (root masses, stumps, logs)	❍		❍		
Hydrological					
Physical					
Temporary water				❍	
Temperature				❍	❍
Upstream land use					●
Water level fluctuation over time				●	●
Chemical					
Groundwater indicator chemicals[14]					❍
Nitrogen and phosphorus					
Toxics					
Soil/Sediment					
Physical					
Basin elevations			❍		
Bulk density		❍			
Depth of mottling				❍	
Geomorphology (slope, basin cross section)			●	●	
Moisture levels and drainage				❍	
Organic content		❍		❍	
Percent sand, silt, and clay		❍			
Sedimentation rate and quality		❍	❍	❍	

[14]Calcium and magnesium.

Parameters to Monitor the Functional Characteristics of Riverine Forests

Parameters to Monitor	Biological: Contributes primary production	Biological: Produces wood	Biological: Provides breeding grounds	Biological: Provides feeding grounds	Biological: Provides nursery areas	Biological: Supports a complex trophic structure	Biological: Supports biomass production	Physical: Affects transport of suspended/ dissolved material	Physical: Alters turbidity	Physical: Modifies water temperature	Physical: Provides temporary floodwater storage	Chemical: Modifies chemical water quality	Chemical: Supports nutrient cycling
Geographical													
Acreage of habitat types	●	●	●	●	●	●	●	●	●	●	●	●	●
Biological													
Plants													
Species, composition, and % cover of:													
Herbaceous vascular	❍		❍	❍	❍	❍	❍	❍	❍	❍		❍	❍
Invasives			❍	❍	❍	❍							
Woody	●	●	●	●	●	●	●	●	●	●	●		●
Basal area	❍	❍					❍						
Canopy aerial extent and structure			❍		❍		❍			❍			
Interspersion of habitat types			❍	❍	❍	❍	❍	❍	❍	❍	❍	❍	❍
Litter fall	❍			❍		❍	❍		❍				❍
Mast/seed production	❍			❍			❍						
Plant health (herbivory damage, disease[15])				❍									
Plant height	❍					❍	❍			❍			
Rate of canopy closure	❍	❍					❍			❍			
Seedling survival[15]		●											
Stem density					❍	❍		❍	❍	❍			
Woody debris (root masses, stumps, logs)		❍	❍	❍	❍	❍		❍					

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Parameters to Monitor the Functional Characteristics of Riverine Forests (cont.)

Parameters to Monitor	Biological: Contributes primary production	Produces wood	Provides breeding grounds	Provides feeding grounds	Provides nursery areas	Supports a complex trophic structure	Supports biomass production	Physical: Affects transport of suspended/dissolved material	Alters turbidity	Modifies water temperature	Provides temporary floodwater storage	Chemical: Modifies chemical water quality	Supports nutrient cycling
Biological													
Animals													
Species, composition, and abundance of:													
Amphibians			❍	❍	❍	❍	❍						
Birds			❍	❍	❍	❍	❍					❍	
Invertebrates			❍	❍	❍	❍	❍						
Mammals			❍	❍	❍	❍	❍						
Reptiles			❍	❍	❍	❍	❍						
Hydrological													
Physical													
PAR[16]	❍						❍	❍	❍				
Secchi disc depth	❍						❍	❍	❍				
Sheet flow								❍	❍		❍	❍	❍
Temperature			❍		❍					❍		❍	
Temporary water			❍	❍	❍	❍					❍	❍	❍
Trash				❍				❍	❍			❍	
Upstream land use								●	●			●	
Water level fluctuation over time			●	●	●			●	●		●		●
Chemical													
Nitrogen and phosphorus	❍						❍		❍			❍	❍
Toxics			❍	❍	❍							❍	

[16] PAR - Photosynthetically active radiation.

Parameters to Monitor the Functional Characteristics of Riverine Forests (cont.)

Parameters to Monitor	Biological							Physical				Chemical	
	Contributes primary production	Produces wood	Provides breeding grounds	Provides feeding grounds	Provides nursery areas	Supports a complex trophic structure	Supports biomass production	Affects transport of suspended/dissolved material	Alters turbidity	Modifies water temperature	Provides temporary floodwater storage	Modifies chemical water quality	Supports nutrient cycling
Soil/Sediment													
Physical													
Bulk density							❍						❍
Depth of mottling							❍				❍		❍
Geomorphology (slope, basin cross section)			●	●	●			●	●	●	●	●	
Moisture levels and drainage							❍				❍		❍
Sediment grain size (OM[17]/sand/silt/clay/gravel/cobble)							❍	❍	❍			❍	❍
Sedimentation rate and quality								❍	❍				
Chemical													
Organic content in sediment				❍		❍	❍	❍	❍			❍	❍
Pore water nitrogen and phosphorus	❍						❍					❍	❍
Redox potential							❍					❍	❍

[17] Organic matter

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APPENDIX I: RIVERINE FORESTS ANNOTATED BIBLIOGRAPHY

This annotated bibliography contains summaries of restoration case studies and basic ecological literature. It is designed to provide restoration practitioners with examples of previous restoration projects as well as overviews of papers from the ecological literature that offer more detail than that covered in the associated chapter. Entries are presented from both peer reviewed and grey literature. They were selected through extensive literature and Internet searches as well as input from reviewers. They are not, however, a complete listing of all of the available literature. Entries are arranged alphabetically by author. Wherever possible, web addresses or other contact information has been included in the reference to assist readers in easily obtaining the original resource. Summaries preceded by the terms 'Author Abstract', 'Publisher Introduction', or similar descriptors were taken directly from their original source. Summaries without such descriptors were written by the authors of the associated chapter.

Allen, J. A. 1990. Establishment of bottomland oak plantations on the Yazoo National Wildlife Refuge complex. *Southern Journal of Applied Forestry* 14:206-210.

This paper reviews a study of the survival and growth rate of trees planted during 10 riverine forest restoration projects on abandoned agricultural fields by the U. S. Fish and Wildlife Service. The restoration sites were all within the Yazoo National Wildlife Refuge Complex located on the Mississippi-Yazoo Rivers alluvial plain in west-central Mississippi. Stands varied in age from 4-8 years after planting. Planted material at each site consisted of either locally collected acorns or 1-0 bare root nursery stock. Five species of oak were typically planted: cherrybark (*Quercus pagoda*), Nuttall (*Q. nuttallii*), Shumard (*Q. shumardii*), water (*Q. nigra*), and willow (*Q. phellos*). Oaks were selected under the assumption that such heavy seeded tree species would be slow to colonize agricultural fields, whereas lighter seeded trees such as American elm (*Ulmus americana*) and green ash (*Fraxinus pennsylvanica*) would more readily establish themselves naturally across a restoration site if a local seed source was available.

A variety of methods were employed to test the affect of controlling competition on young seedlings. Sites were either burned, treated with herbicide, or bushhogged, and some sites were left untreated as controls. However, any impact competition may have had on the survivorship of seedlings was masked by a drought. Even seedlings in areas with vegetation control measures in place showed high mortality when water tables dropped below 12 inches.

Growth rate was compared between trees planted from nursery stock and those planted as acorns in the field. Diameter at breast height (DBH) and overall tree height were greater for the areas planted with nursery stock seedlings.

Natural invasion of other tree and shrub species was also studied. Where large, mature stands of light seeded trees were present near restoration sites, the number of volunteer trees and shrubs outnumbered planted trees. Volunteer species were typically from light seeded species including American elm, green ash, and sweetgum (*Liquidambar styraciflua*).

The monitoring studies used the measures of species presence, survivorship, and growth rate (DBH and total tree height). Using the results from these studies, the author concluded that even just 4 to 8 years after planting, all the restoration efforts were developing diverse vegetation communities capable of becoming fully functioning riverine forests.

Buffington, J. M., J. C. Kilgo, R. A. Sargent, K. V. Miller and B. R. Chapman. 2000. Effects of restoration techniques on breeding birds in a thermally-impacted bottomland hardwood forest. Ecological Engineering 15:S115-S120.

Author Abstract. We evaluated the effects of revegetation techniques on breeding bird communities in a riverine hardwood forest impacted by thermal effluent. In 1993, sections of the Pen Branch riverine on the Savannah River Site, South Carolina, were herbicide-treated (glyphosate), burned, and planted; other sections were planted only while others were unaltered and served as controls. Few differences in the avian community occurred at 1 and 2 years post-treatment among treatments. Plots that were herbicide-treated, burned, and planted had greater species richness in 1994 and abundance in 1995 than sections that were planted only (*P*B0.05). Bird species composition differed slightly among treatments and White-eyed Vireos (*Vireo griseus*), Common Yellowthroats (*Geothlypis trichas*), Indigo Buntings (*Passerina cyanea*), and Red-winged Blackbirds (*Agelaius phoeniceus*) were the most abundant species in the corridor. Revegetation techniques used to restore this thermally-impacted riverine had little effect on the avian communities 1 and 2 years post-treatment.

Clewell, A. F. 1999. Restoration of riverine forest at Hall Branch on phosphate-mined land, Florida. Restoration Ecology 7:1-14.

Author Abstract. I describe a 1.5-ha riverine headwater forest (Hall Branch) that was created 11 years earlier on phosphate-mined and reclaimed land near Tampa, Florida, U.S.A. Favorable hydrologic and edaphic conditions were realized, owing to the proper positioning of the project site in an effectively reclaimed landscape. The soil had developed a distinct A horizon and an incipient B horizon. Planted trees, mainly species of *Acer, Fraxinus, Ilex, Liquidambar, Magnolia, Persea, Quercus, Taxodium*, and *Ulmus*, shared dominance with short-lived volunteer willows (*Salix caroliniana*) that had already begun to senesce. The tree canopy exhibited 85 cover, and some trees had grown to 12.5 m tall. Basal area reached 8.31 m^2/ha for trees 10 cm or more in diameter at breast height. Ten planted tree species produced seeds and yielded seedlings. The floristic composition over the decade consisted of 22 species of trees and 208 shrubs, vines, epiphytes, ferns, graminoids, and forbs. Thirty-eight non-arboreal species were directly transplanted, others arose from a seed bank in muck that was amended on wetter sites, and the rest volunteered via natural dissemination. The frequency of non-arboreal plants was collectively 98. Seventy-three species at the restoration site were characteristic of the mature, undisturbed reference ecosystem. A corresponding area within the reference ecosystem contained essentially the same number of species and the same array of life forms. Copious plant reproduction has transformed the planted forest into an intact ecosystem that no longer needs restoration assistance.

Clewell, A. F. and R. Lea. 1990. Creation and restoration of forested wetland vegetation in the southeastern United States, p. 195-231. In Kusler, J. A. and M. E. Kentula (eds.), Wetland Creation and Restoration: the Status of the Science. Island Press, Washington, D.C.

Author Abstract. This chapter describes forested wetland creation and restoration project experience and establishment methods in the region from Virginia to Arkansas south to Florida and Louisiana. In contrast to marshes, forest replacement is more complex and requires a much longer development period. A wide variety of forest establishment techniques have been employed, some with initial success but none of them proven. Most projects began during the 1980's and are too new for critical evaluation. Most of these projects pertain to bottomland hardwood and cypress replacement. The two most significant trends in project activity have been the direct seeding of oaks on abandoned croplands and the replacement of all trees and sometimes the undergrowth at reclaimed surface mines. Although some young projects appear promising in terms of species composition and structure, it is still too early to assess functional equivalency.

Project success depends largely on judicious planning and careful execution. The most critical factor for all projects is to achieve adequate hydrological conditions. Other important factors may include substrate stability, availability of adequate soil rooting volume and fertility, and the control of herbivores and competitive weeds. A checklist of these and other important issues is appended for the benefit of personnel who prepare project plans and review permit applications.

Success criteria for evaluating extant projects throughout the southeast are either inadequately conceived or usually lacking. Emphasis needs to be placed upon the presence of preferred species (i.e., indigenous trees and undergrowth characteristic of mature stands of the community being replaced) and on the attainment of a threshold density of trees that are at least 2 meters tall. Once such a stand of trees is attained, survival is virtually assured and little else could be done that would further expedite project success. At that point, release from regulatory liability should be seriously considered.

A list of several critical information gaps concerning bottomland restoration in the southeast is also provided and discussed.

Haynes, R. J., J. A. Allen and E. C. Pendleton. 1988. Reestablishment of bottomland hardwood forests on disturbed sites: An annotated bibliography, pp. 104. Biological Report 88(42), U.S. Fish and Wildlife Service.

This annotated bibliography was prepared for people interested in bottomland forest restoration on previously disturbed land such as abandoned or flood-prone agricultural land, surface-mined land, and other areas degraded by alterations in hydrology or vegetative cover. Though prepared in 1988 and thus does not represent the most up to date information, it does list or review over 400 documents relating to bottomland forests or their restoration. References containing information that is directly applicable to bottomland restoration are annotated while many others relating to hydrology, plant propagation, and various plant communities and individual species just listed. Two appendixes are included listing common and scientific names for bottomland forest species and a table of flooding, shade tolerance, and reproductive characteristics of some bottomland forest species.

Johns, D. T., B. Williams, H. M. Williams and M. Stroupe. 1999. Seedling survival and natural regeneration for a riverine hardwood planting on sites differing in site preparation. Tenth Biennial Southern Silvicultural Research Conference. Shreveport, LA. http://www.srs.fs.fed.us/pubs/viewpub.jsp?index=2190

Three pine plantations in the first bottom of Village Creek on the Roy E. Larson Sandylands Preserve in Hardin County, Texas were clear cut and replanted with riverine hardwood species. Three different methods were used to prepare the sites for planting. One was burned, another was treated with herbicide, and the third was sheared, piled, burned, and ripped. Initial seedling density was recorded and survival was monitored monthly to assess which method had the greatest impact on planting success. Nested plots were measured for species composition and relative density of dominant species before clear cutting took place to assess initial community structure. Species composition and percent area cover of herbaceous plants, percent bare ground, and percent debris were also measured. The site that was sheared, piled, burned, and ripped had the highest initial density and survivorship. This was attributed to the beneficial affect of ripping on seedling establishment and burning to control Chinese tallow (*Sapium sebiferum*) and invasive exotic species that otherwise out competes the native species planted. The sites that were burned or treated with herbicide also had low occurrence of Chinese tallow but had low survivorship of seedlings, possibly due to the difficulty of properly planting seedlings without ripping. This project illustrates the necessity of proper pre-planting site preparation and control of exotic species to increase the survivorship of seedlings in reaching restoration goals.

King, S. L. and B. D. Keeland. 1999. Evaluation of reforestation in the Lower Mississippi River alluvial valley. *Restoration Ecology* 7:348-359.

Author Abstract. Only about 2.8 million ha of an estimated original 10 million ha of bottomland hardwood forests still exist in the Lower Mississippi River Alluvial Valley (LMAV) of the United States. The U.S. Fish and Wildlife Service, the U.S. Forest Service, and state agencies initiated reforestation efforts in the late 1980s to improve wildlife habitat. We surveyed reforestations responsible for reforestation in the LMAV to determine the magnitude of past and future efforts and to identify major limiting factors. Over the past 10 years, 77,698 ha have been reforested by the agencies represented in our survey and an additional 89,009 ha are targeted in the next 5 years. Oaks are the most commonly planted species and bare-root seedlings are the most commonly used planting stock. Problems with seedling availability may increase the diversity of plantings in the future. Reforestation in the LMAV is based upon principles of landscape ecology; however, local problems such as herbivory, drought, and flooding often limit success. Broad-scale hydrologic restoration is needed to fully restore the structural and functional attributes of these systems, but because of drastic and widespread hydrologic alterations and socioeconomic constraints, this goal is generally not realistic. Local hydrologic restoration and creation of specific habitat features needed by some wildlife and fish species warrant attention. More extensive analyses of plantings are needed to evaluate functional success. The Wetland Reserve Program is a positive development, but policies that provide additional financial incentives to landowners for reforestation efforts should be seriously considered.

Kolka, R. K., C. C. Trettin, E. A. Nelson and W. H. Conner. 1998. Tree seedlings establishment across a hydrologic gradient in a bottomland restoration. pp. 89-102. The Twenty Fifth Annual Conference on Ecosystems Restoration and Creation.

Author Abstract. Seedling establishment and survival on the Savannah River Site in South Carolina is being monitored as part of the Pen Branch Bottomland Restoration Project. Bottomland tree species were planted from 1993-1995 across a hydrologic gradient encompassing the drier upper floodplain corridor, the lower floodplain corridor and the continuously inundated delta. Twelve species were planted in the three areas based on their flood tolerance and the hydrology of the area. Planted areas are separated with unplanted control strips to assess natural regeneration. A seedling survey conducted in 1997 showed that planted areas had significantly greater seedling densities than unplanted control sections. Water tupelo (*Nyssa aquatica*), green ash (*Fraxinus pennsylvanica*), sycamore (*Platanus occidentalis*), and persimmon (*Diospyros virginiana*) had the highest percent survival in the upper corridor while baldcypress (*Tarodium distichum*) had the best survival in the wetter lower corridor and delta. Water tupelo and green ash survival was low in wetter areas. Survival of planted species is dependent on hydrology, competition and herbivory although it is not possible to differentiate these effects from the available data.

Lakly, M. B. and J. McArthur. 2000. Macroinvertebrate recovery of a post-thermal stream: habitat structure and biotic function. *Ecological Engineering* 15:S87-S100.

This study was conducted on the Pen Branch of the Savannah River as part of a series of tested methods to assess the progress of restoration efforts.

Author Abstract. Macroinvertebrate faunal assemblages, organic matter availability and instream structural complexity were investigated in three systems to determine the current state of recovery of a post-thermal stream. The abundance and diversity of the lower foodchain community has recovered substantially since cessation of thermal flows in 1988; however, the biotic communities remain structurally and functionally distinct as a result of past thermal perturbation. Disparate instream habitat structural components and stream physical changes in the post-thermal and reference systems drive functional differences in the macroinvertebrate community. The post-thermal stream is physically and biologically structured by high densities of aquatic macrophytes while the reference system is driven by high concentrations of coarse woody debris. Consequently, the abundant, diverse macroinvertebrate communities in both systems illustrate a post-thermal shift in energy source from a reliance on allochthonous to autochthonous inputs. Biotic indices such as taxa richness, a family level index and similarity index may not be sufficient to determine functional changes as a result of thermal impacts. However, the distribution of diverse functional feeding groups across streams was successful at characterizing divergence in resource utilization and processing. This distinction between macroinvertebrates' abundance and diversity, and their function in the ecosystem is essential in establishing relevant mitigation plans and endpoints for stream restoration.

McLeod, K. W., M. R. Reed and L. D. Wike. 2000. Elevation, competition control, and species affect bottomland forest restoration. *Wetlands* 20:162-168.

Author abstract. This experiment examined how elevation and control of early successional vegetation would affect the growth and survival of tree species used in restoration. Vegetation was controlled by mowing or spraying with Accord [glyphosate, (phosphononomethyl) glycine in the form of its isopropylamine salt] herbicide. These control methods were applied to either the entire plot or a narrow 1-m strip where seedlings were to be planted. A fifth treatment (control) had seedlings planted into the existing vegetation. Species planted were baldcypress (*Taxodium distichum*), water tupelo (*Nyssa aquatica*), willow oak (*Quercus phellos*), nuttall oak (*Q. nuttallii*), overcup oak (*Q. lyrata*), and cherrybark oak (*Q. falcata* var. *pagodaefolia*). Seedlings were randomly planted in late April 1993 with six rows in each plot and six trees per row on a 2 x 2 m spacing with five replicate plots per treatment. Survival was not enhanced by any competition control treatment, but survival among species differed. All six species had overall survival > 90% in autumn 1993. Species' survival was affected by several summer floods during 1994. Baldcypress and overcup oak survival was greater than 89%, while water tupelo, nuttall oak, and willow oak were all approximately 70%, and cherrybark oak was only 29%. By the end of 1995, survival of all species decreased further, but the species groupings remained the same. Survival and height growth of baldcypress and water tupelo were greatest at lower planting elevations. At higher elevations, survival of cherrybark oak and willow oak were greatest, while overcup oak and Nuttall oak were unaffected by elevation. Thus, controlling the herbaceous vegetation did not affect survival or growth as much as relative planting elevation due to site flooding and the flood tolerance of the species. All of the species in this experiment except cherrybark oak were successfully established.

Nelson, E. A., N. C. Dulohery, R. K. Kolka and W. H. McKee, Jr. 2000. Operational **restoration** of the Pen Branch bottomland hardwood and swamp wetlands - the research setting. *Ecological Engineering* 15:S23–S33.

The Savannah River swamp, a 3020 ha forested wetland on the floodplain of the Savannah River, USA is located on the Department of Energy's Savannah River site (SRS) near Aiken, SC. Historically, the swamp consisted of approximately 50% bald cypress–water tupelo (*Taxodium distichum–Nyssa aquatica*) stands, 40% mixed bottomland hardwood stands, and 10% shrub, marsh, and open water. Creek corridors were typical of southeastern bottomland hardwood forests. Hydrology was controlled by flooding of the Savannah River and by flow from four creeks that drain into the swamp prior to flow into the Savannah River. Upstream dams have caused some alteration of the water levels and timing of flooding within the floodplain. Major impacts to the swamp hydrology occurred with the completion of the production reactors and one coal-fired powerhouse at the SRS in the early 1950s. Flow in one of the tributaries, Pen Branch, was typically 0.3 $m^3 s^{-1}$ (10–20 cfs) prior to reactor pumping and 11.0 $m^3 s^{-1}$ (400 cfs) during pumping from 1954 to 1988. Sustained increases in water volume resulted in overflow of the original stream banks, the creation of additional floodplains, considerable erosion of the original stream corridor, and deposition of a deep silt layer on the newly formed delta. Heated water was discharged directly into Pen Branch and water temperature in the stream often exceeded 65°C. The nearly continuous flooding of the swamp, the thermal load of the water, and the heavy silting resulted in complete mortality of the original vegetation in large areas of the floodplain. In the years since pumping was reduced, no volunteer seedlings of heavy-seeded hardwoods or cypress have been found in the floodplain corridor. Research was conducted to determine methods to reintroduce tree species characteristic of more mature forested wetlands. Species composition and selection were altered based on the current and expected hydrological regimes that the reforestation areas will be experiencing.

Paller, M. H., M. J. M. Reichert, J. M. Dean and J. C. Seigle. 2000. Use of fish community data to evaluate restoration success of a riparian stream. *Ecological Engineering* 15: S171–S187.

Author Abstract. From 1985 to 1988, stream and riparian habitats in Pen Branch and Four Mile branch began recovering from deforestation caused by the previous release of hot water from nuclear reactors. The Pen Branch corridor was replanted with wetland trees in 1995 to expedite recovery and restore the Pen branch ecosystem. Pen branch, Four Mile branch, and two relatively undisturbed streams were electrofished in 1995:1996 to determine how fish assemblages differed between the previously disturbed and undisturbed streams and whether such difference could be used to measure restoration success in

Pen branch. Fish assemblages were analyzed using nonparametric multivariate statistical methods and the index of biotic integrity (IBI), a bioassessment method based on measurement of ecologically sensitive characteristics of fish assemblages. Many aspects of fish assemblage structure (e.g. species richness, disease incidence, taxonomic composition at the family level) did not differ between disturbed and undisturbed streams; however, disturbed streams had higher densities of a number of species. These differences were successfully detected with the multivariate statistical methods; whereas, the IBI did not differ between most recovering and undisturbed sampling sites. Because fish assemblages are strongly influenced by instream habitat, and because instream habitat is strongly influenced by the riparian zone, fish assemblages can be used to measure restoration success. Nonparametric ordination methods may provide the most sensitive measure of progress towards restoration goals, although the IBI can be used during early stages of recovery to indicate when certain ecologically important aspects of structure and function in recovering streams have reached levels typical of undisturbed streams.

Schweitzer, C. J., E. S. Gardiner, J. A. Stanturf and A. W. Ezell. 1999. Methods to improve establishment and growth of bottomland hardwood artificial regeneration, 293 pp. 12th Central Hardwood Forest Conference. Lexington, KY.

Author Abstract. With ongoing attempts to reforest both cut-over and abandoned agricultural land in the lower Mississippi alluvial plain, it has become evident that there exists a need for an efficient regeneration system that makes biological and economic sense. Also, there is a need to address how to minimize competition from invading weeds, to deter predation by small mammals, and to achieve adequate tree establishment. This study was designed as a randomized complete block experiment with treatments arranged as factors (3 species X 2 levels of protection X 4 weed control treatments) with three replications to assess efficacy of seedling protection and weed control to improve seedling growth and survival. The study was conducted on a cleared area in the Delta Experimental Forest, Stoneville, MS. Three tree species, nuttall oak (*Quercus nuttallii* Palmer), green ash (*Fraxinus pennsylvanica* Marsh.), and persimmon (*Diospyros virginia* L) were planted as 1-0 bareroot seedlings in March 1997. Each treatment plot had 25 seedlings, spaced at 0.75 meters X 0.75 meters. Shelter protection was installed on half of the seedlings. Shelters were 1-meter tall, 15-centimeter diameter plastic tree shelters. Each shelter treatment (with or without shelter) received one of four weed control treatments: mechanical mowing (gas-powered weed tilter), fabric mat (woven, black polypropylene material), chemical herbicide (Oust, suffometurcin-rnethyl at 210 grams per hectare), or undisturbed (control). Response of shelters and weed control treatments on seedling survival, height and diameter were followed for one growing season. Seedlings in shelters had greater survival (98 percent) than seedlings without shelters (93 percent). For all three species, height growth was significantly greater for sheltered seedlings (43 centimeters) compared to unsheltered seedlings (15 centimeters). For the unsheltered seedlings, fabric mat weed control increased survival relative to chemical weed control. All seedlings had significantly greater height and diameter growth under the fabric mat weed control compared to growth under the other treatments except for unsheltered oak seedlings.

Stanturf, J. A., E. S. Gardiner, P. B. Hamel, M. S. Devall, T. D. Leininger and M. E. Warren, Jr. 2000. Restoring bottomland hardwood ecosystems in the lower Mississippi alluvial valley. *Journal of Forestry* 98:10-16.

This article offers a critique of several federal programs that are currently used to restore southern bottomland hardwood forests to the floodplains of the Mississippi River. The article explains that several techniques successfully used on federal land are now being applied to private holdings. However, some of the techniques and assumptions used on public land may be inappropriate when applied to smaller, private holdings. These are explained and adaptations to existing programs are offered.

The article also offers a few site-specific techniques for increasing the efficiency and success of bottomland forest restorations. Advise on site preparation, seed handling and storage, and methods to prevent herbivory are among the suggestions. A comparison of costs per acre of each of the different restoration practices is given. The article closes with comments on the future directions and limitations of bottomland forest restoration.

Stanturf, J. A., S. H. Schoenholtz, C. J. Schweitzer and J. P. Shepard. 2001. Achieving restoration success: myths in bottomland hardwood forests. *Restoration Ecology* 9:189-200.

This paper presents the ecological and sociopolitical context of ecological restoration of bottomland forests and discusses nine commonly held misconceptions (the authors use the term 'myths') about it. The nine myths and talking points include:

1. Afforestation is not the same as restoration - the authors stipulate that afforestation is a critical first step in almost every restoration effort.
2. Restoration is easy, anyone can do it - a successful ecological restoration requires selection of the proper plant species and planting techniques for the site. Successful restorations require that a variety of environmental variables be taken into consideration as well as a plan for post-restoration monitoring. These abilities are not often held by the general public.
3. Desired future condition can be specified - though setting restoration goals is important, there are several potential problems with the use of reference sites or historical conditions.
4. The same strategy is appropriate to all ownerships - successful techniques useful in restoring small plots may not be economical when applied to larger scale restorations. Larger scale restorations can manipulate and take advantage of off-site conditions that smaller projects cannot.
5. Plantations have no wildlife value - though not as valuable as ecological restorations with more species diversity, plantations can offer some wildlife benefits, particularly to migratory birds.
6. Understocked stands are sufficient - two common restoration goals are canopy closure and regaining vertical structure, understocked restoration projects (though less expensive in the short-term) will take longer to achieve those goals.
7. Preservation is the only valid goal - site conditions may be present which prevent a fully functioning forest from developing on the site, in these situations active management (i.e. restoration) must be carried out.
8. Ecological and economic goals are incompatible - depending on the goals of restoration and management of bottomland forests, forests can provide wildlife and other benefits while providing income from harvesting or other activities.
9. Restoration can proceed without management - restoration produces the maximum benefits only when sites are monitored and managed over time.

Twedt, D. J., R. R. Wilson, J. L. Henne-Kerr and D. A. Grosshuesch. 2002. Avian response to bottomland hardwood reforestation: the first 10 years. *Restoration Ecology* 10:645-655.

Author Abstract. Riverine hardwood forests were planted on agricultural fields in Mississippi and Louisiana predominantly using either *Quercus* species (oaks) or *Populus deltoides* (eastern cottonwood). We assessed avian colonization of these reforested sites between 2 and 10 years after planting. Rapid vertical growth of cottonwoods (circa 2-3 m/year) resulted in sites with forest structure that supported greater species richness of breeding birds, increased Shannon diversity indices, and supported greater territory densities than on sites planted with slower-growing oak species. Grassland birds (*Spiza americana* [Dickcissel] and *Sturnella magna* [Eastern Meadowlark]) were indicative of species breeding on oak-dominated reforestation no more than 10 years old. *Agelaius phoeniceus* (Red-winged Blackbird) and *Colinus virginianus* (Northern Bobwhite) characterized cottonwood reforestation no more than 4 years old, whereas 14 species of shrub-scrub birds (e.g., *Passerina cyanea* [Indigo Bunting]) and early-successional forest birds (e.g., Vireo gilvus[Warbling vireo]) typified cottonwood reforestation 5 to 9 years after planting. Rates of daily nest survival did not differ between reforestation strategies. Nest parasitism increased markedly in older cottonwood stands but was overwhelmed by predation as a cause of nest failure. Based on Partners in Flight prioritization scores and territory densities, the value of cottonwood reforestation for avian conservation was significantly greater than that of oak reforestation during their first 10 years. Because of benefits conferred on breeding birds, we recommend reforestation of riverine hardwoods should include a high proportion of fast-growing early successional species such as cottonwood.

Wharton, C. H., W. M. Kitchens, E. C. Pendleton and T. W. Snipe. 1982. The ecology of bottomland hardwood swamps of the Southeast: a community profile, 133 pp. FWS/OBS-81/37, U.S. Fish and Wildlife Service, Biological Services Program, Washington, DC.

Author Abstract. This report is one in a series of community profiles whose objective is to synthesize extant literature for specific wetland habitats into definitive, yet handy ecological references. To the extent possible, the geographic scope of this profile is focused on bottomland hardwood swamps occupying the riverine floodplains of the Southeast whose drainage originates in the Appalachian Mountains/ Piedmont or Coastal Plain. References are occasionally made to studies outside this area, primarily for comparative purposes or to highlight important points. The sections detailing the plant associations and soils in the study area are derived from field investigations conducted specifically for this project.

In order to explain the complexities of the ecological relationships that are operating in these bottomland hardwood ecosystems, this report details not only the biology of floodplains but also the geomorphology and hydrological components and processes that are operating on various scales. These factors, in concert with the biota, dictate both the ecological structure and function of the bottomland hardwood ecosystems. We have utilized the ecological zone concept developed by the National Wetlands Technical Council to organize and explain the structural complexity of the flora and fauna.

The information in this profile will be useful to environmental managers and planners, wetland ecologists, students, and interested laymen concerned with the fate and the ecological nature and value of these ecosystems. The format, style, and level of presentation should make this report adaptable to a variety of uses, ranging from preparation of environmental assessment reports to supplementary or topical reading material for college wetland ecology courses. The descriptive materials detailing the floristics of these swamps have been cross-referenced to specific site locations and give the report the utility of a field guide handbook for the interested reader.

APPENDIX II: RIVERINE FORESTS
REVIEW OF TECHNICAL METHODS MANUALS

This Review of Technical Methods Manuals includes a variety of sampling manuals, Quality Assurance/Quality Control (QA/QC) documents, standardized protocols, or other technical resources that may provide practitioners with the level of detail needed when developing a monitoring plan for a coastal restoration project. Examples from both peer reviewed and grey literature are presented. Entries were selected through extensive literature and Internet searches as well as input from reviewers. As with the Annotated Bibliographies, these entries are not, however, a complete list. Entries are arranged alphabetically by author. Wherever possible, web addresses or other contact information is included in the reference to assist readers in easily obtaining the original resource. Summaries preceded by the terms 'Author Abstract', 'Publisher Introduction', or similar descriptors were taken directly from their original source. Summaries without such descriptors were written by the authors of the associated chapter.

Allen, J. A., B. D. Keeland and J. A. Stanturf. 2001. A guide to bottomland hardwood restoration, 132 pp. Information and Technology Report USGS/BRD/ITR-2000-0011 General Technical Report SRS-40, U.S. Geological Survey, Biological Resources Division U.S. Department of Agriculture, Forest Service, Southern Research Station, Asheville, NC. http://www.srs.fs.fed.us/pubs/viewpub.jsp?index=2813

This guidebook is an essential resource to anyone planning to restore an area of bottomland forest. It briefly introduces the ecology of bottomland forests, their extent, the degree of degradation, and need for restoration. It then guides readers through the entire restoration process from general planning issues such as where to obtain planted material through to post-restoration monitoring and management of existing forests. It instructs readers on how to evaluate sites for restoration, which factors biotic and abiotic need to be taken into consideration before the proper species can be selected and planting begin. It covers: site preparation, seed collection, handling, and storage, and also has chapters on planting seeds vs. seedlings, including the tools and methods used in each. The guidebook also touches on methods of restoration other than direct planting. It covers the selection and planting of not only canopy species but understory plants as well, something that is otherwise not well documented in the literature. The guidebook also instructs readers on how to control undesirable species and protect the restoration site from animals, fire, and human impacts. Post-restoration monitoring is also covered in this document, what to measure, how to measure it, and what this information tells you is presented clearly and concisely. Lastly, management and rehabilitation of existing bottomland forests is covered for restoration of sites that haven't been completely denuded of trees. The guidebook also has a series of appendixes that include information on different forest cover types, common and scientific names of plant species common to bottomland forests, a partial list of seed and seedling suppliers, as well as species to site relationships for the Midsouth and Southern Atlantic Coastal Plain to aid restoration practitioners in selecting the proper plant materials for their site conditions.

Dane, J. H. and G. C. Topp. 2002. Methods of Soil Analysis: Part 4-Physical Methods, 1692 pp. Soil Society of America, Madison, WI.

Publisher's Description. Due to the rapid and numerous changes in measurement methods associated with soil physical and mineralogical properties, it was decided not to print a third edition of the highly popular Methods of Soil Analysis. Part 1—Physical and Mineralogical Methods. The decision was made to split the volume into two parts. The part containing soil physical measurements is now published as Methods of Soil Analysis: Part 4—Physical Methods. The approach in Part 4 differs substantially from that in Part 1 in that the new book uses a more hierarchical approach. As such it is divided into eight chapters, with each chapter covering a major aspect of soil physical properties. Following the table of contents, the reader can easily find the specific topic or measurement that is of interest. Compared with Part 1, new methods have been added and some of the older methods have been updated or deleted.

Delaware Riverkeeper Network. 2003. Adopt-a-buffer toolkit: monitoring and maintaining restoration projects, 124 pp. Delaware Riverkeeper Network, Washington Crossing, PA. www.delawareriverkeeper.org/

The Delaware Riverkeeper's monitoring manual was written to help maintain consistency and accuracy of data collected by volunteers during riparian restoration projects in Delaware and Pennsylvania. Although some of the species discussed are important only to those areas, the rest of the guidance offered in the manual could be extremely useful to riverine forest restoration monitoring projects throughout the country. The manual briefly describes a few common restoration techniques and closes with a variety of adaptive management/maintenance suggestions to minimize the negative impact of invasive species and damage to trees and herbaceous plantings. Ideas on how to retain volunteers are also presented. The majority of the manual is devoted to describing a 2-tier monitoring system. The first tier is a quick assessment of plant species present and status of constructed portions of the restoration project (e.g., to assess damage caused by erosion). Guidance on the use of photo points is also provided. Tier two measurements are more detailed and include the use of wildlife and macroinvertebrate surveys as well as methods for performing stream cross sections. The manual also includes blank data collection forms that could be used or easily adapted for use as needed depending on location.

de Vries, P. G. 1986. Sampling Theory for Forest Inventory: A Teach-Yourself Course. Springer-Verlag, Berlin.

de Vries has attempted to address many of the shortcomings of other statistical sampling texts by simplifying the process of learning advanced statistics and putting them to practical use in forestry sampling. His book covers a variety of sampling techniques including: random sampling, cluster and double sampling, use of points and circular plots, line intersect and list sampling, and a variety of others. de Vries has tried, where ever possible, to provide examples and take readers through the step by step process of how statistical analyses have been developed in order to gain a more thorough understanding of the theory and proper application of different procedures. Several appendices are also included that review many introductory statistical concepts, however, the text is not intended for the uninitiated. An existing background in calculus and introductory statistics is encouraged before using this resource. Upon completion of his book and a short period of time for the new material to sink in, de Vries confidently states that readers will 'experience the satisfaction of mastering some sampling methods widely used in forest inventory, that he will be able to read critically more professional literature than before, and that he will possess a sound basis on which to expand his knowledge of sampling.'

Hoover, J. J., K. J. Killgore and G. L. Young. 2000. Quantifying habitat benefits of restored backwaters. EMRRP Technical Notes Collection ERDC TN-EMRRP-EI-01, U.S. Army Engineer Research and Development Center, Vicksburg, MS. http://www.wes.army.mil/el/emrrp/pdf/ei01.pdf

Backwater areas act as important nursery and spawning habitats for fish. This technical report describes methods of quantifying and enhancing fish species that use backwater areas, areas subject to dewatering during low river flows. Brief lists or descriptions of fish species that use backwater habitats and methods to sample young-of-the-year populations are presented. The use of plexiglas light-traps to efficiently sample young-of-year is explained for a variety of circumstances. The development of Habitat Suitability Indexes (HSI), a statistical method useful in determining which species use particular habitats and therefore might benefit from a restoration, is presented in greater detail. Example restoration projects where the HIS method was used (Lake Whittington, a Mississippi River oxbow lake and Lake George, a Mississippi delta backwater) are also provided. Contact information of the authors is also included.

Killgore, K. J. and J. J. Hoover. 1992. A guild for monitoring and evaluating fish communities in bottomland hardwood wetlands, 7 pp. WRP Technical Note WRP TN FW-EV-2.2, U.S. Army Engineer Waterways Experiment Station, Vicksburg, MS.

This technical note is a summary of the adult and larval fish communities of the Rex Hancock/Black Swamp Wildlife Management Area, Cache River system, Arkansas. Fish communities are classified according to habitat preference and reproductive strategy. Brief descriptions of three habitat categories are given: lentic-oxbow lakes, lentic-floodplain ponds, and lotic-channels. Four reproductive modes are also defined. Tables listing which bottomland forest fish species use which habitats at varying life stages is also presented. By knowing which communities of fish are capable of using each habitat, the classifications provided can be used to select and evaluate fish species for monitoring studies in southern bottomland forest wetlands.

Klute, A. 1986. Methods of Soil Analysis: Part 1-Physical and Mineralogical Methods, 1188 pp. Soil Science Society of America, Madison, WI.

Publisher's Description. Great strides have been made in the conception of physical and mineralogical characteristics of soils and how they relate to each other and to chemical properties. The methods of analyses included here provide a uniform set of procedures that can be used by the majority of soil scientists and engineers.

Kolka, R. K., C. C. Trettin and E. A. Nelson. 1998. Development of an assessment framework for restored forested wetlands. Proceedings of the Conference on Ecosystems Restoration & Creation. Tampa, Florida. May 14-15. http://www.srs.fs.fed.us/pubs/viewpub.jsp?index=1541

Author Abstract. Development of an assessment framework and associated indicators that can be used to evaluate the effectiveness of a wetland restoration is critical to demonstrating the sustainability of restored sites. An interdisciplinary approach was developed to assess how succession is proceeding on a restored bottomland site in South Carolina relative to an undisturbed reference and a naturally agrading site. Comparison of populations and processes across successional gradients and treatments allows the effect of disturbance and restoration activities to be evaluated. Studies involving vegetation communities, organic matter and nutrient dynamics, seedling establishment and competition, and avian, herpetofauna, fish and macroinvertebrate communities have been implemented. Seedling establishment and competition studies suggest non-chemical and minimal mechanical site preparation techniques, tree shelters and root pruning should be considered as alternatives depending on restoration objectives and site conditions. The restored site contains many of the functional capabilities of a wetland with respect to fauna, however certain species tend to dominate populations in Pen Branch when compared to late successional wetlands. Fish populations show higher population densities in the restored site as compared to the reference site. A conceptual framework for integrating biotic and abiotic processes into a restoration response model will be used to synthesize ecosystem response and to identify indicators for restoration assessments.

Lindbo, D. T. and S. L. Renfro. 2003. Riparian and Aquatic Ecosystem Monitoring: A Manual of Field and Lab Procedures. 4th ed. Saturday Academy's Student Watershed Research Project, Beaverton, OR.

The Student Research Watershed Project has developed a set of field and lab data collection procedures that has successfully translated scientific methodologies for use by non-scientists. The procedures were designed for use by students (grades 8 – 12) and can easily be adapted for volunteer efforts to collect baseline and restoration monitoring data for streamside and aquatic (in-stream) habitats. Methods for the collection of physical, chemical, and biological criteria are included. The manual covers the steps necessary to design a monitoring plan as well as a quality assurance project plan. Rationale behind and the steps involved in monitoring the following parameters are also included: stream flow, temperature, dissolved oxygen, pH, alkalinity, solids and turbidity, conductivity, phosphorus, nitrogen, chlorine, microbes, and macroinvertebrates. Information on the collection of data on in-stream habitat, riparian vegetation, stream reach mapping, photo monitoring, and soils is also included. Example data sheets are provided to assist in the systematic and complete recording of monitoring results by different parties.

McCobb, T. D. and P. K. Weiskel. 2002. Long-term hydrologic monitoring protocol for coastal ecosystems, 93 pp. Protocol, USGS Patuxent Wildlife Research Center, Coastal Research Field Station, University of Rhode Island, Narragnasett, RI. http://science.nature.nps.gov/im/monitor/protocols/caco_hydrologic.pdf

Author Abstract. Long-term monitoring of hydrologic change using a standard data-collection protocol is essential for the effective management of terrestrial, aquatic, and estuarine ecosystems in the coastal park environment. This study develops a consistent protocol for monitoring changes in ground-water levels, pond levels, and stream discharge using methods and techniques established by the U.S. Geological Survey for use in the Long-term Coastal Monitoring Program at the Cape Cod National Seashore. The protocol establishes a hydrologic sampling network in the four ground-water-flow cells in the Seashore area, and provides justification for the measurement methods selected and for the spatial and temporal sampling frequency. Data collected during the first year of monitoring are included in this report; common hydrologic analyses such as hydrographs for ground-water and pond levels, and rating curves between stream stage and discharge for streamflow, are presented for selected sites. Long-term hydrologic monitoring at the Seashore will aid in interpretation of the findings of other monitoring programs. Developing and initiating long-term hydrologic monitoring programs will provide a better understanding of effects of natural and human-induced change at both the local and global scales on coastal water resources in park units.

Merritt, R. W. and K. W. Cummins, (eds.). 1996. An Introduction to the Aquatic Insects of North America. Third edition ed. Kendall/Hunt Publishing Company, Dubuque, IA.

While the bulk of Merritt and Cummins is on identification of aquatic insects of North America, they include several chapters useful in project planning as well. Various experts in the field of aquatic insect collection and identification have submitted chapters on: the general morphology of aquatic insects, designing studies, collection equipment and techniques, aquatic insect respiration, habitat and life history, and the ecology and distribution of aquatic insects. The rest of the manual is devoted to identification keys for each family of aquatic insect found in North America with many detailed and useful pictures of identifying characteristics.

Since this book is continental in scope, it is suggested that practitioners first look for identification keys prepared for their local or regional waterways. This will reduce much confusion in the identification process by eliminating species that are not found locally. Any local aquatics expert or science librarian should be able to locate these materials. If local materials are not available, then Merritt and Cummins will be useful, however, be sure to check the distribution of species identified whenever possible.

Ossinger, M. 1999. Success standards for wetland mitigation projects - a guideline, 31 pp. Washington State Department of Transportation, Environmental Affairs Office. http://pnw.sws.org/forum/success.PDF

This report offers guidance and examples on how to write specific success criteria for mitigation and restoration projects. Though it was designed to address mitigation projects in the Pacific Northwest, its information and approach make it useful throughout the United States. It outlines the steps necessary for planning the monitoring and management of a mitigation/restoration project. Guidance in writing the following program elements is provided: how to set project goals, how to select specific project objectives (i.e. what functions or values will the mitigation/restoration provide), how to select performance objectives (i.e. what structural characteristics need to be in place to provide desired functions), selection of success standards (measurable benchmarks used to determine success of performance objectives), monitoring method (how will the success standard be measured), contingency measure (what to do if the success standards are not met). Several examples are provided of each of these steps. These examples, while not all-inclusive, facilitate the application of this method to diverse areas and project types.

Shiver, B. D. and B. E. Borders. 1996. Sampling Techniques for Forest Resource Inventory. John Wiley and Sons, Inc., NewYork, NY.

Author Preface. The purpose for writing this book was to create a forest inventory textbook that clearly explains the sampling methods associated with the inventory of forest resources. There are several books available which do a good job of explaining the theory of the various

sampling techniques used in forest inventory. However, the transition from theory to practice is not easily made without extensive course work in theoretical statistics and mathematics. This book provides thorough coverage of forest inventory topics for the practitioner rather than the theoretician and should be understandable to undergraduate forest resources students and professionals who must inventory forest resources.

Examples are used extensively throughout the book to illustrate various estimators and to demonstrate different uses for sampling methods. Problems are also included at the end of each chapter to help instructors and students.

Some of the topics discussed, such as point sampling and 3P sampling, were developed specifically for timber inventory. Other topics, such as mark-recapture methods were developed for inventory of mobile wildlife populations. Many of the topics, however, can be utilized to inventory virtually any of the resources in a forest (understory vegetation, soils, water, etc.)

As the book has developed over the last several years, we find that we are using it as a reference as well as a textbook. Some of the topics such as double sampling with point sampling and sampling with partial replacement have been available only in scattered journal articles or in more theoretically oriented textbooks. Inventory is a job which most forest resource managers will use repeatedly throughout their careers. This book should allow them to work confidently in forest inventory regardless of the specific inventory problem.

Sparks, D. L., A. L. Page, P. A. Helmke, R. H.Loeppert, P. N. Soltanpour, M. A. Tabatabai, C. T. Johnson and M. E. Sumner. 1996. Methods of Soil Analysis: Part 3-Chemical Methods, 1358 pp. Soil Science Society of America, Madison, WI.

Publisher's Description. This volume covers newer methods for characterizing soil chemical properties as well as several methods for characterizing soil chemical processes. This book will serve as the primary reference on analytical methods. Updated chapters are included on the principles of various instrumental methods and their applications to soil analysis. New chapters are included on Fourier transform infrared, Raman, electron spin resonance, x-ray photoelectron, and x-ray absorption fine structure spectroscopies.

Steyer, G. D., R. C. Raynie, D. L. Steller, D. Fuller and E. Swenson. 1995. Quality management plan for Coastal Wetlands Planning, Protection, and Restoration Act monitoring program, 82 pp. Open-File Report 95-01, Louisiana Department of Natural Resources, Coastal Restoration Division, Baton Rouge, LA. http://www.lacoast.gov/cwppra/reports/MonitoringPlan/index.htm

This document is a Quality Assurance Project Plan (QAPP) used for all restoration projects conducted under the Coastal Wetlands Planning, Protection, and Restoration Act (CWPPRA) and similar legislation for coastal Louisiana. Though it does not explain how to develop a QAPP for new wetland restoration monitoring projects, it can be used as a template by which monitoring plans can be developed. Detailed explanations of how data is to be collected, acceptable error rates, and methods to ensure high quality data is collected, recorded, and analyzed are included. Quality assurance guidelines are provided for field data collection, remote sensing and airphoto interpretation, computer systems to be used, data entry procedures, data review, laboratory procedures, and documentation and reporting. Any restoration practitioner attempting to develop a monitoring plan or preparing a QAPP for their project may find this document a valuable example to follow.

Uranowski, C., Z. Lin, M. DelCharco, C. Huegel, J. Garcia, I. Bartsch, M. S. Flannery, S. J. Miller, J. Bacheler and W. Ainslie. 2003. A regional guidebook for applying the hydrogeomorphic approach to assessing wetland functions of low-gradient, blackwater riverine wetlands in peninsular Florida, 590 pp. ERDC/EL TR-03-3, U.S. Army Engineer Research and Development Center, Vicksburg, MS. http://www.wes.army.mil/el/wetlands/wlpubs.html

This manual was prepared for use in assessing the functional capacity of blackwater, forested wetlands on the western coast of Florida using the Hydrogeomorphic (HGM) method. It provides a brief overview of the general HGM method for classification and assessment and explains how the HGM process was implemented for this particular type of forested wetland system and why. Although the equations provided for assessing functions were calibrated using data from western Florida, they can be adapted and re-calibrated using data from other areas. Methods for determining a blackwater forest's ability to perform the functions of temporary surface water storage, maintenance of characteristic subsurface hydrology, cycling of nutrients, removal and sequester of elements and compounds, retention of particles, export of organic matter, maintenance of plant communities, and provision of wildlife habitat are provided in detail. References to additional literature as needed are also provided.

U.S. EPA. 1996. The volunteer monitor's guide to quality assurance project plans, 59 pp. EPA 841-B-96-003, U.S. Environmental Protection Agency, Washington D.C. http://www.epa.gov/volunteer/qapp/vol_qapp.pdf

Author Abstract. The Quality Assurance Project Plan, or QAPP, is a written document that outlines the procedures a monitoring project will use to ensure that the samples participants collect and analyze, the data they store and manage, and the reports they write are of high enough quality to meet project needs.

U.S. Environmental Protection Agency-funded monitoring programs must have an EPA-approved QAPP before sample collection begins. However, even programs that do not receive EPA money should consider developing a QAPP, especially if data might be used by state, federal, or local resource managers. A QAPP helps the data user and monitoring project leaders ensure that the collected data meet their needs and that the quality control steps needed to verify this are built into the project from the beginning.

Volunteer monitoring programs have long recognized the importance of well-designed monitoring projects; written field, lab, and data management protocols; trained volunteers; and effective presentation of results. Relatively few programs, however, have tackled the task of preparing a comprehensive QAPP that documents these important elements. This document is designed to help volunteer program coordinators develop such a QAPP.

U.S. EPA. 2002. Guidance for quality assurance project plans, 57 pp. EPA QA/G-5, U. S. Environmental Protection Agency, Washington, D. C. http://www.epa.gov/swerust1/cat/epaqag5.pdf

This document is designed to guide those involved with Quality Assurance Project Plan (QAPP) development for environmental monitoring and data analysis. It describes various issues to be addressed when preparing a QAPP, with an emphasis on systematic planning. The report is divided into three chapters. An introduction that describes the target audience and the importance of systematic sampling. A second chapter describes all of the pieces of a QAPP, focusing on environmental data collection and analysis. The third chapter describes methods for developing QAPPs for projects that use previously collected data.

The importance of having high quality, reliable data cannot be over estimated. Use of this document or the EPA's *Volunteer monitor's guide to quality assurance project plans*, will help restoration practitioners develop monitoring plans that will provide the high quality, reliable data necessary to monitor and manage restoration projects. The step-by-step approach of this document takes restoration practitioners through the entire planning, data collection, data analysis, and reporting process from start to finish. Ensuring that all aspects of the monitoring project are well thought out ahead of time and that contingency plans are in place.

Weaver, R. W., S. Angle, P. Bottomley, D. Bezdicek, S. Smith, A. Tabatabai and A. Wollum. 1994. Methods of Soil Analysis: Part 2-Microbiological and Biochemical Properties, 1121 pp. Soil Science Society of America, Madison, WI.

Publisher's Description. Laboratories interested in soil science analysis will find it advantageous to use the methods contained in this book. It is particularly relevant and useful to laboratories with interest in environmental microbiology or bioremediation. Analytical methods are essential to progress in science and the methods presented in this book are recognized as being among the best currently available.

APPENDIX III: LIST OF RIVERINE FOREST EXPERTS

The experts listed below have provided their contact information so practitioners may contact them with questions pertaining to the restoration or restoration monitoring of this habitat. Contact information is up-to-date as of the printing of this volume. The list below includes only those experts who were 1) contacted by the authors and 2) agreed to submit their contact information. Some of those listed also reviewed the associated habitat chapter. In addition to these resources, practitioners are encouraged to seek out the advice of local experts as well faculty members and researchers at colleges and universities. Engineering, planning, and landscape architecture firms also have experts on staff or contract out the services of botanists, biologists, ecologists, and other experts whose skills are needed in restoration monitoring. These people are in the business of providing assistance in restoration and restoration monitoring and are often extremely knowledgeable in local habitats and how to implement projects on the ground. Finally local, state, and Federal environmental agencies also house many experts who monitor and manage coastal habitats. In addition to the National Oceanic and Atmospheric Administration (NOAA), the Environmental Protection Agency (EPA), the Army Corps of Engineers (ACE), Fish and Wildlife Service (FWS), and the United States Geologic Survey (USGS) are important Federal agencies to contact for assistance in designing restoration and monitoring projects as well as potential sources of funding and permits to conduct work in coastal waterways.

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CHAPTER 14: HUMAN DIMENSIONS OF COASTAL RESTORATION

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INTRODUCTION

Coastal habitat restoration, from an ecological perspective, is primarily aimed at restoring the functional (biological, physical, and chemical) characteristics of coastal ecosystems. These functions, described in the preceeding habitat chapters, can be measured and monitored to gauge the ecological success of a restoration project. From a human dimensions perspective, in contrast, the emphasis is on identifying and describing how people value, utilize and benefit from the restoration of coastal habitats. While ecological and biophysical data are an essential component, decisions regarding coastal restoration projects, and evaluation of their success, will ultimately be based on societal value preferences. The restoration of coastal environments is fundamentally a human endeavor. Failure to address human dimensions issues at the outset of a restoration effort will likely result in rejection by the very community the project is intended to benefit. This is particularly true for coastal public trust resources, which include the water column, submerged lands, beaches, and associated plants and animals. Inquiry into the human dimensions of coastal restoration should begin with three fundamental questions:

1. Who cares about coastal restoration (i.e., who are the **stakeholders**)?
2. Why is coastal restoration important to them?
3. How will coastal restoration change people's lives (i.e., what are the social benefits/ impacts)?

Restoration projects that from the beginning incorporate a human dimensions approach and attempt to answer and address the questions *who cares? and why is it important?,* are more likely to succeed than those that do not. This is true of all restoration efforts, not just those specifically designed to achieve human dimensions benefits. Even restoration efforts aimed primarily at attaining biophysical and ecological goals will need the support from various agencies, organizations, industries, and communities - all of which operate in the human dimensions sphere - to be successful.

Similar to ecological parameters, changes in human values and behaviors associated with coastal restoration, and the social benefits of coastal restoration, can and should be measured and monitored over time. Also as with ecological effects, standard social science procedures and methods should be adhered to in order to properly develop and monitor appropriate human dimensions goals and objectives for coastal restoration projects. Monitoring changes in human thought and action in conjunction with a coastal restoration project will require a multidisciplinary approach. Some of the social science (i.e., human dimensions) disciplines restoration practitioners need to consider include sociology, psychology, resource economics, geography, anthropology, outdoor recreation, and political science. Coastal restoration monitoring will likely necessitate the need for interdisciplinary collaborative research between two or more of these disciplines, as well as research that integrates human dimensions with the ecological and biophysical sciences.

ORGANIZATION OF INFORMATION

This chapter provides those who are engaged in restoration efforts with a basic understanding of the human dimensions of coastal restoration.

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It is intended to help restoration practitioners identify:

1. Human dimensions goals and objectives of coastal restoration projects
2. Measurable parameters that can be monitored to determine if those goals are being met, and
3. Social science research methods, techniques, and data sources available for monitoring these parameters

The next section, *Coastal Restoration: The Role of Social Values,* offers a general discussion of the diverse and dynamic social values that people place on natural resources, and the role these values play in natural resource policy and management. The third section, *Human Dimensions Aspects of Coastal Restoration*, covers some of the general factors to consider in the selection and monitoring of human dimensions goals/objectives of coastal restoration. The fourth section, *Discussion of Specific Goals, Objectives and Measurable Parameters*, provides a discussion of some specific human dimensions goals, objectives and measurable parameters that may be included in a coastal restoration project. A *Matrix of Human Dimensions Goals and Parameters to Monitor* and a *Selected Annotated Bibliography* of key references are provided as appendices at the end of this chapter (Appendices I and II, respectively). Also included as appendices are a *Glossary of Human Dimensions Terms* (terms bolded in text appear in glossary) and a *List of Human Dimensions Experts* (and their areas of expertise) that readers may contact for additional information or advice (Appendices III and IV, respectively).

COASTAL RESTORATION: THE ROLE OF SOCIAL VALUES

Ecological restoration is one component in the broader context of natural resource management (or stewardship) that also includes government regulation, resource allocation, consumer decision-making, and social activism. Natural resource management can be viewed conceptually as the intersection of four interconnected systems:

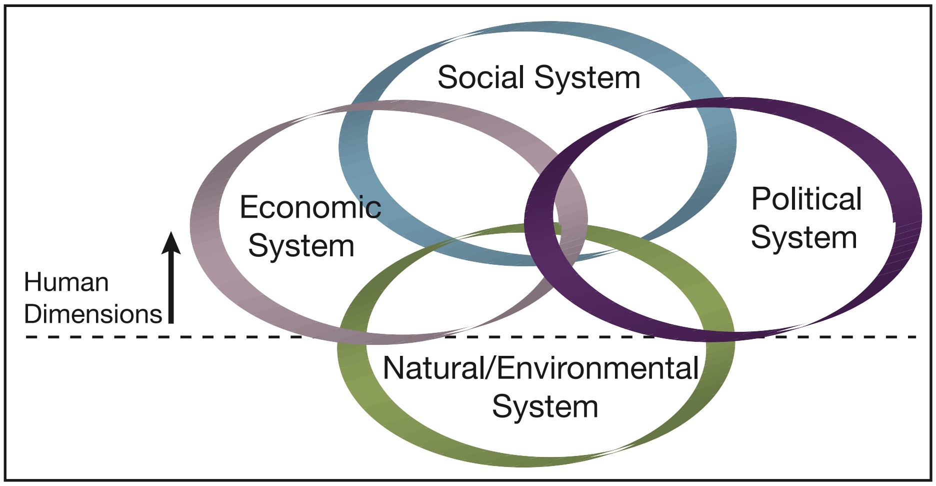
- Natural environmental system of biosphere elements, natural resources, ecosystems, fish and wildlife etc.
- Political system of policies, courts, laws, regulations, legislators, lobbyists, and management agencies
- Economic system focused on the allocation of land, labor and capital, economic impacts, employment, and budgets
- Social system of human **attitudes, norms,** values, beliefs, behaviors, customs, traditions, motivations and preferences

All four systems are interrelated and interdependent in this model, and the natural system, which is typically the focus of restoration efforts, both provides and receives inputs from the political, economic, and social systems. The political, economic, and social systems collectively make up what is referred to as the *human dimensions* of natural resource management, depicted as everything above the dotted line in Figure 2. However, natural resource values originate and are endorsed in one system only: the social system (Kennedy and Thomas 1995). These values are then expressed to natural resource managers and society through the political, economic, and social systems. In turn, these value expressions (e.g., environmental laws, congressional budgets, volunteerism, voting behavior) largely determine the fate of the natural systems that sustain us.

The important point here is that the natural/environmental system does not originate natural resource values, only people do. There are no pre-determined values in nature that will somehow guide us toward some pre-ordained "correct" ecological condition. While restoration practitioners may ponder the question "what to restore?" an equally important question is "restore to what pre-existing condition, and for what purpose?" That is, do we want our landscapes and coastal habitats to look and function the way they did 50 years ago, 100

Figure 1. Volunteers plant salt marsh plants at the Eastern Neck National Wildlife Refuge on Eastern Neck Island, MD. Photo by NOAA Restoration Center, from the NOAA Photo Library. http://www.photolib.noaa.gov/habrest/r0006505.htm

Figure 2. Conceptual model of natural resource management systems. Modified from Kennedy and Thomas 1995.



years ago, or 300 years ago? (if that is even possible); what ecosystem does society want, at what cost, and with what trade-offs? Answers to these questions will only come from the social system and the values society imparts on natural and environmental resources. Ultimately, coastal communities (and other stakeholders) will need to decide what coastal ecosystem they want when deciding on the specific goals and objectives (both ecological and human dimensions) of a particular restoration project. This decision should not be viewed as an absolute dichotomy between a pristine unimpacted ecosystem and a totally impacted ecosystem allowing many types of environmentally damaging human activities. Rather, there is a whole range of possible ecosystem types (from pristine to developed) which present opportunities for compromise when identifying the ecological and human dimensions goals of a restoration project.

In this sense, natural resource management can be viewed as social value management whereby managers strive to balance diverse natural resource social values within current society with the needs and values of future generations in an ecologically sustainable manner (Kennedy and Thomas 1995). Since societal values are what drive natural resource management, all coastal restoration efforts should be viewed as both a recognition of and response to these values. While the actual elements being restored are biological and physical in nature, the reasons for restoring them are human dimensions based (i.e., fish do not vote, osprey do not pay taxes).

Natural resource values are diverse in society and the same object or resource can be valued in many different ways by different people. These values, which are devices of our minds, are shaped by our culture, by society, through scientific discovery, and through our interactions with the natural environment. The diversity of natural resource values can be viewed along a continuum ranging from **human-dominant** to **human-mutual values** (Kennedy and Thomas 1995). Human-dominant values emphasize the use of natural resources to meet basic human needs. These are often described as **utilitarian**, materialistic, consumptive, or economic in nature. An example would be valuing a whale as a source of food and energy. The human-mutual end of this continuum emphasizes spiritual, aesthetic, and nonconsumptive values in nature (e.g., the enjoyment people derive from whale watching). For example, an indigenous tribe may gain sustenance from whale meat and blubber while simultaneously deriving spiritual and heritage (human-mutual) values from a whale hunt. Therefore, values along this continuum are not necessarily mutually exclusive and the same resource can be a source of both values.

When considering social values, a distinction is made between **held values** and **assigned values**. Held values are conceptual precepts and ideals held by an individual about something. Natural resource examples include the symbolism of a bald eagle or the enjoyment of watching a sunset. Assigned values refer to the relative importance or worth of something, usually in economic terms. Examples include the value of water for irrigation or hydropower, land for development, or forests for timber supply. A similar natural resource value dichotomy is drawn between **non-instrumental** versus **instrumental values**. Non-instrumental values refer to resources that are valued for what they are, whereas instrumental values refer to the usefulness of something as a means to some desirable human end. Aesthetic and spiritual values in nature would be considered non-instrumental whereas economic, utilitarian, and life support values would be considered instrumental. For the most part, human dominant values tend to be assigned and instrumental, whereas human mutual values are typically held and non-instrumental.

Natural resource values are not only diverse in present-day society, they are also continually in flux. A comparison of predominant attitudes towards filling wetlands and whale hunting at the turn of the 20th century with those at the turn of the 21st century illustrates just how much natural resource social values can shift over the course of just a few generations. Several important societal changes took place in the United States during the second half of the 20th century that radically changed how natural resources are managed and how natural resource agencies function. These changes include:

- A general shift in environmental values away from human-dominant (utilitarian and consumptive) and towards the human-mutual/nonconsumptive end of the continuum. This included increased aesthetic/spiritual appreciation of nature, outdoor recreation use values, and animal rights values.
- Raised public environmental awareness and human health concerns related to environmental condition as a result of the environmental movement of the late 1960's early 1970's. This movement resulted in a plethora of environmental laws that still provide the foundation for environmental policy and management to this day.
- More people claiming a stake in environmental resources and demanding input into the natural resource decision-making process. These "new" stakeholders included environmentalists (e.g., non-governmental organizations, grassroots and community groups), landowners, farmers, animal rights groups, nonconsumptive users, and the general public (Decker et al. 1996).
- The role of the judicial system in natural resource policy and management greatly increased as agency actions (and inactions) were successfully challenged more often in court.

Figure 3. Young naturalist inspecting a horseshoe crab shell. The carapace was empty. If this was a live animal, picking up by tail could cause injury to the crab. Photo by Mary Hollinger, NODC biologist, NOAA, from the NOAA Photo Library. http://www.photolib.noaa.gov/coastline/line0682.htm

For natural resource agencies, survival in a post-Earth Day political environment would require a fundamental shift in their relationship with the owners of the resources they held in trust, i.e., society as a whole. Prior to the 1960's, natural resource management was in the hands of professional agency "experts." These experts were well trained in the natural sciences, and this background was adequate for managing our natural resources. This approach to managing natural resources (be they forests, wildlife, fisheries, etc.) was in response to widespread environmental overuse and damage that occurred in the absence of any significant or meaningful management. During this time, managers worked on behalf of the public, and were able to do what they felt best for the resource. Over time, natural resource agencies increasingly focused their attention on meeting the needs of a relatively small group of "clients" or "constituents" who paid for the agencies services through license sales, special excise taxes (e.g., Sport Fish Restoration Act) and resource lease sales (Decker et al. 1996). For fish and wildlife agencies, these "traditional users" were typically anglers, hunters, and trappers. For commodity driven agencies such as the U.S. Forest Service (USDA) or Minerals Management Service (USDOI) the traditional clients were the logging and oil industries, respectively. The prevailing notion was that the general public need not be concerned with natural resource management which was in the hands of professional agency "experts" (i.e., management based on science, not social values). However, as noted above, changes since the 1960's have significantly altered how we choose to manage and use our natural resources. Demand for resources has grown enormously, conflict over uses is common, values towards what is "right" have changed, and most importantly, the public has demanded to be allowed to participate in the decision-making process. Our environmental laws now require it. While a solid understanding of the natural sciences is essential, the idea that these sciences alone can tell us how to manage natural resources has been increasingly questioned by agencies and the general public. Resource management is today driven by social values. We must determine "why a particular restoration effort is important," and "who cares," if we are to be successful in our efforts.

Figure 4. Seagulls occupying almost every piling along a Tangier Island waterman's dock (Chesapeake Bay, VA). Photo by Mary Hollinger, NODC biologist, NOAA, from the NOAA Photo Library. http://www.photolib.noaa.gov/coastline/line0980.htm

HUMAN DIMENSIONS ASPECTS OF COASTAL RESTORATION: GENERAL FACTORS TO CONSIDER

IDENTIFYING GOALS AND OBJECTIVES

Goals are general statements about desired project outcomes. Goals are typically further defined through multiple objectives, which are more specific statements about desired project outcomes. It is strongly recommended that the human dimensions goals and objectives of a coastal restoration project be identified and clearly stated early in the planning process. Identification and evaluation of goals and objectives should be open to all individuals or groups with a stake in the outcome (i.e., stakeholders) so that everyone has input into and understands, in general terms, the desired direction of the project. It is also suggested that an **adaptive management** approach be incorporated so that goals and objectives can be re-assessed, and modified as needed, at various stages throughout the project's life.

Coastal habitat restoration is driven by desired outcomes (i.e., goals) that can be ecological, social, or economic in nature. Some projects will be more oriented towards ecological/habitat related goals and others more oriented towards human dimensions goals. Furthermore, an individual restoration project may have several stated goals, reflecting the multiple functions performed by healthy coastal ecosystems and the multiple social values connected to or resulting from those functions. The ecological and human dimensions goals of coastal restoration are often closely interconnected. The term **ecosystem services** describes the full range of goods and services provided by natural ecological systems that cumulatively function as fundamental life-support for the planet (Costanza et al. 1997). Since ecosystem services are critical to human welfare and survival, many ecological goals/objectives associated with habitat restoration can be readily restated as social or economic goals/objectives. For example, the ecological goal of increasing primary productivity may be an effective way to achieve the human dimensions goal of reducing property damage in coastal areas (through reduced wave energy and erosion potential). Likewise, the ecological goal of enhancing fish breeding and nursery grounds will likely advance the human dimensions goal of increasing fishery yields.

Ecological and human dimensions goals of coastal restoration may not always, however, be compatible with one another. For example, the human dimensions goal of increasing opportunities for coastal recreation and tourism may, beyond some threshold level of use, be incompatible with the ecological goal of improving water quality. Similarly, two or more human dimensions goals may not be compatible with each other. An example of this would be the goal of improving aesthetic values in the form of viewsheds and scenic vistas versus the goal of enhancing access to restored coastal resources in the form of roads, parking lots, and boat ramps. Restoration practitioners, locally affected

Figure 5. Two or more human dimensions goals may not be compatible…boat marinas in the distance compete with pristine kayak routes in Orcas Island Marina, San Juan Islands, Washington State. Photo courtesy of James Mason.

Coastal Ecosystem Services

The life-support functions performed by ecosystem services can be divided into two groups: production functions (i.e., goods) and processing and regulation functions (i.e., services). Costanza et al. (1997) estimated the economic value of ecosystem services for the entire biosphere to be in the range of $16-54 trillion per year, with an average of $33 trillion per year. More than one-third of this amount ($12.6 trillion) was attributed to functions performed by coastal ecosystems. By comparison the global gross national product (GNP) is somewhere around $18 trillion per year. While these are considered fairly rough estimates, they nonetheless highlight the economic value of ecosystem services. Since ecosystem services are often not quantified in terms comparable with economic services and manufactured capital, they are often devalued by policymakers.

Production functions of coastal ecosystems include:

- Food production (e.g., fish, shellfish, waterfowl)
- Raw materials (e.g., timber, harvestable grasses, peat)
- Genetic resources (e.g., medicines, commercial products)

Processing and regulation functions include

- Disturbance regulation (e.g., storm protection, flood control, drought recovery, and erosion control)
- Climate regulation (e.g., greenhouse gas regulation)
- Regulation and supply of water for drinking, irrigation and industry (groundwater recharge and discharge)
- Waste treatment and pollution control
- Nutrient cycling (removal, retention, and transformation)
- Habitat for plants and animals

communities, and coastal resource managers will need to explicitly identify trade-offs and carefully consider value priorities amongst a range of competing, and often contentious goals and objectives. When considering these trade-offs it is important to keep in mind the following definition of restoration:

> *"The process of reestablishing a self-sustaining habitat that in time can come to closely resemble a natural condition in terms of structure and function"* (Turner and Streever 2002).

Thus, human uses of restored coastal habitats that are unsustainable would not be considered appropriate goals or objectives of coastal restoration projects. In general, goals and objectives based on human mutual and non-use values associated with coastal habitats will be more compatible with ecological goals than those based on human dominant values. However, consumption-oriented objectives (e.g., increase recreational and commercial fishery harvests) are not necessarily inconsistent with ecological goals or with the definition of restoration if such uses are managed in a wise and sustainable manner.

In addition to identifying the desired human dimensions outcomes or anticipated benefits of proposed projects, coastal restoration practitioners should also consider **environmental equity**, or how those benefits will be distributed throughout the affected community. The following questions regarding environmental equity should be addressed:

- Will the project be designed to benefit a relatively small number of individuals over a limited geographic area or will the benefits be more evenly dispersed throughout the population?
- Will the anticipated benefits have regional or national significance, either as a stand-alone project or as part of a network of similar restoration projects?
- In terms of **environmental justice** concerns, how will the proposed project affect the

distribution of environmental quality among people of different racial, ethnic or socio-economic groups?

Related to environmental equity is the concept of **intergenerational equity**, which focuses on the temporal distribution of project impacts (both positive and negative) across generations. Some intergenerational equity questions that might be raised for coastal restoration projects are:

- How will the anticipated benefits and costs be distributed over time and across generations?
- Are the anticipated project benefits stated as short-term or long-term goals?
- If goals are short-term, are there any long-term negative impacts associated with these goals that might be passed on to future generations?
- If goals are long-term, are there any short-term negative impacts associated with these goals that will be absorbed by the current generation?

Another factor to consider in terms of selecting human dimensions goals/objectives of coastal restoration projects is the probability of achieving those goals/objectives. While success is never guaranteed due to unpredictable and uncontrollable social and environmental factors, some desired outcomes or anticipated human dimensions benefits clearly will be more within the locus of control of the practitioner than others. In general, human dimensions goals and objectives that are more directly linked to desired ecological outcomes (e.g., improve water quality, reduce flooding) will have a higher probability of success than those with many intervening factors (e.g., improve tourism, improve commercial fishing). For purposes of project evaluation, coastal restoration practitioners may find it helpful to rank human dimensions goals and objectives by relative probability or likelihood of success (e.g., low, medium, and high).

Difficulties associated with monitoring project success and attributing measurable parameters to particular goals and objectives are discussed in the next section.

ISSUES IN MONITORING MEASURABLE PARAMETERS

Establishing a Baseline

In order to monitor changes in human dimensions parameters over time, it is necessary to first establish a baseline or starting point against which future measures can be compared. Appropriate baseline data may or may not be available depending on the particular goals and measurable parameters to be monitored. If baseline data are not available, restoration practitioners will need to design a plan for collecting and analyzing human dimensions information prior to implementation of restoration activities. If baseline human dimensions data do exist, it will be important to determine whether or not the data are available at the geographic level required for your project. For example, results reported at a state, regional or sub-regional level will be of little use for monitoring impacts of local restoration projects. Another factor that should be considered when using existing data is the frequency and timeliness of the available data. That is, when was the data last collected and is the data collected regularly (e.g., annually, every five years) or was it a one-time effort (See **Cross-sectional** versus **Longitudinal Studies** box below). Human dimensions data collected frequently at regular intervals will be more useful for restoration monitoring than one-time or sporadic data collection efforts.

In some cases it may be feasible to access "raw data" (i.e., data that are not analyzed/summarized) and conduct a specific project analysis at the desired level of detail. If such

Cross-sectional versus Longitudinal Studies
(Source: Babbie 1989)

In the social sciences, cross-sectional research refers to studies that investigate some phenomenon by taking a cross section (i.e., snapshot) of it at one time and analyzing that cross section carefully. By comparison, longitudinal studies are designed to permit observations over an extended period of time. There are three types of longitudinal studies: (1) **trend studies**, those that study changes within some general population over time, (2) **cohort studies**, those that examine more specific subpopulations or cohorts (e.g. age groups) over time, and (3) **panel studies**, those that study the same set of people over time. While longitudinal studies are generally more costly and time consuming, they are often advantageous for monitoring changes in measurable parameters over time.

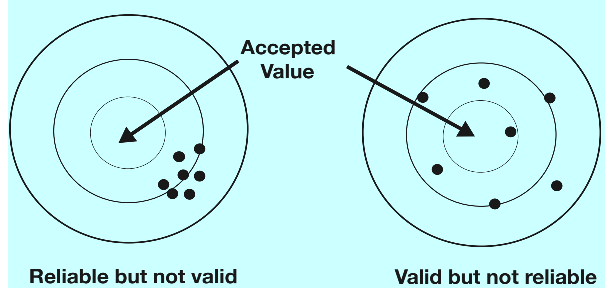
an analysis is necessary, it is recommended that you consult with an expert who is familiar with the database and other statistical issues that may arise. Some existing data sources (i.e., **secondary data**) and research methods that might be useful in monitoring particular human dimensions goals and objectives are provided in the next section.

Project Scale Issues

Coastal restoration efforts can range in size from local projects covering just a few acres to entire watersheds covering thousands of acres. In addition to spatial scale diversity, restoration projects will vary in terms of cost, labor involved, type of activity, and level of activity intensity, among others. The size and scope of a restoration project can influence the choice of project goals and should be considered when designing a human dimensions monitoring plan. Certain human dimensions goals will be nearly impossible to evaluate for smaller projects because of the difficulties associated with monitoring measurable parameters. Monitoring some measurable parameters may simply be too costly or time consuming for small-scale projects to undertake. Even if such sampling is conducted, depending on the sampling effort expended, the results may be too imprecise or inaccurate as to be useful in any practical sense. Regardless of project size and scale, practitioners should keep both **reliability** and **validity** in mind when monitoring human dimensions goals and objectives of coastal restoration projects (see **Reliability** and **Validity** box below).

Another factor to consider when conducting social science assessments is **causality**, i.e., to what extent one event is caused by the other. For the purposes of coastal restoration monitoring it is important to understand the cause and effect relationship between the restoration project and the parameter you are measuring. The section below (and accompanying matrix in Appendix I) describes several suggested measurable parameters that might be effective for monitoring particular human dimensions goals. However, the strength of the causal relationship between the restoration effort and any observed change in the measurable parameter will be project specific. That is, the influence of other factors (causes) on the observed effect will vary

Reliability and Validity
(Source: Babbie 1989)



In statistical terms, reliability refers to the likelihood that a given measurement procedure or technique will yield the same result each time that measure is repeated (i.e., reproducibility of the result; consistency of a measuring instrument). Validity, on the other hand, refers to how close to a true or accepted value a measurement lies (i.e., the degree to which a measuring instrument measures what it is supposed to measure). While it is not often possible to know what the true value is, it is possible to identify factors that reduce accuracy such as instrument error or measurement error.

project by project. Caution should be used when attributing post-restoration changes in human dimensions parameters to the restoration project. Restoration practitioners should assess and, to the extent possible, quantify the influence of all other factors to determine the proportion of the observed changes attributable to the restoration project. Causality should be considered in the restoration monitoring planning stage to strengthen cause and effect relationships and minimize the probability of reaching an erroneous conclusion.

While causality is an issue for all project monitoring regardless of scale, in general, causality will be more difficult to establish for small-scale restoration projects than for larger projects (project scale issue). For example, restoring 25 acres of wetlands may have a positive impact on both commercial fishing and eco-tourism. However, the actual impact, measured in fishery yields and tourist expenditures, may be very small in relation to all the other factors affecting these parameters (e.g., fishing regulations, weather, the economy, gas prices). Low causality combined with random variation could make it very difficult to conclude, with any degree of confidence, that the restoration project did, in fact, have a positive impact on these goals.

Larger restoration projects are also susceptible to extraneous factors that may influence the parameters measured. However, on a larger scale, parameter estimates will generally be more precise and the probability of reaching an erroneous conclusion regarding causality should be greatly reduced. Whenever possible, smaller individual restoration projects should be linked or networked together as part of a restoration monitoring program for an entire estuary, watershed, region or some other appropriate geographic level. Networking restoration efforts allows the goals of small community projects to be connected to some larger regional plan, and will also facilitate **adaptive management**. Monitoring and project evaluation can then be conducted using a tiered approach with several different management levels (e.g., individual project, community, estuary). Examples of this approach are the San Francisco Bay and Galveston Bay Restoration Plans. The matrix in Appendix I indicates which measurable parameters restoration practitioners <u>should</u> be able to monitor regardless of project size or scope (indicated by a closed circle ●), and which measurable parameters may be possible to monitor for <u>some</u> individual or small-scale projects but in other instances monitoring such parameters may only be feasible at the restoration program level (i.e., estuary, watershed, etc.). These circles are intended to provide only broad general guidance, and exceptions may exist for any given restoration project. Practitioners are encouraged to consult with human dimensions experts (see Appendix IV) and carefully evaluate the feasibility of monitoring any of these parameters for their particular project.

Ethical Guidelines in Conducting Social Science Research

Ethical guidelines should always be considered when conducting social science research that involves human subjects. Webster's New World Dictionary defines ethical as "conforming to the standards of conduct of a given profession or group." Within the social sciences, different professional associations have codified their own ethical rules for researchers in that particular discipline to adhere to. Ethical issues arise from the kinds of research questions social scientists investigate and the methods they use to obtain information about people's thoughts and behaviors (Frankfort-Nachmias and Nachmias 1992). Social science research often involves an intrusion into people's lives, disrupts their regular activities, and takes up their time and energy. Surveys may ask sensitive questions (e.g., income, age) that respondents may not feel entirely comfortable answering. This section briefly describes some of the basic tenets of research ethics that apply to most of the social sciences. There are rules that one must abide by. However, rules, standards, and exceptions vary according to discipline and research methodology employed. It is strongly recommended that restoration practitioners review the code of ethics for the particular type of research they are conducting and consult with an expert prior to implementing a social science research design.

One ethical guideline is that social science research should be voluntary. No one should be forced or coerced into participating in a survey, focus group, interview, or other data collection method. Participants should know that they can refuse to participate and that they can terminate involvement at any time. A related ethical criterion in social research is **informed consent**. Informed consent emphasizes the importance of both accurately informing research participants as to the nature of the research and obtaining their verbal or written consent to participate (Babbie 1989). The purpose, procedures, data collection methods and potential risks (both physical and psychological) should be clearly explained to participants without any deception.

Another important ethical tenet is the right to privacy defined as "the freedom of the individual to pick and choose for himself the time and circumstances under which, and most importantly, the extent to which, his attitudes, beliefs, behavior, and opinions are to be shared with or withheld from others" (Ruebhausen and Brim 1966, *in* Frankfort-Nachmias and Nachmias 1992). Issues of privacy in social research can arise over the sensitivity of information collected, the setting in which it is collected, and the dissemination of the information. Two common approaches to protect the privacy of participants are anonymity and confidentiality (Frankfort-Nachmias and Nachmias 1992). A respondent is considered anonymous when the researcher cannot identify a given response with a given respondent. Anonymity can be assured by separating the identity of individuals (e.g., name, social security number, phone number) from the information they give. One way to assure anonymity is simply not to collect any identifying information (Frankfort-Nachmias and Nachmias 1992). If complete anonymity cannot be guaranteed, researchers should at least assure participants that the information they provide will be kept confidential – i.e., an individual's information will not be revealed to the public. Data can still be presented in aggregate form as long as individual responses cannot be linked to a particular person. One technique to increase confidentiality is to link identifying variables to the person's information in the database using a code number. Both identifiers and code numbers should be destroyed once data analysis is completed.

Ethics and Social Science Research Key Elements:

- Voluntary
- Informed Consent
- Privacy
- Anonymity
- Confidentiality

DISCUSSION OF SPECIFIC GOALS, OBJECTIVES, AND MEASURABLE PARAMETERS

The diverse values people derive from healthy functioning coastal ecosystems can be expressed within one of ten main goal categories shown below. The goals discussed below are not intended to be mutually exclusive or completely independent of one another. In some cases, as mentioned previously, goals may be conflicting, in other cases two or more of these goals will be complementary (e.g., protecting historic/ cultural values and enhancing access in coastal areas will likely improve tourism and general market activity). Nor is the list intended to be exhaustive, or for all goals to apply to all restoration projects. There may well be additional goals not identified here that would be appropriate and specific to a given project, and that should be included. Similarly, there are certain to be goals that just wouldn't apply to any number of restoration projects and therefore should not be included in a plan. Each of the currently identified goals is described in more detail below, along with related objectives and measurable parameters. Suggested social science research methods, techniques and available data sources to monitor these parameters are also provided. If a goal is appropriate for a particular project, practitioners can then determine if a coastal restoration project meets its intended human dimensions goals and associated objectives.

HUMAN DIMENSIONS GOALS OF COASTAL RESTORATION

- Coastal Recreation, Tourism, and Access (page 14.14)
- Enhance Community Investment (page 14.23)
- Enhance Educational Opportunities (page 14.29)
- Protect or Improve Human Health (page 14.30)
- Protect Traditional, Cultural, and Historic Values (page 14.36)
- Enhance Non-market and Aesthetic Values (page 14.41)
- Improve General Market Activity (page 14.43)
- Reduce Property Damage and Enhance Property Values (page 14.46)
- Enhance Transportation and Commerce (page 14.51)
- Improve Commercial Fisheries and Shellfisheries (page 14.54)

Additional sources of information (references and web sites) are provided at the end of each goal category section and in the annotated bibliography at the end of this chapter. These sources are intended to provide the reader with a starting point for researching this topic, not as a comprehensive list. Since many other sources relevant to your particular project needs may exist, and new research is conducted every day, we recommend that practitioners conduct their own literature review and consult with human dimensions experts before developing and implementing a monitoring plan.

The matrix in Appendix I indicates measurable parameters to monitor for each of the specific human dimensions goals shown. This matrix is the product of a recent workshop titled *Monitoring the Human Dimension Aspects of Coastal Restoration* (see box about the workshop below). It is intended to help restoration practitioners identify potential human dimensions goals and measurable parameters typically connected to coastal restoration projects. However, this list is not necessarily exhaustive, and other goals and parameters (not shown here) may also be appropriate for any given project. Since each restoration project is different, the optimum parameters to measure will depend on the specifics of your project. When choosing among measurable parameters, consideration should be given to **content validity**. Content validity is based on the extent to which a measurement (i.e., parameter) reflects the specific intended domain of content (i.e., stated goal and objective). That is, how well does the parameter measure whether or not a particular project goal has been met. It is also important to keep in mind that while some parmeters, on their own, may not serve as very good indicators of goal attainment, when used in combination with other parameters they may be very useful. Measuring multiple, often related, parameters for a particular goal (or objective) can help validate your measurement and strengthen your conclusions regarding goal attainment.

Workshop on Monitoring the Human Dimension Aspects of Coastal Restoration:

In April, 2004 over 40 experts convened for three days to discuss human dimensions goals, objectives, and monitoring of coastal restoration projects. This workshop was sponsored by The Program for the Human Dimensions of Marine and Coastal Ecosystems, a collaboration between The University of Massachusetts-Amherst, Department of Natural Resources Conservation, Human Dimensions Research Unit and NOAA's National Ocean Service. Professionals with diverse human dimensions and coastal restoration expertise and backgrounds (e.g., sociology, cultural anthropology, resource economics, geography, recreation and tourism, fisheries management etc.) came from all over the United States to participate. Participants included representatives from government agencies, non-governmental organizations (NGOs), and over 15 universities. This workshop was an important first step in identifying the human dimension aspects of coastal restoration and formulating a systematic approach to addressing those aspects.

Coastal Recreation, Tourism and Access Goals (see matrix Appendix I):

- Increase the number of recreational opportunities
- Increase the level of recreation activity
- Increase the quality of recreational opportunities
- Improve tourism and ecotourism
- Enhance access to coastal resources

COASTAL RECREATION, TOURISM, AND ACCESS

Goals and Objectives

The use of coastal areas for recreation and tourism in the Unites States has increased dramatically in recent years. More than one-half of all Americans visit a coastal area each year and coastal recreation and tourism are critically important for the U.S. economy. People flock to coastal areas to participate in a variety of recreational activities, most of which are either dependent upon or greatly enhanced by healthy functioning coastal ecosystems.

Figure 6. Kayaking along the Patuxent River, Chesapeake Bay, Maryland. Photo by Mary Hollinger, NODC biologist, NOAA, from the NOAA Photo Library. http://www.photolib.noaa.gov/coastline/line2034.htm

Healthy ecosystems are the attraction to which people are often drawn. The creation of opportunities for coastal recreation and tourism, via a healthy ecosystem, can result in a number of positive social and economic impacts including the creation of jobs, an increased tax base, increased local household incomes and improved infrastructure. However, depending on the activity type, style, participants' modes of conduct, and use level allowed, many forms of coastal recreation and tourism can be detrimental to the very ecosystems they depend upon. Therefore, coastal restoration practitioners need to consider whether or not project goals associated with recreation, tourism and access will conflict with other project goals or undermine the restoration effort as a whole. Some forms of coastal recreation are more "eco-friendly" than others and therefore are more compatible with ecological restoration goals. Similarly, certain types of tourism and

Figure 7. Recreational angler fishing for striped bass (Chesapeake Bay, MD). Photo by Ronald Salz, NOAA NMFS, Silver Spring, MD.

Figure 8. Sailboats racing in America's Cup off Newport, Rhode Island. Photo by Commander John Bortniak, NOAA Corps. From the NOAA Photo Library. http://www.photolib.noaa.gov/corps/corp1728.htm

Coastal Recreation and Tourism in the U.S.: Selected Facts and Figures

(Sources: Leeworthy and Wiley 2001; Restore America's Estuaries 2002; NOAA International Year of the Ocean web site).

- In the U.S., about 89 million people (age 16 and older) participate in some form of marine recreation each year
- Beaches are the number one tourist destination in the U.S.
- An estimated 21 million people (age 16 or older) participate in saltwater fishing each year
- Recreational saltwater fishing creates over $6.6 billion in wages and an estimated 288,000 jobs annually (USDI and USDC 1997)
- Nearly 11 million people (age 16 or older) participate in snorkeling or SCUBA diving each year
- Over 31 million people (age 16 or older) participate in coastal viewing activities such as bird watching, other wildlife, and viewing or photographing scenery

Selected Coastal Recreation Activities

Visit beaches	Personal watercraft
Fishing	Wind surfing
Water-skiing	SCUBA diving
Visit waterside	Canoeing
Motorboating	Waterfowl hunting
Bird watching	Surfing
Viewing other wildlife	Kayaking
Swimming	Rowing
Sailing	Viewing scenery
Snorkeling	Photography

recreation will be more compatible with the human dimensions goals of enhancing and protecting aesthetic, historic and cultural values in coastal areas than will other types of tourism and recreation. Coastal stakeholders will need to decide what type of coastal ecosystem they want when assessing the appropriateness of restoration goals related to recreation, tourism and coastal access.

Recreational goals associated with coastal restoration can be categorized into three main types: (1) increase the level of recreation activity, (2) increase the number of recreational opportunities, and (3) increase the quality of recreational opportunities. Specific objectives under the goal 'increase level of recreation activity'[3] may be to increase the number of annual recreation visitor days (**RVDs**) in any one or several of the coastal recreation activities shown above. Other objectives connected to this goal would be to increase economic activity and jobs in various outdoor recreation sectors.

Conflict, in outdoor recreation, is defined as behavior of an individual or group that is incompatible with the social, psychological, or physical goals of another person or group (Manning 1999). **Outdoor recreation conflict** can occur between persons engaged in the same activity, in different recreational activities (e.g., jet-skis and anglers), or between recreationists and other non-recreation users (e.g., commercial fishermen and anglers). **Crowding** is a form of conflict that is based on an individual's judgment of what is appropriate in a particular recreation activity and setting. Use level is not interpreted negatively as crowding until it is perceived to interfere with one's objectives or values. Besides use level, factors that can influence perceptions of crowding include participant's motivations, expectations, and experience related to the activity, and characteristics of those encountered such as group size, behavior, and mode of travel (e.g., motorized versus non-motorized) (Manning 1999). While many other factors are involved, in general, as use level increases the potential for conflict and crowding in outdoor recreation settings will increase as well.

Another potential recreation-related goal is to increase the number of recreational opportunities in coastal environments[3]. If opportunities for coastal recreation increase at a faster rate than use level, this goal may actually reduce conflict and crowding by dispersing participants over a larger area. Objectives related to this goal include:

Figure 9. Beaches provide multiple recreational opportunities including sunbathing, swimming, sailing, and parasailing (Lauderdale by the Sea, FL). Photo by Ralph F. Kresge, NOAA Corps Collection, from the NOAA Photo Library.

[3] See "Coastal Recreation, Tourism, and Access Related Goals" in Appendix I.

- Add or improve recreation facilities (e.g., coastal parks, nature centers, marinas, boat ramps, trails, toilets)
- Add access points
- Increase the number of commercial providers (e.g., charterboats, eco-tourism outfitters, guides)
- Reduce the number of beach closures, shellfish area closures and finfish consumption advisories

The third type of recreational goal is aimed at improving the quality of recreational opportunities[4] available in coastal areas. One objective related to this goal could be to increase user satisfaction for any number of recreational activities. Satisfaction in outdoor recreation is defined as the difference between desired and achieved goals (Manning 1999). Since conflict is goal interference attributed to another's behavior, reducing perceptions of conflict (and crowding) will likely increase satisfaction ratings. People typically have multiple goals or motivations for engaging in a particular activity and many outdoor recreation motivations are not activity-specific. For example, anglers often cite motivations not related to actually catching fish (e.g., for relaxation, to be outdoors, to share experiences with friends and family) as being more important than catch-related motivations (e.g., the excitement of the catch, to catch a trophy fish) (Salz et al. 2001). Quality of recreational opportunities might be increased by focusing on catch-related indicators (e.g., catch/harvest rates, average fish size, number of trophy fish caught), reducing fish/shellfish advisories and closures, reducing beach closures, or improving aesthetics of the recreational experience (e.g., scenery and viewscapes) and other nonactivity-specific components.

Because coastal recreation and tourism are so closely interconnected, many of the specific objectives (discussed above) associated with increasing the level, number and quality of recreational opportunities would also apply to the goal of improving tourism[4] in general. People who are attracted to coastal destinations for recreation will also spend money on food, lodging, souvenirs, gifts, gas and other items that benefit the tourism industry. In addition to recreation, people visit coastal areas to learn about and appreciate maritime history, culture, folklore and traditional ways of life. Enhancing these opportunities may be identified as an

Figure 10. Having fun at the beach, Beach havaen, New Jersey (1930). Photo by Mr. Benton Hickok, America's Coastlines Collection, from the NOAA Photo Library. http://www.photolib.noaa.gov/coastline/line1753.htm

Figure 11. Sign for public beach access. Photo courtesy of NOAA Coastal Services Center web site.

[4] See "Coastal Recreation, Tourism, and Access Related Goals" in Appendix I.

objective if a connection can be made between the restoration project and this type of coastal tourism.

Closely related to recreation and tourism goals of coastal recreation is the goal of enhancing access to coastal resources. In order to take advantage of the many coastal recreation and tourism opportunities that exist, people must have access to coastal habitats[4]. Increasing opportunities for access to coastal areas of recreational, historical, aesthetic, ecological, or cultural value is cited as a high priority under the federal Coastal Zone Management Act. When discussing coastal access it is important to make the distinction between private access and public access. Commercial, residential and industrial development (and associated infrastructure) along the coast continues to increase as the number of people visiting and moving to coastal areas increases. Privatization of coastal lands limits the public's perpendicular access to the coast (see Figure 12). Lateral access along the coast is a public right protected by the Public Trust Doctrine. Under the common law Public Trust Doctrine submerged lands and water below the mean high water mark (in most states), are held in trust by the states for public use and enjoyment (e.g., fishing, shellfishing, boating, walking) (Coastal States Organization 2000).

Many of the objectives associated with enhancing coastal access are similar to those for increasing the number and level of recreational opportunities (discussed above; also see Appendix I). Access may also be enhanced for commercial uses such as commercial fishing. Coastal restoration projects can enhance access through the physical functions of healthy coastal ecosystems including shoreline stabilization, erosion control, flood control, and sediment retention. These natural functions may also preclude the need for hard structural shoreline stabilization solutions (e.g., jetties, breakwaters, and seawalls) which can not only impede access but may also be dangerous to beach users.

Similar to increasing coastal recreation, the goal of enhancing access as part of a coastal restoration project is a double-sided issue. While there are many associated social and economic benefits, public access to coastal resources may also have detrimental effects on native plants, animals, and geographic features of restored habitats (NOAA Coastal Recreation and Tourism website). For restoration efforts oriented towards ecosystem benefits, rather

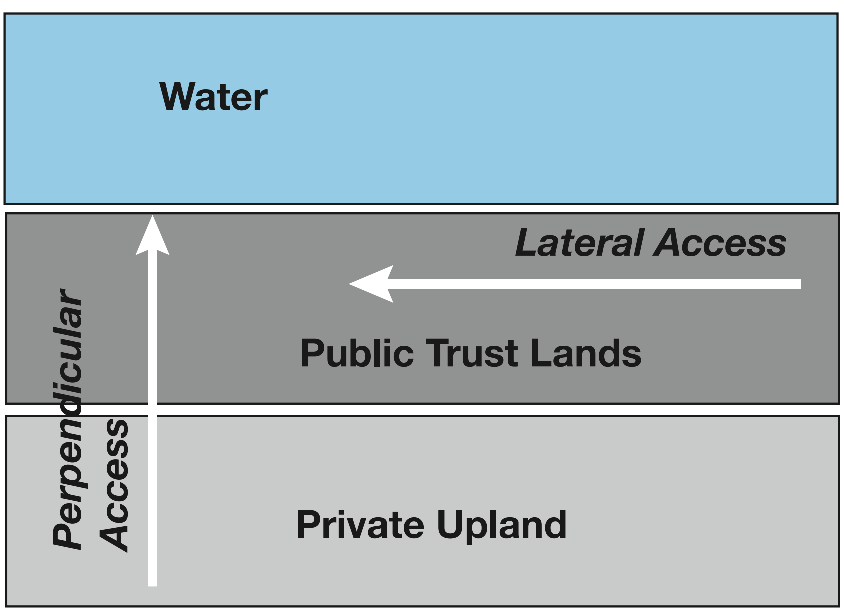


Figure 12. An illustration explaining the difference between lateral access and perpendicular access in coastal areas.

than human dimensions benefits, one of the goals may be to reduce access in order to protect sensitive ecological features or species at risk. If, however, enhancing access is a goal of restoration, practitioners need to consider ways to plan for and accommodate associated human impacts while protecting the natural environment. Strategies that might be employed include:

- Gates and buffers placed around sensitive areas
- Public education about erosion impacts, litter, and wildlife disturbance
- Signage to indicate paths and discharge improper behavior
- Regulations with fines and penalties for improper behavior (NOAA Coastal Recreation and Tourism website)

Monitoring Measurable Parameters

Measurable parameters for recreation, tourism, and access related goals of coastal restoration are listed in Appendix I. Suggested methods and existing data sources that may be helpful in monitoring these parameters can be found here. Additional sources of information (web sites and general references) are also provided.

Survey Research

Monitoring many of the parameters related to recreation goals and objectives will involve collecting information from the recreation participants themselves. These include both cognitive variables (e.g., perceptions of conflict and crowding, and user satisfaction) and behavioral variables (e.g., economic expenditures, number, size and species of fish caught, and activity avidity). Some of this information may already be collected by various federal and state natural resource agencies, universities and non-governmental organizations (see references below and Appendix II). Since this list is not exhaustive, it is recommended that you contact federal, state, and local agencies in your project area for more information on existing human dimensions data sources. Many of these existing data sources may be more useful for program level monitoring as results are typically summarized over a wide geographic area. If existing data are not available to monitor recreation/tourism related goals at the spatial scale required for an individual project, practitioners may decide to conduct their own data collection.

Survey research is the administration of questionnaires to a sample of respondents selected from some defined population (Babbie 1989). This research method is widely used in the social sciences and is especially suited for making descriptive studies of large populations. Space does not allow for a thorough discussion of social science survey research methods here. Instead, we provide a general overview of the topic and direct the reader to additional sources of information that may be useful in designing and implementing survey research.

Types of Survey Error
(Source: Salant and Dillman 1994)

- **Coverage Error** – occurs when the list – or frame – from which a sample is drawn does not include all elements of the population that researchers wish to study
- **Sampling Error** – occurs when researchers survey only a subset or sample of all people in the population instead of conducting a census
- **Measurement Error** – occurs when a respondent's answer to a given question is inaccurate, imprecise, or cannot be compared to other respondent's answers
- **Nonresponse Error** – occurs when a significant proportion of the survey sample do not respond to the questionnaire and are different from those who do in a way that is important to the study

Earlier in this chapter we introduced the statistical terms reliability and validity (see side box, page 14.10). Anyone conducting survey research should be aware of the different sources of error that can affect the reliability or validity of survey results. While survey error can never be completely eliminated, through early identification of potential sources, survey researchers may be able to minimize this error in the design and implementation phases of the study. The four types of error researchers need to be aware of are described in the box below. Please refer to the additional readings for more detailed discussion of reliability, validity, and ways to minimize errors in survey research.

Three major survey research methods are used to elicit information from respondents: the mail questionnaire, the personal interview, and the telephone survey (Frankfort-Nachmias and Nachmias 1992). Hybrids and combinations of these three basic approaches are also used. For example, an on-site interview may be conducted to collect names, addresses, and/or phone numbers of willing participants for a follow-up mail or telephone survey. Drop-off surveys involve surveyers going door-to-door to personally deliver questionnaires to households or businesses. Another variant is the windshield survey where questionnaires, along with a self-addressed stamped envelope, are placed on car windshields at strategic locations (e.g., boat launch site, beach parking lot). Deciding which survey method is best suited for your particular research objectives may depend on a number of factors. These include:

- Study topic – quantity, type, complexity and sensitivity of questions asked
- Survey population – availability of phone number and/or addresses, anticipated response rates, demographics (e.g., age, ethnicity, income)
- Money – amount budgeted and facilities available for interviewing
- People – number and experience of available staff and survey expertise of researchers
- Time – how much time you have to produce results

Each of the three major survey types (mail, personal, telephone) has different advantages and disadvantages associated with them. These are listed and briefly explained below under factors to consider when selecting a survey method. For a more complete discussion of each survey type please refer to the survey research references provided at the end of this section.

Another important step in survey research is selecting a sample. A **sample**, as defined in this context, is a set of respondents selected from a larger population for the purpose of a survey (Salant and Dillman 1994). Sample surveys are powerful in that they allow one to describe the characteristics of an entire population based on relatively few respondents. Sampling may not be necessary for small study populations where you attempt to survey all individuals or households in your target population. However, for most survey research, sampling is an efficient way to save time and money while still collecting high quality statistical information.

If you decide that sampling is necessary for your restoration monitoring plan, you need to identify the **target population**, consider if you need a population list, and select the sample (Salant and Dillman 1994). The **population list** is the list from which the sample is drawn. Population lists can come from many different sources and there are many kinds of lists such as telephone directories, club membership, landowners property tax lists, and license holders (e.g., hunting, fishing, shellfishing). Population lists may not always be necessary as in the case of random-digit dialing telephone surveys or with personal on-site interviews (e.g., you identify all the boat launch sites in the study area and then randomly select boaters to interview at those

Factors to Consider When Selecting a Survey Method
(Sources: Salant and Dillman 1994; Frankfort-Nachmias and Nachmias 1992; Babbie 1989)

- **Cost –** mail surveys are generally less expensive than telephone surveys. Both mail and telephone surveys allow for wide geographic contact at minimal cost. Personal interviews are typically the most costly method.
- **Staff expertise / training** - since they are self-administered, mail questionnaires do not require trained interviewers. Both telephone and personal interviews require trained interviewers.
- **Interviewer-respondent interaction bias –** self-administered mail surveys eliminate bias that may result from the personal characteristics of interviewers, variability in their skills or the tendency for respondents to give answers they think the interviewer wants to hear. Potential for this kind of bias is greater with personal interviews than telephone interviews.
- **Privacy and anonymity –** it is easier for respondents to answer personal or sensitive questions in writing at home (i.e., mail survey) than to a stranger on the phone or an interviewer in public
- **Considered answers and consultations –** mail questionnaires are preferable when questions demand a considered (rather than immediate) answer or if answers require consulting personal documents or other people
- **Noncoverage error –** lists of names, addresses or phone numbers are sometimes difficult to obtain and are almost never complete. Telephone surveys can avoid the problem of unlisted numbers by using random-digit dialing.
- **Nonresponse error –** some people are less likely to respond to a mailed questionnaire than others. Those interested in the topic are more likely to respond while those who cannot read or understand the questions are unlikely to respond. Item nonresponse may also be an issue if respondents skip over difficult or boring questions. Nonresponse can also be a problem with telephone surveys as people may resent the intrusion of being called at home. Other people may screen their calls or may be difficult to contact on the phone. Response rates for personal interviews are typically higher than either mail or telephone surveys.
- **Question complexity –** for mail surveys, questions must be straightforward enough to understand solely based on printed instructions. No opportunity exists for verbal clarification or for probing to clarify ambiguous answers, as does with personal or telephone interviewing. Mail questionnaires and personal interviews can include maps, tables, and graphical aides that cannot be shown over the telephone.
- **Control of interview situation –** with mail surveys the researcher has no control over who fills out the survey and cannot know for sure if the intended respondent answered the questions. Control of interview situation is highest for personal interviews and lowest for mail surveys.
- **Speed –** in general, telephone surveys produce faster results than either mail surveys or personal interviews. With computer-assisted telephone interviewing (CATI) data collection and data entry are combined into one step as respondent's answers are directly entered into the database.

sites). Once you have identified your target population and a population list (if necessary) you are ready to select the sample. Sample designs range from very basic **simple random sampling** to more complicated approaches involving multiple stages, **systematic sampling** intervals, **stratification**, **weighting,** and **clustering**. Space does not allow for adequate discussion of survey sampling designs here. For more information refer to the references at the end of this section. It is also recommended that you consult with a survey research expert to determine the survey design best suited for your monitoring effort.

Additional sources and survey research experts should also be consulted when designing a questionnaire for coastal restoration monitoring. Questionnaires should be designed to minimize measurement error and close attention should be paid to the exact wording, order, layout, and complexity of survey questions and instructions. Some issues to consider are (Salant and Dillman 1994):

- Do the questions contain emotional or biased words?
- How specific are the questions and what level of specificity is desired?
- Are respondents able to answer the questions?
- Are respondents willing to provide the information?

Practitioners may also want to consider using a **focus group** to assist in survey questionnaire design (see box below on focus groups). It is also strongly recommended that you pre-test your questionnaire on a sub-sample of the target population in order to identify and minimize any potential sources of error prior to full survey implementation.

Monitoring Facilities and Accessibility

Monitoring parameters related to recreation facilities and accessibility at the project level is fairly straightforward. For individual projects, an inventory can be kept to track changes over time in the number of marinas, boat slips, boat ramps, trail miles, commercial providers, and infrastructure development that are the direct result of the restored habitat. However, it may not be possible to link increased demand for coastal recreation facilities and infrastructure to improved water quality or ecosystem health within one small geographic area. Rather, changes in these parameters are more likely to result from the cumulative effect of many restoration projects rather than any one individual project. Therefore, these parameters may provide a better measure of recreation, tourism, and access goals if they are monitored at the program level (e.g., estuary, watershed, state).

Focus Groups

Focus groups are sometimes used to provide a head start on knowing which questions to ask in a survey. A focus group is a small group of people (i.e., 8 to 12) that are brought together by a moderator to discuss their opinions on a list of predetermined issues. Focus groups are designed to collect very detailed information on a limited number of topics. This data collection method can provide valuable insights into how and why people feel, think, and talk about an issue the way they do (NOAA Coastal Services Center, Human Dimensions of Coastal Management web site). Focus groups can be used either in conjunction with survey research or to help support findings of other methods. They are also occasionally used in a limited context as the primary data collection method for researching oral histories.

The number of new access points (both private and public) created by an individual restoration project can be monitored by practitioners through observation. Changes in the number of coastal access points can also be monitored at the program level. Most coastal states keep a detailed inventory of access points available to the public. It is recommended that you consult the appropriate state and local agencies and chambers of commerce in your project area to determine what data on coastal recreation facilities and access are available if you plan to monitor these parameters.

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Coastal Recreation, Tourism and Access Web Sites

- 1998 Year of the Ocean Coastal Tourism and Recreation Paper: http://www.yoto98.noaa.gov/yoto/meeting/tour_rec_316.html
- Developing Naturally: An Exploratory Process for Nature-Based Tourism, Clemson University: http://www.strom.clemson.edu/publications/Potts/DevNatbook.pdf
- Effectiveness of State Programs in Providing Public Access to the Shore, NOAA Office of Ocean and Coastal Resource Management: http://www.ocrm.nos.noaa.gov/czm/czmeffectiveness.html
- Environmental Impact Reduction Checklist for Recreation and Tourism, U.S. Environmental Protection Agency: http://es.epa.gov/oeca/ofa/pollprev/tour.html
- Environmental Implications of the Tourism Industry, Resources for the Future: http://www.rff.org/CFDOCS/disc_papers/PDF_files/0014.pdf
- Factors Related to Recreational Boating Participation in the U.S., Responsive Management: http://www.rbff.org/pressroom/Factors-Boatingreport.pdf
- Guidance for Best Management Practices For Caribbean Coastal Tourism, Island Resources Foundation: http://www.irf.org/ir_bmp.html
- Guidelines for Monitoring and Detecting Visitor Impacts, Sustainable Ecosystems Institute: http://www.sei.org/bulletin.html
- Nature-based Tourism, U.S. EPA, Office of Sustainable Ecosystems and Communities: http://www.epa.gov/ecocommunity/tools/econatt5.pdf
- NOAA Coastal Services Center Coastal Recreation and Tourism web site: http://www.csc.noaa.gov/techniques/recreation/index.html
- Oregon Sea Grant's Coastal Recreation and Tourism Pages: http://seagrant.oregonstate.edu/crt/
- Providing Public Access in Coastal Areas: Options for Landowners, Great Lakes Sea Grant Network: http://www.msue.msu.edu/imp/modtd/33840311.html
- Recreational Boating and Fishing Foundation Sponsored Research web site: http://www.rbff.org/research/
- Social, Environmental, and Economic Impact Analyses for Tourism, Western Rural Development Center: http://extension.usu.edu/wrdc/ctah/section9.html

Survey Research Methods - Some Suggested Readings

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- Dillman, D. A. 1978. Mail and Telephone Surveys: The Total Design Method. John Wiley, New York, NY.
- Fowler, Floyd J., Jr. 1993. Survey Research Methods, 2nd ed. Sage Publications, Newbury Park, CA.
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Figure 13. Community volunteers plant a salt marsh plant. *Spartina alterniflora*, at the Eastern Neck National Wildlife Refuge on Eastern Neck Island, Maryland. Photo courtesy of NOAA Restoration Center. http://www.photolib.noaa.gov/habrest/r0006500.htm

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- Krueger, R. A. 1994. Focus Groups: A Practical Guide for Applied Research. Sage Publications, Thousand Oaks, CA.
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ENHANCE COMMUNITY INVESTMENT

Goals and Objectives

Coastal restoration efforts are increasing throughout the United States and many of these projects are undertaken with the support of local residents, interest groups, and government agencies. However, some restoration efforts have resulted in public resistance and conflicts between stakeholders with different views on whether and how ecological restoration of public trust resources should proceed (Vining et al. 2000). Restoration and maintenance of healthy coastal habitats will require the long-term support of a broad cross-section of the public, and particularly support from the local community where the restoration takes place (Restore America's Estuaries 2002). Local stewardship and investment (i.e., buy-in) will facilitate long-term conservation and success of restoration sites. Community buy-in should also ensure that policies and social norms designed to protect restored habitats are self-enforced. Therefore, an important human dimensions goal of coastal restoration projects is to enhance community investment. Investment, in this context, is broadly defined and can include the allocation of resources (people, time, money, equipment, facilities), policy changes, or psychological investment (attitude change).

Before considering the different ways community investment in coastal restoration can be enhanced, it is important to first define community. One definition of community is

Figure 14. A student posing with planting equipment. Palmetto Estuary, Manatee County, Florida. Photo credit: Mark Sramek, NOAA Restoration Center, SE region, from the NOAA Photo Library. http://www.photolib.noaa.gov/habrest/r0022918.htm

a group of people who interact socially, have common history or other ties, meet each other's needs, share similar values, and often share physical space (U.S. EPA 2002). Another way to define community is as a "place" shaped by either natural boundaries (e.g., watershed), political or administrative boundaries (e.g., city, neighborhood), or physical infrastructure (U.S. EPA 2002). Thus, a comprehensive understanding of the multi-faceted concept *community* should incorporate both a *sense of community* as described in the first definition and a *sense of place* as described in the second definition. For a detailed discussion on community definition and identification of community characteristics relevant to coastal restoration monitoring refer to the EPA document - Community Culture and the Environment: A Guide to Understanding a Sense of Place.

One important objective within the overall goal of enhancing community investment is to increase volunteerism in coastal restoration activities. Volunteers are often an essential component for the success of restoration projects. People have different, and often multiple, motivations for volunteering in ecological restoration efforts including helping the environment, exploration and learning, spiritual enhancement, social interactions, and self-esteem (Grese et al. 2000). To meet this objective, practitioners should create opportunities for community members to participate in the implementation, maintenance, and monitoring phases of coastal restoration projects (Restore America's Estuaries 2002). People who live and work within the immediate vicinity of a restoration site can be alert to natural and anthropogenic changes in restored ecosystems. Volunteers can bolster community support, reduce project costs and bring energy and enthusiasm to restoration efforts (US EPA and NOAA). Good sources for volunteers include non-profit environmental groups, schools, public community service groups, and private service groups organized by local corporations. While volunteerism is encouraged, it is imperative that volunteers are properly trained and supervised in order to maintain the scientific integrity of your restoration project (Vining et al. 2000). For more information on volunteerism please refer to the web site given in the box on Volunteering for the Coast.

In addition to their many other benefits, coastal restoration projects may strengthen community members' sense of community and sense of place. By fostering collaborations and increased communications, restoration projects can bring individuals and groups within the community closer to one another and break down some of the social barriers that might have previously existed. One of the most effective ways to

Volunteering for the Coast

www.csc.noaa.gov/techniques/volunteer/index.html

Volunteering for the Coast is a web site for anyone interested in environmental stewardship through personal actions. The information provided on this site is for individuals looking for volunteer opportunities, coordinating volunteer efforts, or seeking ways to build successful volunteer programs.

Figure 15. Replanting marsh grass in an effort to protect and rebuild this beach near Annapolis, Maryland. Photo credit: Mary Hollinger, NODC biologist, NOAA, from the NOAA Photo Library. http://www.photolib.noaa.gov/coastline/line2326.htm

build trust among community members is to start with small restoration projects that have immediate visible results that all stakeholders can measure and contribute to. The elements of trust, reciprocity, and community cohesion are all captured in the term **social capital**. Social capital describes the internal social and cultural coherence of society, the norms and values that govern interactions among people and the institutions in which they are embedded. Social capital is the glue that holds societies together and without which there can be no economic growth or human well-being. Thus, enhancing community investment in coastal restoration is linked to enhancing social capital within the community.

Other specific objectives associated with the goal of enhancing community investment in coastal restoration include:

- Increase the extent to which restoration projects are accepted and encouraged within the local political structure (e.g., town meetings and community master plans)
- Increase the interest, involvement and buy-in of locally run non-governmental organizations (NGOs) and local businesses in restoration efforts
- Increase community members awareness and knowledge of, and appreciation for coastal restoration

Monitoring Measurable Parameters

There are several parameters that can be measured to monitor the goal of enhancing community investment. Volunteerism can be measured by counting the number of volunteers or number of volunteer hours devoted to a restoration project. These variables can be measured at all stages of the restoration project including planning, funding, implementation, maintenance, and monitoring. Basic demographic information (e.g., age, gender, occupation, zip code, ethnicity) can be solicited from volunteers to determine involvement levels according to town/neighborhood, ethnic group, socioeconomic group, or age group. If community investment is a stated goal of your restoration project, such information may be used to target groups that appear to be less invested. Another indicator of community investment is the activity level of non-governmental organizations (NGOs) or non-profits associated with a restoration project. This activity can be initiated by small, local NGOs and grassroots groups or by local chapters of larger organizations (e.g., Sierra Club, Audubon Society). Some communities may find it beneficial to form an NGO around a particular coastal restoration project. NGO activity can be measured in terms of inputs or resources expended (e.g., time, people, energy, money) or in terms of outputs (e.g., web sites, educational materials) directly related to the restoration effort.

Sponsorship of a restoration project by local corporations can also be an indicator of community investment. The National Corporate Wetlands Restoration Partnership (CWRP) is a public-private partnership between the federal government, state governments, and private corporations to restore wetlands and other aquatic habitats. The CWRP's objective is to protect, enhance, and restore wetlands and other aquatic habitats by partnering to leverage the collective resources, skills, and processes of the private and public sectors. For more information see their web site at: http://www.coastalamerica.gov/text/cwrp.html.

Community investment may also be measured by the extent to which coastal restoration is accepted and encouraged within the local political structure. Specific parameters that can be monitored include whether or not a restoration project is part of the community master plan (both short-term and long-term planning) and how often it comes up at official town meetings and other political forums. Attendance at town meetings when the restoration project is on the agenda may be an indicator of general interest in restoration, although not necessarily community buy-in or investment. Town policies such as zoning changes and tax incentives that are related to coastal restoration and a town's monetary contribution (i.e., portion of cost sharing) towards a coastal restoration effort may also be indicative of community investment.

Community investment in coastal restoration can also be measured by the attitudes and behaviors of community members. One measurable parameter is the extent to which locals use the restored coastal areas. Another indicator is the level of community communications related to coastal restoration such as local newspaper articles, newsletters, radio programs, and local television news segments. Surveys, personal interviews, focus groups, and voting behavior can also be used to measure community members' attitudes (i.e., psychological investment) towards coastal restoration projects. Some other social science research methods used for community assessment are shown in the table below.

Community Investment and Volunteering Web Sites

- Community Engagement and Volunteerism - A wealth of tools for school administrators, teachers, parent/family volunteers, and others who coordinate volunteer and community partnership activities between schools and other organizations, including businesses. http://www.tenet.edu/volunteer/main.html
- Concerned Citizens - Provides information on how you, your family, and your community can protect the environment. http://www.epa.gov/epahome/citizen.htm
- Healthy Communities Programs - Descriptions of services, training, and technical assistance offered by the National Civic League, including stakeholder analysis, visioning, assets mapping, facilitation, etc. http://www.ncl.org/cs/services/healthycommunities.html
- Managing Volunteer Programs - An overview of many volunteer management issues, from insurance to supervision techniques to assessing volunteer management practices. http://www.mapnp.org/library/staffing/outsrcng/volnteer/volnteer.htm
- Monitoring Water Quality - Provides information and guidance for volunteer water quality monitoring. http://www.epa.gov/owow/monitoring/vol.html
- National Park Service Volunteer Guidelines - Although the primary purpose of this document is to assist National Park Service volunteer coordinators in the management of their respective programs, this publication has also been a good resource for many

Community Assessment Research Methods (Source: U.S. EPA, Community Culture and the Environment: A Guide to Understanding a Sense of Place, 2002)

Method	Description
Asset Mapping	A graphical representation of a community's capacities and assets.
Cognitive Mapping	A method used to collect qualitative data and gain insight into how community members perceive their community and surrounding natural environment.
Concept Mapping	A method that collects data about how community members perceive the causes or related factors of particular issues, topics, and problems.
Social Network Mapping	A method used to collect, analyze, and graphically represent data that describe patterns of communication and relationships within a community.

private volunteer organizations. http://www.nps.gov/volunteer/vipguide.htm

- Volunteer Estuary Modeling – An Environmental Protection Agency manual with information and methodologies for volunteer efforts aimed at monitoring estuarine water quality. http://www.epa.gov/owow/estuaries/monitor/
- Volunteer Today: The Electronic Gazette for Volunteerism – An e-newsletter designed to 1) build the capacity of individuals to organize effective volunteer programs, and 2) enhance the profession of volunteer management. http://www.volunteertoday.com/
- Watershed Restoration: A Guide for Citizen Involvement – NOAA document providing information on how citizens can improve their watersheds. http://www.cop.noaa.gov/pubs/das/das8.html

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Figure 16. A group of boy scouts and their leaders plant native wetland plants in Palmetto, Manatee County, Florida. Photo credit: Peter Clark, Tampa bay Watch, from the NOAA Photo Library.

Protection: A Citizen's handbook for Protecting Ecosystems and Communities. EPA 230-B-96-003. Office of Policy, Planning and Evaluation, Washington, D.C.

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ENHANCE EDUCATIONAL OPPORTUNITIES

"Human needs and aspirations the world over can only be satisfied as environmental awareness leads to appropriate action at all levels of society…Appropriate action requires a solid base of sound information and technical skills. But action also depends upon motivation which depends upon widespread understanding, and that, in turn, depends upon education."

\- Mostafa K. Tolba (former Director) United Nations Environment Program

"Successful restoration requires an informed public willing to support the policies, funding, and lifestyle changes necessary to maintain healthy and productive ecosystems."

\- Quoted from Restore America's Estuaries: A National Strategy to Restore Coastal and Estuarine Habitat (2002)

Goals and Objectives

Coastal restoration projects provide educational opportunities for increasing people's awareness, understanding and appreciation of coastal habitats, ecosystem functions, and nature in general. Opportunities may also be created to conduct research and educate the public on the human dimensions benefits associated with restoration. Outreach and education can be incorporated into coastal restoration projects at all stages (i.e., planning, implementation, and monitoring) as both the process and the outcome can enhance educational opportunities. Specific objectives within this goal include:

- Increase opportunities for formal education: exposure of K-12 students to environmental education through classroom activities and field trips, teacher training and knowledge base, curriculum development
- Increase opportunities for informal education: hands-on learning, brochures, television and radio public service announcements, newspaper articles and editorials, posters, informational kiosks, web sites (including text, pictures, real-time video and virtual tours of restored areas), workshops, public forums
- Increase opportunities in academia: undergraduate and graduate student learning and training, research projects, academic publications, journal articles, seminars, workshops, and poster sessions
- Increase opportunities for experiential education: interpretive centers and programs, interpretive signage, and guided eco-tours

Public school educational programs connected with a coastal restoration project can include:

Figure 17. Coastal habitats provide many unique and exciting educational opportunities for students of all ages. Photo from the NOAA Photo Library.

- An assessment of student perceptions, attitudes and knowledge about coastal habitats and restoration efforts
- Identification of how learning goals can be made compatible with student learning potential
- Identification of how subject matter exercises can be introduced at restoration project sites and in the classroom, and
- Assessment of how communication links can be established with other schools and learning facilities (e.g., museums, nature centers) to extend the learning chain (Nordstrom 2003)

The use of restoration project sites to promote educational goals can be accomplished through both active (e.g., on-site tours, lectures, and programs conducted by specialists) and passive (e.g., posting signs for tourists passing the area) learning techniques (Nordstrom 2003). It is important that posters and signs describing coastal restoration projects are designed for interpretive rather than solely scientific value, and are presented at the appropriate comprehension level using common terms, simple story lines, colorful word pictures, and bold graphics (Hose 1998).

Monitoring Measurable Parameters

In order to monitor measurable parameters associated with enhancing educational opportunities, restoration practitioners will need to contact the various schools, universities and colleges, museums, media outlets, nature centers and other educational sources in the area that may be involved with coastal habitat education. Counts of the number of interpretive centers and programs, research projects, students and teachers trained, school field trips, classroom activities, and guided eco-tours should be readily attainable from these sources. Similarly, the number of opportunities for informal education (see above) related to a restoration project can also be quantified. However, in assessing whether or not particular educational goals (or objectives) have been met, it is important to establish a clear connection between the restoration project and any observed increase in these educational activities. For example, an elementary school may be developing a curriculum on wetlands that is independent of a local wetlands restoration project. It is, therefore, recommended that coastal restoration practitioners be proactive in advancing their educational goals by contacting schools, universities and local media and developing creative ways to turn restoration projects into educational opportunities.

PROTECT OR IMPROVE HUMAN HEALTH

Goals and Objectives

An important human dimensions goal of coastal restoration is to protect and improve human health. Healthy coastal ecosystems perform many ecological services and life-supporting functions (e.g., pollution removal, water filtration, flood protection) that are critical to our health and survival. When these ecosystems become degraded human health and safety are jeopardized. The Estuary Restoration Act of 2000 clearly states that priority should be given to restoration projects that "promote human health and safety and the quality of life for individuals and families." Specific objectives under the general goal of promoting human health and safety include:

- Reduce the number of health advisories for fish, shellfish, and waterfowl consumption
- Reduce the number and duration of shellfish area closures
- Reduce the number of drinking water health advisories
- Increase the level of compliance with federal and state water quality standards
- Reduce the number, area, and duration of beach closures
- Reduce the incidence of disease related to seafood consumption and water-borne illnesses
- Reduce biotoxin levels and the number, area, and duration of harmful algal blooms (HABs)
- Reduce the number of hypoxia events

Toxic substances, such as metals (e.g., mercury and lead) and toxic organic chemicals (e.g., PCBs and dioxin) that originate from industrial discharges, runoff from city streets, mining activities, runoff from landfills, atmospheric deposition, and a variety of other sources, can severely disrupt the nearshore waters habitat. These toxic substances can cause death or reproductive failure in the fish, shellfish, and

Figure 18. One human dimensions goal of coastal restoration is to increase the number of "swimable and fishable" bodies of water. Photo courtesy of the County of Orange, California web site.

wildlife that use the habitat. In addition, they can accumulate in animal and fish tissue (leading to fish consumption advisories), become attached to sediments, or find their way into drinking water supplies, posing long-term health risks to humans. Pesticides and herbicides used on farmlands and lawns can be washed into ground and surface waters by rainfall, snowmelt, and irrigation practices and may, ultimately, find their way to nearshore waters. These contaminants are usually very persistent in the environment and can accumulate in fish, shellfish, and wildlife to levels that pose a risk to human health and the environment. Restored wetlands can reduce these risks by filtering toxics and other pollutants out of the system before they can bio-accumulate or contaminate drinking water supplies.

A condition known as *hypoxia,* or oxygen depletion, occurs primarily during the summer in over half of the major estuaries in the United States (Rabalais 1998). Its duration and extent range from a few weeks and limited areas to several months and expansive areas. Human activities such as changes in land use and nutrient enrichment increase the likelihood of this phenomenon. Increases in nutrient inputs clearly and directly relate to population density in watersheds draining to coastal areas. Population-driven increases in nutrient loading are causing problems in the form of oxygen depletion, habitat loss, fish kills, and increasing the frequency and duration of harmful algal blooms (Rabalais 1998). Since coastal wetlands (and other habitat types) naturally reduce nutrient loading to receiving waters, reducing the number of hypoxia events in a particular body of water may be an objective of coastal restoration.

Human beings are exposed principally to the naturally occurring toxins produced by harmful algal blooms (HABs) through the consumption of contaminated seafood products which can result in illness and even death. Many scientists have suggested that increases in HABs are somehow linked to increased pollution of coastal habitats. Therefore, coastal restoration efforts may be an effective management tool for protecting human health from HABs. The most significant public health problems caused by harmful algae are: Amnesic Shellfish Poisoning, Ciguatera Fish Poisoning, Diarrhetic Shellfish Poisoning, Neurotoxic Shellfish Poisoning, Paralytic Shellfish Poisoning, and Pfiesteria (see box below). Each of these syndromes is caused by different species of toxic algae which occur in various coastal waters of the United States and throughout the world. For more information on these syndromes go to the Woods Hole Oceanographic Institute Harmful Algae Page web site at: http://www.whoi.edu/redtide/illness/illness.html

Public health protection is a shared responsibility between federal, state, and local agencies and Native American tribes. This responsibility includes informing citizens of the possible health hazards associated with eating chemically contaminated fish, shellfish, and waterfowl from contaminated waters. This is done through consumption advisories that are issued for particular water bodies and species,

Fish Kills in Chesapeake Bay

During the 1990's, massive fish kills occurred in estuaries in North Carolina and Delaware and in the Chesapeake Bay and its tributaries. Watermen working in the area of the kills experienced flu-like symptoms, rashes, and memory loss. The kills and associated fish ulcers have been linked to conditions related to excess nutrients, including low oxygen levels and blooms of toxic algae and infectious disease agents. Excess nutrients are introduced into estuarine systems through changes in water management and land use throughout the watershed. Some forms of restoration, as well as changes in regional management approaches, can help to alleviate this problem and enhance human health and enjoyment in this region. Source: NOAA web site "Harmful Algal Blooms" http://www.hab.nos.noaa.gov/pfiesteriafacts.html

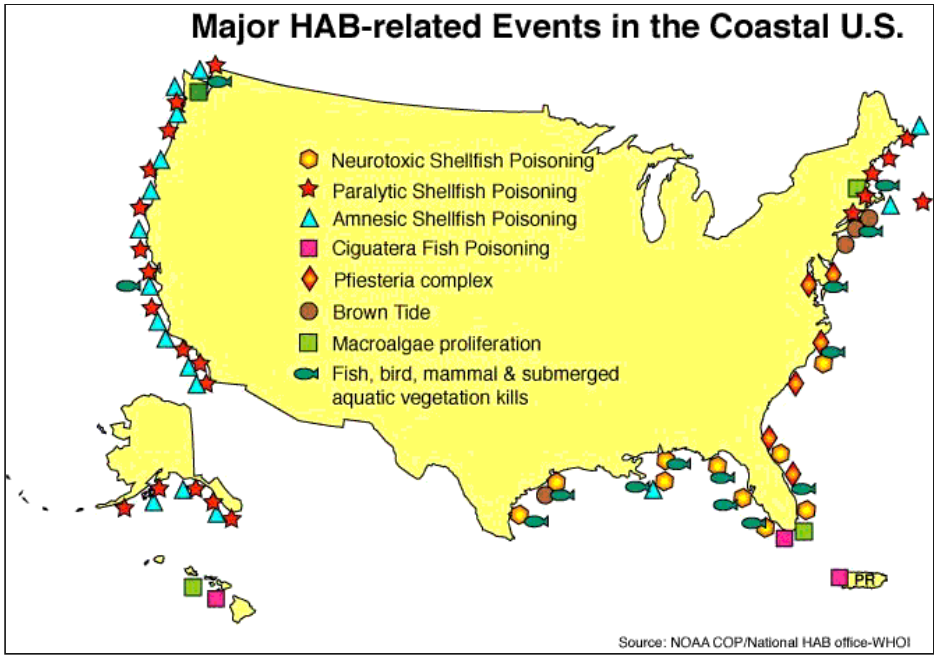

Figure 19. Major HAB-related events in the coastal U.S. as of 2004. Photo courtesy of U.S. National Office for Marine Biotoxins and Harmful Algae Blooms, Woods Hole Oceanographic Institution, Woods Hole, MA.

and can apply to either the general population or specific vulnerable subpopulations such as pregnant women or children.

Human health is also protected by beach and shellfish area closures generally issued by state or local natural resource agencies. Pathogens are microorganisms such as bacteria and viruses that can cause human health problems. These organisms enter water bodies from sources such as inadequately treated effluent from sewage treatment plants, storm water drains, faulty septic systems, medical waste, runoff from livestock pens, and boats that discharge untreated or poorly treated sewage. When found at unsafe levels in nearshore waters, pathogens can lead to beach and shellfish bed closures. Shellfish area closures are generally based on state and national water quality standards. Unlike consumption advisories, which are merely suggestive, shellfish area closures are legally enforced and persons found poaching shellfish in closed areas can be fined or imprisoned. Conditional harvesting programs allow the shellfish digger to take shellfish from areas that are usually classified as uncertified or closed. During periods of little or no rainfall, when non-point source runoff is not carrying high levels of bacteria and other contaminants into these areas, water quality improves to the point where it meets the high standards for certified shellfishing areas.

Officials at the state and local level make public health decisions about beach closings. The Beaches Environmental Assessment and Coastal Health (BEACH) Act of 2000 requires each state and territory with coastal recreation waters to adopt health-based bacteria standards that are “as protective of human health” as EPA’s 1986 criteria for bacteria. Federal grants are provided to states for beach monitoring and public notification programs, technical guidance, scientific studies, and Federal water quality standards to backstop state and territorial efforts where necessary.

Coastal restoration projects may also help achieve the human health objectives related to drinking water quality. The EPA’s Office of Ground Water and Drinking Water (OGWDW), together with states, tribes, and its many partners, protects public health by ensuring safe drinking water and protecting ground water. OGWDW, along with EPA’s ten regional drinking water programs, oversees implementation of the Safe

Drinking Water Act, which is the national law safeguarding tap water in America. For more information about ground water and drinking water quality go to the EPA web site at: http://www.epa.gov/OGWDW/

In addition to protecting us from disease and illness, healthy coastal ecosystems can also promote mental health. There are many psychological benefits associated with recreating and working in healthy environments that can be enhanced by coastal restoration efforts. Clean, healthy ecosystems have been linked to the promotion of community welfare and social capital and the reduction of crime in some areas. Coastal restoration also promotes the physiological benefits associated with certain types of coastal recreation such as hiking, kayaking, or swimming.

Monitoring Measurable Parameters

As with other human dimensions coastal restoration goals, program level monitoring on a large geographic scale (e.g., entire estuary or watershed) may be required to evaluate some of the measurable parameters associated with human health. Shellfish advisories and area closures may, in some cases, be localized enough to allow for project level monitoring of this parameter. Depending on the restoration project, parameters related to drinking water quality might also be measured at the individual project level. Due to the migratory nature of many fish species, fish advisories often cover a wide geographic area. Therefore, it will be very difficult, if not impossible, to attribute changes in recommended fish consumption levels over time to an individual restoration project. Data on incidence of shellfish consumption diseases and water-borne illnesses, hypoxia events, and HABs may not be available at the geographic scale required for individual project level monitoring. Even if such data are available (or collected by the restoration practitioner) at the desired scale, it may still be difficult to establish a direct causal link between a particular restoration effort and a change in any of these parameters over time. Many other factors can affect these variables, particularly when measured on a small geographic scale.

Existing data sources from various federal, state, local, and Tribal authorities are available for many of the health-related parameters restoration practitioners may want to measure. Environmental and natural resource agencies in coastal states routinely collect information on hypoxia events and harmful algal blooms (HABs) that may be of use for coastal restoration monitoring. Many universities also conduct research on HAB outbreaks that may be used to monitor changes in the number, area, and duration of HABs over time. To find out more about available HAB data in your project state visit the NOAA Coastal Services Center Harmful Algal Bloom Project web site at: http://www.csc.noaa.gov/crs/habf/resources.html

The National Listing of Fish and Wildlife Advisories (NLFWA) describes health advisories issued by the federal government, states, territories, tribes, and local governments. Restoration practitioners can use the NLFWA to get information on nearly 2,800 advisories in the United States at http://www.epa.gov/waterscience/fish/. Information provided for each advisory includes:

- Species and size of fish or wildlife under advisory
- Chemical contaminants covered by the advisory
- Location and surface area of the waterbody under advisory
- Population subject to the advisory
- Local contacts (including names, phone numbers, and websites)

The NLFWA web site can be used to generate national, regional, state, or local maps that illustrate advisory information. For monitoring restoration parameters related to human health, it is also recommended that you contact the local, state, or tribal health advisory representative in your project area. http://map1.epa.gov/scripts/.esrimap?name=Listing&Cmd=StContacts

EPA has developed a Beach Advisory and Closing Online Notification system (BEACON) to make state beach advisory and closing data available to the public. In BEACON, each beach is geographically displayed on a map that links the beach to data. Restoration practitioners can select a beach and view the available data for that beach by either choosing a state and county or typing the beach name. Information provided for each beach includes contact information, monitoring and notification program information, general beach characteristics, advisories and closings, and location data. For more information or to use the BEACON system go to: http://oaspub.epa.gov/beacon/beacon_national_page.main

Every community water supplier must provide an annual report (sometimes called a consumer confidence report) to its customers. The report provides information on local drinking water quality, including the water's source, the contaminants found in the water, and how consumers can get involved in protecting drinking water. For many areas these reports can be accessed online at EPA's Local Drinking Water Information web site (http://www.epa.gov/safewater/dwinfo.htm). This site contains detailed information that restoration practitioners may be able to use in monitoring changes in water quality over time. It is also recommended that you contact local water suppliers and state and local health officials for additional information.

In addition to state and local health agencies, the federal Centers for Disease Control and Prevention (CDC) is another good source of existing information on the incidence of disease and illness. CDC is recognized as the lead federal agency for protecting the health and safety of people. Within CDC, the National Center for Health Statistics is the agency responsible for monitoring the health status of the population. For more information visit their web site at: http://www.cdc.gov/nchs/about.htm.

Hypoxia, Harmful Algal Bloom and Fish Toxicity Web Sites

- NOAA National Centers for Coastal Ocean Science, Harmful Algal Blooms web site: http://www.cop.noaa.gov/Fact_Sheets/HAB.html
- NOAA Coastal Services Center Harmful Algal Bloom Project web site: http://www.csc.noaa.gov/crs/habf/resources.html
- National Office for Marine Biotoxins and Harmful Algal Blooms - Woods Hole Oceanographic, The Harmful Algae Page: http://www.whoi.edu/redtide/

Hypoxia, Harmful Algal Bloom and Fish Toxicity References

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PROTECT TRADITIONAL, CULTURAL, AND HISTORIC VALUES

Goals and Objectives

Culture is in many ways shaped, defined, and adapted based on one's surrounding natural environment (see box below for definition of culture). Environmental conditions and available resources can determine such things as the kinds of available food, materials from which clothing, tools, and shelters can be fashioned, and the cycle of human activities necessary for survival (Taylor 1992). Coastal regions of the U.S. are rich in cultural traditions and history that are intricately connected with the coastal resources found in those areas. Many people's

Definition of Culture
(Source: Parker and King 1998)

Culture is a system of behaviors, values, ideologies, and social arrangements. These features, in addition to tools and expressive elements such as graphic arts, help humans interpret their universe as well as deal with features of their environments, both natural and social. Culture is learned, transmitted in a social context, and modifiable. Synonyms for culture include lifeways, customs, traditions, social practices, and folkways. The terms folk culture and folklife might be used to describe aspects of the system that are unwritten, learned without formal instruction, and deal with expressive elements such as dance, song, music, and graphic arts as well as storytelling.

Figure 20. The Fishermen's Memorial at Gloucester, Massachusetts commemorating the thousands of fishermen who have lost their lives from this port. Photo by Nance S. True-worthy, from the NOAA Photo Library. http://www.photolib.noaa.gov/fish/fish0990.htm

Cultural Diversity in Coastal Louisiana
(Source: Louisiana Coastal Wetlands Conservation and Restoration Task Force and the Wetlands Conservation and Restoration Authority 1998)

Coastal Louisiana's residents represent a diversity of nationalities and cultures, including French, Spanish, Portuguese, German, Italian, English, Caribbean, Croatian, African, and American Indian. The largest and oldest immigrant group to colonize the wetlands is of French descent. New Orleans was founded by Bienville in 1718. Exiled Acadians from what is now Nova Scotia, Canada, began moving into the region beginning in the 1750's. All immigrants to Louisiana's wetland landscapes developed cultural practices tied to the annual-use cycle that is still linked to the region's natural resource base. Traditionally, thousands of coastal residents have been engaged in farming, hunting, trapping, shrimping, crabbing, oystering, and fishing.

cultural identity and integrity are dependent upon healthy coastal ecosystems (see box on the cultural diversity in coastal Louisiana). Some examples include the lobstermen of Maine, the Chesapeake Bay watermen, Louisiana Cajuns, and the Makah Tribe in the Pacific Northwest. Therefore, a potential goal of coastal restoration is to protect the traditional, cultural and historic values associated with the coastal resources we are attempting to restore.

Many coastal communities and indigenous peoples can trace their heritage of living off the land and sea back many generations. Traditional uses and practices associated with coastal resources are often consumptive in nature (e.g., fishing, hunting, gathering). The term "**subsistence**" is used to describe customary and traditional uses of renewable resources (i.e., food, shelter, clothing, fuel) for direct personal/family consumption, sharing with other community members, or for barter. Subsistence communities are often held together by patterns of natural resource production, distribution, exchange, and consumption which help maintain a complex web of social relations involving authority, respect, wealth, obligation, status, power, and security. Values associated with subsistence lifestyles include hard work, self-sufficiency, independence, reciprocity, trust, close-knit communities, and kinship networks.

Coastal resources can also be important for spiritual, religious, and ceremonial uses and for the continuity of maritime customs, traditions, folklore, and myth. Traditional uses might also

Figure 21. Eskimo woman and child ice fishing in the Bering Sea. Photo obtained from NOAA Photo Library. http://www.photolib.noaa.gov/fish/fish1363.htm

Figure 22. A prayer for calm seas, the Blessing of the Fleet is held on the Fourth of July in Kodiak Island, Alaska. Reverend Archimandrite Innocent (on the right) and the Reverend Sergios Gerken, at left, sprinkle holy water. Their Russian Orthodox faith arrived in 1784, when traders started Russia's first colony in North America. Photo courtesy of George F. Mobley, National Geographic Magazine, November 1993.

The Blessing of the Fleet, Stonington Connecticut

This annual event celebrates the cultural heritage and way of life of the fishing community of southeastern Connecticut, and is a way to honor those who have lost their lives at sea. "The Blessing" is a community celebration that reflects Portuguese culture and the Portuguese traditions of many of the fishermen. The festivities include a parade through town, and the actual blessing of the boats when the regional Bishop blesses the boats as they pass by in procession. A memorial wreath with a symbolic broken anchor is thrown overboard in honor of those fishermen who have been lost at sea. Similar "Blessing of the Fleet" events take place in fishing communities throughout the country.

include long-term or periodic use of an area for social events and community gatherings. For members of these communities, the value of protecting their traditional way of life is, of course, tremendous. However, cultural and historic values associated with coastal communities are also widely appreciated and valued by people outside those communities as well. For example, many people who visit or reside in fishing villages enjoy watching the commercial fishing boats, learning about local maritime history, and derive satisfaction from knowing that such traditional lifestyles still exist. Maritime festivals and other traditional social gatherings in coastal communities often attract tourists, providing coastal regions with additional economic benefits. In addition to historic and traditional use values associated with coastal resources, certain species of plants and animals also contain cultural symbolic value. These values are expressed through official state designations (i.e., the state fish or the state bird), wildlife license plate sales, and the purchase of fish and wildlife related merchandise.

People often impart special meaning to natural resources and hold certain place-based attachments to particular natural settings. Many of us reminisce about the way things used to be and have fond memories of childhood coastal experiences (e.g., fishing with a grandparent, collecting shells on the beach) that we hope to pass along to our children and grandchildren. Thus, coastal restoration may also protect the values associated with family traditions that are dependent upon healthy coastal environments.

Monitoring Measurable Parameters

The study of *culture* is the subject of investigation by specialists in several disciplines including anthropology, archaeology, ethnography, cultural geography, folklore, history, historic preservation, and sociology (Taylor 1992). Each of these disciplines studies culture from a different perspective and uses different techniques and methodologies for the collection and analysis of data (Taylor 1992) (see box on page 14.39 on interviewing). For more information on researching and documenting cultural values, please refer to the references

Interviewing
(Source: Taylor 1992)

Interviewing is an efficient technique for gathering data and the one most often used by many cultural specialists. When a fieldworker conducts an interview, he or she must determine the amount of control to be applied. A non-directed (or non-structured) interview encourages discussion of a wide range of topics that are largely determined by the interests of the informant. A directed (structured) interview is usually characterized by the interviewer's attention to very specific topics and questions. Sometimes the interviewer may change the approach. For example, an interviewer might switch from a directed to a non-directed approach if it becomes evident that an informant's storehouse of traditional knowledge presents an unusual opportunity for the documentation of many general aspects of local culture. Data elicited during interviews can be recorded in writing in the form of fieldnotes, or as answers to questions on a questionnaire. They can also be recorded verbatim on audiotape with a tape recorder, or recorded both aurally and visually on videotape with a video camera and sound unit. In the case of interviews recorded on audio or videotape, it is proper to ask the informant to sign a consent form in order to establish that he or she has given permission for the use of information on the tape. The text of the form should specify as accurately as possible where the tape recording will be deposited and how it may be used. If the informant wishes to place restrictions on the use of the recording, these restrictions should be written on the form.

and web sites provided at the end of this section. It is also recommended that you consult with an expert in one of the fields listed above before attempting to monitor these parameters.

While documenting maritime culture within a community or project area is possible, establishing a causal link between an individual restoration project and the protection of those cultural, historic and traditional use values may prove far more difficult. Although maritime cultural traditions are greatly dependent upon healthy coastal ecosystems, many other social, economic, and environmental factors will likely determine whether or not those traditions will continue and survive. Linking coastal restoration to the preservation of cultural values may also be difficult because the cultural benefits associated with restored ecosystems may be both spatially and temporally far removed. For example, restoring a marsh may enhance the nursery and breeding grounds of commercially valuable fish. However, since the mature stocks of fishes are usually geographically far removed from the marsh nursery, the cultural benefits may accrue to some geographically distant fishing village. It may also take several years before commercial fishery yields show any sign of increase, during which time many other confounding environmental social, economic, and regulatory changes may take place. Given these difficulties, monitoring the goal of protecting cultural and historic values is, in most cases, more feasible at the program level (or for very large individual restoration efforts). That is, the cumulative effect of many individual restoration projects throughout a watershed, estuary, or region may help to protect maritime cultural values and this effect may be measurable on a large spatial and temporal scale. Still, individual restoration

Figure 23. Makah Tribal members of the Pacific Northwest paddling traditional hollowed out red cedar canoes. Photo from the Makah Cultural and Research Center web site.

projects may be directly linked to particular cultural events and gatherings. An example would be a community "clam bake" that is made possible by the improved water quality resulting from a local restoration effort.

Traditional, Cultural, and Historic Values Web Sites

- American Folklife Center, Library of Congress: http://www.loc.gov/folklife/
- Cultural Resources Information on the Internet - Annotated descriptions of agencies and organizations with programs in cultural resources. http://www.nrcs.usda.gov/technical/cultural.html
- Indiana University, Oral History Research Center. http://www.indiana.edu/~ohrc/index.html
- Utah State University, Oral History Program. http://www.usu.edu/~oralhist/oh.html

Traditional, Cultural, and Historic Values References

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ENHANCE NON-MARKET VALUES AND IMPROVE AESTHETIC VALUES

Goals and Objectives

In economics, the term value refers to the price individuals are willing to pay in order to obtain a good or service. Traditional market goods and services are supplied by private firms and bought by consumers who pay market prices for them (NOAA 1995). However, for some goods and services no traditional market exists whereby suppliers and consumers agree on a price. These are cumulatively referred to as **non-market goods and services**. Restoration of coastal habitats can enhance the value of non-market goods and services.

Figure 24. The Great Egret is a common species seen in the lagoons of Mar Negro (Jobos Bay National Estuarine Research Reserve, Puerto Rico. Photo from the NOAA Photo Library. http://www.photolib.noaa.gov/nerr/nerr0506.htm.

Non-market economic values are often divided into two main categories: **direct use values** and **non-use values**. Direct use value refers to the set of values derived from any direct use of natural environments including for recreation, ecosystem services, or aesthetic enjoyment. Many of the ecosystem services provided by healthy coastal habitats (e.g., flood protection, nutrient cycling, pollution reduction, nursery grounds) cannot be valued using traditional market-based approaches. Coastal restoration projects may also enhance aesthetic values, a non-market good associated with our appreciation for beauty in nature (plants, animals, scenic landscapes, seascapes, viewsheds, etc.). A specific objective may be to increase the acres of land preserved or open space within a given community. Many recreational values associated with coastal habitats (e.g., fishing, wildlife viewing, beach use) are also considered non-market values since they are not traded in a traditional market (see section on page 14.14 on Coastal Recreation, Tourism, and Access).

Non-use values are values not associated with current use and include such "non-uses" as maintaining the option to personally use part of the natural environment in the future (**option value**), leaving part of the natural environment for others to use in the future (**bequest value**), and the knowledge that part of the natural environment will continue to exist even if the individual holding this value never contemplates using it (**existence value**). Specific restoration project objectives under the goal of enhancing non-market values could be to increase any one or combination of these direct use or non-use social values.

Many people believe that natural environments also possess intrinsic value defined as values not assigned by humans but are instead inherent in the object or its relationship to other objects. Intrinsic values differ from other non-market values in that they are considered non-economic. **Intrinsic values** are often overlooked in environmental policy decision-making because they are typically more difficult to quantify than economic values.

Monitoring Measurable Parameters

There are a number of non-market valuation techniques available for measuring the value of goods and services in the absence of markets (see box below). Each of these has different strengths, weaknesses, assumptions, caveats and potential sources of error. We offer below some basic background information on some of the techniques used in determining non-market values. However, due to space limitations we cannot provide a detailed discussion of the complexities involved with implementing these techniques. Some suggested additional sources of information are given below and in the annotated bibliography at the end of this chapter. It is also strongly recommended that you consult with a non-market valuation expert before attempting to incorporate any of these methods into your restoration monitoring plan.

Economic Value Web Sites

Coastal and Ocean Resource Economics Program, NOAA, National Ocean Service. http:/marineeconomics.noaa.gov

Common Non-market Valuation Techniques
(Source: NOAA 1995)

- **Travel Cost Method** – Can be used to estimate recreational values associated with coastal restoration. This technique assumes that visitors to a particular site incur economic costs, in the form of outlays of time and travel expenses, to visit the site. In effect, these economic expenditures reflect the "price" (albeit implicit) of the goods and services provided by the site, and are an indirectly observable indication of the minimum amount that a visitor is willing to pay to use the site (with all its associated attributes). As coastal ecosystems become healthier one would expect both the number of people utilizing such areas for recreation and the average expenses incurred to get to those areas to increase.
- **Random Utility Models** – Also used for non-market recreation values. However, the focus of this method is on the choices or preferences of recreationists among alternative recreational sites. This type of model is particularly appropriate when substitutes are available to the individual so that the economist is measuring the value of the quality characteristics of one or more site alternatives (e.g., a fully restored coastal wetland and a degraded coastal wetland).
- **Hedonic Pricing Method** – Valuation technique intended to capture the willingness-to-pay measures associated with variations in property values that result from the presence or absence of specific environmental attributes (e.g., water pollution, scenic views, wildlife abundance). By comparing the market value of two properties that differ only with respect to a specific environmental attribute, economists may assess the implicit price of that amenity (or its cost when undesirable) by observing the behavior of buyers and sellers.
- **Contingent Valuation Method** – A direct way to measure non-market values by questioning individuals on their willingness-to-pay for a good or service (see above for survey research methods). The dollar values obtained for the good or service are said to be contingent upon the nature of the constructed (hypothetical or simulated) market and the good or service described in the survey scenario.

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IMPROVE GENERAL MARKET ACTIVITY

Goals and Objectives

The previous section discussed the restoration goal of enhancing the non-market value of goods and services for which no traditional market of buyers and sellers exists. The restoration of coastal habitats may also advance the economic goal of improving general market activity for goods and services that are routinely traded in traditional markets. Coastal restoration efforts that generate increased tourism, recreational and commercial activity will, in turn, improve general market activity. Objectives within this goal include increasing economic expenditures, total economic impacts, profits, jobs, and income levels within a given geographic area (e.g., county, region, state). The box below provides an explanation of economic expenditures and impacts using recreational fishing as an example.

Figure 25. Cigar's Marina in Louisiana is an example of a small business that offers fishermen a place to stay, eat, as well as go fishing. Photo by Lauri Lawson, NMFS, from the NOAA Photo Library. http://www.photolib.noaa.gov/fish/fish1208.htm

Economic Expenditures and Impacts Associated with Recreational Fishing
(Source: Salz et al. 2001)

During the course of a fishing trip, anglers purchase a variety of goods and services, spending money on bait, tackle, groceries, boat fees, lodging, restaurants, travel costs, and other trip-related expenditures. These purchases directly affect the sales, income, and employment of businesses that supply goods and services to saltwater anglers in a given geographic area. Businesses providing these goods and services must also purchase goods and services and hire employees, which in turn, generate more sales, income, and employment in an area. Three levels of economic impacts result from purchases by saltwater fishermen: 1) direct, 2) indirect, and 3) induced. Direct impacts are the sales, income, and employment generated from initial purchases (expenditures) by anglers (e.g., bait and tackle stores or sporting goods stores selling bait to anglers). Indirect impacts are sales, income, and employment of support industries that supply the directly affected industries (e.g., bait and tackle stores must purchase bait from dealers or fishermen, tackle from wholesalers, and electricity from power supply companies, and must pay labor). Induced impacts represent the sales, income, and employment resulting from expenditures by employees of the direct and indirect sectors (e.g., bait and tackle store employees purchase groceries and incur utility bills). Total impacts equal the sum of direct, indirect, and induced impacts.

Improving general market activity will also have the added public benefit of increasing state and local tax bases by generating additional sales tax and income tax revenue. In addition, revenues will also increase from special federal excise taxes on certain outdoor recreation related items (e.g., boat fuels, fishing, and hunting gear) that are dedicated towards resource conservation activities (i.e., Federal Aid in Sport Fish and Wildlife Restoration programs).

Monitoring Measurable Parameters

While detecting improvements in general market activity and attributing those changes to the improved health of restored coastal ecosystems may be possible for small individual projects, in many cases monitoring this goal will be more practical at the program level or for very large individual projects. There are three primary reasons for this: (1) many other social, economic, political, and environmental variables can influence trends in economic indicators and sorting these out on a small geographic scale is not often possible, (2) existing sources of economic data and model parameters for economic impact analyses are generally available at a larger spatial scale (i.e., county, metropolitan area, state) than most individual restoration projects cover, and 3) the cost of conducting an economic impact assessment for a small individual restoration project may be prohibitive and, in some cases, outweigh the benefits. Nonetheless, there may be some unique cases where it is possible to directly link expenditures and job creation to a particular project, even on a small geographic scale. For example, if restoration of some coastal habitat (e.g., coral reef, wetland) creates economic opportunities for eco-tourism providers that were not previously present at that location, the resulting jobs and profits can be directly attributed to the restoration project.

One way to monitor the goal of improving general market activity is to conduct an **economic impact analysis**. Economic impact analysis traces the flows of spending associated with tourism activity in a region to identify changes in sales, tax revenues, income, and jobs due to tourism activity. The principal methods utilized are spending surveys, analysis of secondary data from government economic statistics, economic base models, **input-output models** and **multipliers** (Frechtling 1994).

Input-output analysis (IOA) is the most common approach available for describing the structure and interactions of businesses in a regional economy. An IOA is capable of tracking the quantity and purchase location of expenditures, support businesses, and employees of the directly and indirectly affected industries. Also, IOA assessments can be used to reveal how expenditures affect the overall economic activity in a particular region, such as sales, income, and employment. Regional modeling systems, such as **IMPLAN** (impact analysis for planning), are used by economists for IOA. IMPLAN (and other similar models) can help restoration practitioners determine the economic importance of particular coastal activities that are dependent upon healthy coastal ecosystems. Using IMPLAN, economic expenditure and impact data can be generated for each expenditure category (e.g., restaurant, lodging, automobile) at the county level.

Multipliers represent a quantitative expression of the extent to which some initial change in the market is expected to generate additional "ripple" effects throughout the economy. They express the degree of interdependency between sectors in a region's economy and therefore vary considerably across regions and sectors. Many different types of multipliers can be used when conducting an input-output analysis (IOA). Multipliers may be expressed as ratios of sales, income or employment, or as ratios of total income, or employment changes relative to direct sales. One commonly used multiplier for IOA is the ratio of the indirect and induced effects to the direct (i.e. the initial) change itself (see box titled "Economic Expenditures and Impacts Association with Recreataional Fishing" for an explanation of these effects).

Information for monitoring employment impacts and income levels can be obtained from the Federal Bureau of Labor Statistics (BLS, http://www.bls.gov) within the U.S. Department of Labor. This agency conducts surveys and compiles data on several employment indicators. Some of the BLS surveys that may be relevant for monitoring general market activity include:

- Nonfarm Payroll Statistics from the Current Employment Statistics (State & Area) - monthly data on employment, hours, and earnings by industry and geographic area.
- Quarterly Census of Employment and Wages - comprehensive employment and wage data by industry and geographic area for workers covered by State Unemployment Insurance laws.
- Occupational Employment Statistics - annual data on employment and wages for about 750 occupations and 400 nonfarm industries for the nation, plus occupational data by geographic area
- Local Area Unemployment Statistics - monthly and annual employment, unemployment, and labor force data for Census regions and divisions, States, counties, metropolitan areas, and many cities, by place of residence

Economic Analyses / Impacts References

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REDUCE PROPERTY DAMAGE / ENHANCE PROPERTY VALUE

Goals and Objectives

For certain projects, restoration of coastal areas can be beneficial to local landowners by reducing damage to their property caused by flooding, storms, water level fluctuations, erosion, and drought. Reduced property damage may also apply to public property and physical infrastructure (see box below on physical infrastructure). The role of coastal habitats (e.g., marshes, wetlands, SAV) in ameliorating hurricane storm surges depends on a variety of factors including the physical characteristics of the storm, coastal geomorphic setting, and the track of a storm when it makes landfall. Human dimensions objectives under the goal of reducing property damage resulting from coastal flooding, storms, and/or erosion include reducing the:

- Number of houses lost
- Total cost of property damage
- Damage to transportation and commerce infrastructure (see the next section, *Enhance Transportation and Commerce*, for discussion of this objective)
- Amount of federal and state funds used for disaster relief
- Number of flood insurance claims filed
- Risk ranking for restored coastal areas on FEMA Flood Insurance Rate Maps
- Cost of insuring coastal property

In addition to these potential benefits, coastal restoration efforts may also reduce the necessity for coastal armorment projects (e.g., groins, sea walls, jetties). Armorment, or hard stabilization, solutions are often the traditional response for protecting upland property and structures from coastal erosion (Pilkey and Wright 1988). While armorment may, in some cases, be an effective way to reduce property damage, this approach has come under heavy criticism in recent years. Some of the negative impacts associated with sea walls, in particular, include:

- Aesthetic degradation of coastal viewscapes
- Reduction in access to the beach
- Production of rubble that can be dangerous to swimmers
- Increased erosion and degradation of beaches
- Degradation of habitat
- Increased taxpayer burden that only benefits a few property owners (Pilkey and Wright 1988; Dean 2001)

Virtually every state coastal management program has some regulatory component which either heavily discourages or completely prohibits construction of new hard stabilization structures. Coastal restoration may be a more socially and politically accepted substitute for armorment in reducing property damage in some areas.

About 90 percent of natural disasters in the United States are flood related and the majority of the damage caused by floods occurs in

Figure 26. Erosion at Oval Beach, Saugatuck, Michigan. Photo credit: Michigan DNR, Land and Water Management Division, Coastal Programs Unit, from the EPA Great Lakes web site.

Physical Infrastructure
(Source: Louisiana Coastal Wetlands Conservation and Restoration Task Force and the Wetlands Conservation and Restoration Authority 1998)

Physical infrastructure refers to capital facilities and land assets - private, State, Federal, parish or municipal - that are necessary to (1) support development and (2) protect public health, safety, and well-being. It includes, but is not limited to, water supply and wastewater disposal, transportation (ports, roads, bridges, airports, rail, navigation, highways), solid waste disposal, drainage, flood protection, industrial parks, electricity, oil and gas structures, and educational facilities and parks.

coastal communities (Platt 1999). The National Flood Insurance Program (NFIP) was initiated in 1968 and since 1973 has been coordinated by the Federal Emergency Management Agency (FEMA). The goal of NFIP is to provide low-cost federal flood insurance to individuals living in communities with approved floodplain management regulations (see box on page 14.49 for more on NFIP). One criticism of the program is that in many years it operates in the red – i.e., program outlays exceed revenues resulting in net borrowing from the U.S. Treasury (Platt 1999). Therefore, restoration efforts that reduce the risks and costs associated with coastal flooding may also reduce the federal taxpayer subsidy created by NFIP claims.

The NFIP's Community Rating System (CRS) provides discounts on flood insurance premiums in those communities that establish floodplain management programs that go beyond NFIP minimum requirements. Communities receive flood insurance credits for coastal restoration projects that reduce the risk of erosion damage, protect natural and beneficial floodplain functions, create open space, and reduce flood damage to property. One example of mitigation activities eligible for NFIP credits is beach nourishment that focuses on facilitating natural dune replenishment through the planting of native dune vegetation. Placement of sand on beaches is not eligible for NFIP credits. Minor physical flood control projects such as stabilization of stream banks, modification of existing culverts, and creation of small stormwater retention basins may also be eligible. Major structural flood control (hard stabilization) structures, such as levees, dams, and seawalls are not eligible for NFIP premium discounts.

In addition to paying flood insurance claims, the federal government (and states to a lesser

Figure 27. Shoreline erosion - Red Lantern Restaurant, Lake Michigan, Indiana. Photo courtesy of R. Royce, National Park Service, Indiana Dunes National Lakeshore, obtained from EPA Great Lakes web site.

Figure 28. Shoreline erosion - house in shambles, Ogden Dunes Indiana. Photo courtesy of Carole Y. Swinehart, Michigan Sea Grant Extension, from the EPA Great Lakes web site.

extent) also allocates a tremendous amount of money for disaster relief. Hurricane Andrew, which hit southern Florida in 1992, resulted in $26.5 billion in damage alone (NOAA web site: http://www.noaa.gov/hurricaneandrew.html). While property damage caused by hurricanes, Nor'easters and other natural disasters cannot be avoided, it can, in some cases, be reduced through coastal restoration efforts. For more information on NFIP and federal disaster relief visit the FEMA web site at: http://www.fema.gov. State emergency management agencies (SEMAs) and local authorities may also be good sources of information.

National Flood Insurance Program
(Source FEMA 2002)

The NFIP is a Federal program that allows property owners in participating communities to purchase low-cost flood insurance in exchange for state and community floodplain management regulations (i.e., mitigation) that reduce future flood damages. This program is designed to provide an insurance alternative to disaster assistance to reduce the escalating costs of repairing damage to buildings and their contents caused by floods. The number of NFIP policies has increased from about 95,000 before the Flood Disaster Protection Act of 1973, to 2.2 million in 1989, to over 4.3 million in 2002. The amount of flood insurance coverage in force as of 2002 was over $606 billion.

The value of property adjacent (or in close proximity) to a coastal restoration project may also increase as a result of enhanced aesthetic and recreational values associated with the restored habitat. Improvements in viewscape quality, water quality and wildlife viewing opportunities after restoration, may all increase the market value of land and homes in the restored area (see section above titled "Enhance Non-market and Aesthetic Values"). Increased private property values also have the added public benefit of increasing tax revenues for the local community.

Monitoring Measurable Parameters

Data for monitoring property damage related measurable parameters such as flood zone map designations, flood insurance rates, and disaster relief expenditures are available from FEMA at the community level. FEMA has produced flood hazard maps for over 19,200 communities covering approximately 150,000 square miles of floodplain areas (FEMA 2002). Flood hazard maps are used for state and community floodplain management regulations, for calculating flood insurance premiums, and for determining whether property owners are required by law to obtain flood insurance as a condition of obtaining mortgage loans or other Federal or federally related financial assistance. FEMA's flood hazard maps are also used by States and communities for emergency management and for land use and water resources (FEMA 2002). The Federal Insurance and Mitigation Administration (FIMA) and the FEMA Regional Offices conduct field investigations following major flood disasters to evaluate how well the NFIP floodplain management requirements performed. During these investigations, a team of experts inspects disaster-induced damages to residential and commercial buildings and other structures and infrastructure.

Detailed and accurate information on property damage caused by flooding may be more difficult to obtain since there is no one agency in the United States with specific responsibility for collecting and evaluating detailed flood loss information (NOAA, National Weather Service web site). This means that flood loss information can come from several sources using different methods for calculating and reporting damage. State and municipal losses are often self-insured. Some portion of the cost to repair a washed out road or bridge might be covered in a budget line item for routine maintenance, while another portion may be financed by a separate line item in the next year's budget. In some cases, a structure may be replaced by one of higher quality, costing more than the replacement value or repair costs of the original structure (NOAA, National Weather Service web site). For private property owners, some will either not have insurance or be under-insured. The costs for this sort of repair are almost impossible to establish. For those that are insured, claims may not fully reflect actual losses (NOAA, National Weather Service web site). While FEMA is a good place to start, restoration practitioners may also need to contact state and local agencies to monitor the goal of reducing property damage. For small projects, property loss data may be collected by surveying landowners in the vicinity of the restoration effort.

It may be possible to determine the effectiveness of a restoration effort in reducing property damage by directly comparing restored coastal areas with other nearby areas (non-restored) after a storm event. However, for a valid comparison which isolates the effect of the restoration effort, the two areas would have to be nearly identical in all other features that may influence level of property damage (e.g., hydrological, topographical, geological, building design). A study done in the aftermath of Hurricane Andrew clearly showed that the effect of storms on the human population and infrastructure in the coastal zone can be ameliorated by the maintenance of extensive coastal marshes and barrier islands (see box below, Louisiana Coastal Wetlands Conservation and Restoration Task Force and the Wetlands Conservation and Restoration Authority 1998).

Practitioners should be able to locate data on both appraised and market property values

Hurricane Andrew Storm Surge
(Source: Louisiana Coastal Wetlands Conservation and Restoration Task Force and the Wetlands Conservation and Restoration Authority 1998)

Hurricane Andrew gave direct evidence that the physiography of marshes where a storm makes landfall affects the degree to which the storm surge is dampened. The surge amplitude in the Terrebonne marsh system decreased from 9.3 ft above sea level in Cocodrie to 3.3 ft (Swenson 1994) in the Houma Navigation Canal approximately 23 miles due north. This equates to a reduction in surge amplitude of approximately 3.1 inches per linear mile of marsh and open water between Houma and Cocodrie. Similarly, the magnitude of the storm's surge was reduced from 4.9 ft at Oyster Bayou to 0.5 ft at Kent Bayou located 19 miles due north. This equates to a reduction in surge amplitude of approximately 2.8 inches per linear mile of fairly solid marsh between these sites.

in their area to determine whether a coastal restoration project has met the goal of enhancing property values. The appraised value is a certified appraiser's opinion of the worth of a home while the market value is what price the house will bring at a given point in time. Market data on property sales and characteristics are available through real estate services and municipal sources. A commonly used source of information on property values is the Multiple Listing Service (MLS), a service created and run by real estate professionals which gathers all of the property listings into a single place so that purchasers may review all available properties from one source.

However, tracking changes in nearby property values over the course of a restoration project alone will not indicate whether those changes are, in any way, the result of the restoration project. Property values (both appraised and market) fluctuate all the time due to numerous other factors (e.g., mortgage rates, inflation, employment trends). Isolating the effect of a restoration project on property values may be very difficult. One method used by resource economists that attempts to do just that is hedonic pricing. Hedonic pricing is a non-market valuation technique intended to capture the willingness-to-pay measures associated with variations in property values that result from the presence or absence of specific environmental attributes (e.g., water pollution, scenic views, wildlife abundance) (NOAA, National Weather Service 2000). By comparing the market value of two properties that differ only with respect to a specific environmental attribute, economists may assess the implicit price of that amenity (or its cost when undesirable) by observing the behavior of buyers and sellers. The validity of this method depends on the ability to find two houses that are so identical in all other attributes (e.g., schools, community services, air quality etc.) that the relatively small increase in value due to a restoration project will be detectable.

Coastal Property Damage and Property Value Web Sites

- Association of State Floodplain Managers web site: http://www.floods.org/home/default.asp
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Coastal Property Damage and Property Value References

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ENHANCE TRANSPORTATION AND COMMERCE

Goals and Objectives

Throughout history coastal regions have been a focal point for trade, commerce, and navigation, all of which depend on reliable transportation. The nation's economy is highly dependent on coastal transportation (by water, road, and railway) for moving commodities and connecting our ports to the interior of the country and the rest of the world (see box below on coastal transportation in Louisiana). Both catastrophic (e.g., hurricanes) and non-catastrophic (e.g., beach erosion) processes, such as flooding, drought, erosion, and sedimentation can negatively impact coastal transportation. As coastal areas become more crowded with tourists and residents, the need for efficient and reliable transportation becomes even greater. This is particularly true during coastal hazards when millions of people need to be evacuated from a relatively small area in a short period of time. With the projected rise in sea level, protection of low-lying coastal areas, and particularly coastal evacuation routes, from flooding will likely become more of an issue in the next century. Some coastal restoration objectives associated with the goal of enhancing transportation and commerce include reducing the:

- Sedimentation of navigation channels and inlets
- Flooding of roads, bridges, railroads, and evacuation routes
- Breaching of barrier islands, and
- Damage to coastal infrastructure and ports

While such processes are naturally occurring, their effects can be greatly worsened by anthropogenic degradation of coastal habitats. As discussed earlier (see "Reduce Property Damage" section), many coastal habitats function as a natural buffer, lessening the damage to property, roads, infrastructure, and navigation channels resulting from these coastal processes. Therefore, another human dimensions goal of coastal restoration is to restore the damage-preventing functions performed by coastal habitats in order to enhance transportation efficiency, reliability, and safety. Seawalls and other hard stabilization structures are often constructed for this purpose. However, as discussed in the previous section, in some areas coastal restoration may be a viable and socially

Coastal Transportation in Louisiana
(Source: Louisiana Coastal Wetlands Conservation and Restoration Task Force and the Wetlands Conservation and Restoration Authority 1998)

Louisiana provides a prime illustration of the importance of coastal transportation to the economy of coastal regions and the nation as a whole. Louisiana ranks first in the nation in total shipping tonnage, handling over 450 million tons of cargo each year through the public and private installations located within the State's jurisdiction of six deep-draft ports: New Orleans, Greater Baton Rouge, Lake Charles, South Louisiana, Plaquemines Parish, and St. Bernard. These ports are the mainstays of Louisiana's maritime shipping industry, and have given the region both national and international prominence. In addition, the privately owned Louisiana Offshore Oil Port offloads approximately 10-13% of the country's imported crude petroleum that eventually is moved via pipelines to refineries and consumers throughout the nation. Significant contributions to the State's economy are also made by the fifteen smaller ports that are situated within the coastal zone, primarily serving the oil and gas and fishing industries. The Gulf Intracoastal Waterway is a critical shallow-draft transportation link that carries an annual average of 70 million tons of freight (primarily liquid bulk items such as petroleum and petroleum products) between the Mississippi and Texas state lines. An alternate Gulf Intracoastal Waterway route, linking Morgan City and Port Allen, averages 25 million tons of cargo shipped per year. In addition to the 3,000 miles of commercially navigable waterways, coastal Louisiana has railroad transportation, Interstate, U.S. and state highways, commercial and general aviation airports, and an extensive network of oil and gas pipelines.

preferred solution for protecting transportation infrastructure (e.g., roads, bridges, railroads, evacuation routes).

Restoration projects may also promote an increase in coastal transportation facilities (e.g., marinas, boat ramps, boat slips, and commercial docks) and accessibility (e.g., roads) which can also be viewed as transportation related benefits of restoration. However, since such benefits may conflict with other ecological and human dimensions goals/objectives, they may not be desirable goals for all projects. In other cases, the goal of enhancing transportation will be compatible and closely linked to several human dimensions goals discussed in this chapter. Enhanced transportation will likely increase the level of coastal recreation and tourism, improve general market activity, reduce property damage, enhance property value, and improve commercial fishing.

Monitoring Measurable Parameters

Measurable parameters for monitoring the effectiveness of a restoration project in protecting transportation and commerce related infrastructure (e.g., roads, bridges, railroads, ports, evacuation routes) from flooding and other damage are discussed above in the section titled *Reduce Property Damage / Enhance Property Value*. These include changes in FEMA flood risk assessments for particular areas, as well as the costs associated with repairing damaged transportation infrastructure. By comparing historical data with post-restoration data it may be possible to determine if a particular restoration effort has reduced the flooding potential and/or damage to a given stretch of road. Practitioners should use caution, however, in drawing such cause-and-effect conclusions. Other factors, not related to the restoration project, such as construction of hard stabilization structures, changes in hydrology and geomorphology, sea level changes, and tidal fluctuations can also influence these measurable parameters. By directly comparing a restored stretch of coast with a nearby unrestored stretch it may be possible to isolate the effectiveness of restoration in reducing road damage and flooding (i.e., assuming all other characteristics of the two areas are nearly identical). State departments of transportation can provide you with detailed coastal evacuation maps if you are particularly interested in monitoring the effectiveness of a restoration project in reducing road damage and flooding of evacuation routes.

Figure 29. Destruction of the seawall at Narragansett Pier in southern Rhode Island due to the New England Hurricane of 1938. Archival Photography by Steve Nicklas, NOS, NGS, from the NOAA Photo Library.

Coastal restoration efforts that abate the processes of erosion, sedimentation, and flooding, may also reduce the costs associated with hard stabilization and channel dredging designed to protect transportation routes. Monitoring these costs over time may provide some indication of the effectiveness of coastal restoration in enhancing transportation. In most cases, such monitoring will be more feasible at the program level as the influence on hard stabilization and channel-dredging costs of multiple restoration projects over a large geographic area will be more detectable than any one individual project. Information on hard stabilization and channel dredging costs can be obtained from the Army Corps of Engineers, the agency that coordinates most of these projects, or from state and local coastal management agencies.

Monitoring measurable parameters related to transportation facilities and accessibility at the project level is fairly straightforward. For individual projects, an inventory can be kept to track changes over time in the number of marinas, boat slips, boat ramps, and access points that are directly the result of a restoration effort. However, it may not always be possible to link increased demand for transportation facilities and coastal access to restoration within a small geographic area. Rather, changes in these parameters are more likely to result from the cumulative effect of many restoration projects rather than any one individual project. Therefore, these measurable parameters may provide a better measure of transportation related goals and objectives if they are monitored at the program level (e.g., estuary, watershed, state). Most state coastal management agencies keep a detailed inventory of coastal access points, marinas, and launch sites that can be used for monitoring purposes.

Coastal Transportation References

- Louisiana Coastal Wetlands Conservation and Restoration Task Force and the Wetlands Conservation and Restoration Authority. 1998. Coast 2050: Toward a Sustainable Coastal Louisiana. 161 pp. Louisiana Department of Natural Resources. Baton Rouge, LA. http://www.lacoast.gov/Programs/2050/MainReport/report1.pdf

IMPROVE COMMERCIAL FISHERIES AND SHELLFISHERIES

Goals and Objectives

Coastal habitats serve as breeding, nursery and feeding grounds for many species of commercially valuable fish and shellfish (see specific habitat chapters for more detail on this ecological function). The majority of commercially harvested fish and shellfish are dependent on estuaries and their wetlands (see box on Habitat Loss in the Gulf of Mexico below). When these habitats become degraded, their ability to produce healthy, abundant, and sustainable fish populations is greatly diminished. Therefore, an important human dimensions goal of coastal restoration is to improve commercial fisheries and promote sustainable fishing communities by restoring fish and shellfish habitats. This overall goal includes both socio-cultural and economic objectives. For a discussion of the socio-cultural and historical heritage values associated with commercial fishing communities see previous section titled "Protect Traditional, Cultural and Historic Values". In addition to these values, commercial fisheries also have tremendous economic value. Nationally, commercial fisheries landings (all species) weighed 9.4 billion pounds and were valued at $3.2 billion in 2002 (NOAA, NMFS, Commercial Fisheries web site). Economic objectives of coastal restoration may include increasing the total commercial fishing and shellfishing harvest value, increasing total profits, and increasing the number of jobs in the fishing industry.

If improving commercial fisheries is a primary goal of your project, it is important

Figure 30. Sorting the catch. Photo by NOAA Office of Marine and Aircraft Operations, from the NOAA Photo Library. http://www.photolib.noaa.gov/fish/fish0058.htm

to consider which particular types of fisheries or fishing sectors you want to improve, and focus your restoration efforts accordingly. One major distinction when considering commercial fisheries is between large-scale and small-scale operations (although there are gradients in between these extremes). **Large-scale commercial fishing** fleets, owned by corporations with large capital investments, are highly mobile in their global pursuit of fish populations. By comparison, **small-scale fishing operations** have relatively small capital investment and levels of production, and are more limited in terms of mobility and resource options. Terms that are commonly used to describe small-scale fishermen include artisanal, native, coastal, inshore, tribal, peasant, and traditional. If the objective is to enhance cultural values associated with fishing communities, not just economic values, emphasis should be placed on restoring ecosystems that will benefit small-scale fishing operations.

Habitat Loss in the Gulf of Mexico
(Source: Gulf Restoration Network web site - http://www.gulfrestorationnetwork.org/)

Over 50 percent of the Gulf region's wetlands have been lost since 1790. Furthermore, the Gulf ranked as one of the worst regions in the country in a recent Environmental Protection Agency report in terms of coastal water pollution and toxicity. Coastal wetlands are extremely important to the majority of the Gulf's fish species due to their dependence on both estuarine and marine waters at some point in their life cycle. It is currently estimated that 95 percent of the commercially and recreationally important species in the Gulf of Mexico depend on both the waters of the open Gulf and the inshore and nearshore waters of the Gulf's numerous bays and estuaries. Some representative species include shrimp, red drum, and king mackerel.

Fishing operations also differ in terms of species targeted and gear used. While some target species populations are being managed sustainably, many others are depleted and continue to be overfished. Certain commercial fishing gear types are particularly harmful to marine ecosystems in terms of habitat destruction (e.g., bottom trawling), incidental mortality (e.g., dolphins in tuna purse seine nets) and bycatch (e.g., discarded dead juvenile fish caught in shrimp trawl nets). Therefore, when designing coastal habitat restoration projects aimed at benefiting commercial fisheries, practitioners need to decide which commercial fishery (i.e., scale, gear type, species) they want to improve. In doing so they should consider what the ecological and human dimensions objectives

Figure 31. Harvesting the herring after closing the purse on the Maine coast (1969). Photo from the NOAA Photo Library. http://www.photolib.noaa.gov/fish/fish0771.htm

of the project are and what the consequences of improving that fishery will be.

Monitoring Measurable Parameters

Restoration of nearly every habitat included in this volume will likely have some positive impact on commercially sought after species of fish and shellfish. However, depending on the mobility of these species, actually monitoring improvements in commercial fishing due to restoration efforts may be extremely difficult, especially at the individual project level. For sedentary species, such as oysters and clams, practitioners can monitor the commercial harvest within a designated restored area over time to determine if restoration helped to improve that fishery. However, many other commercially important species (particularly finfish) may only spend part of their life-cycle (e.g., juvenile stage) within a restored area. Since the mature stocks of fish are usually geographically far removed from the nursery grounds, the fishery benefits in terms of increased productivity and profits will also be far removed (Wiegert and Pomeroy 1981). This is particularly true for highly migratory species such as striped bass, bluefish, and salmon that may travel thousands of miles throughout their lives. Establishing a direct causal link between a particular restoration effort and improvement of a commercial fishery is made more difficult by all the extraneous environmental, regulatory, technological, economic, and social factors that can influence fishery yields. With the exception of relatively sedentary species, monitoring improvements in commercial fisheries due to restoration is more likely to be successful at the program level. For example, the recovery of striped bass populations along the Atlantic coast in the early 1990's is attributed to a combination of restrictive fishing regulations and restored breeding and rearing inland habitats (e.g., Hudson River and Chesapeake Bay watersheds). The use of ecological indicators such as striped bass larval and juvenile fish abundance (i.e., young-of-year indices) to predict adult year-class strength reaffirms the link between habitat restoration and fisheries productivity.

Commercial fisheries data, including catch, weight, and harvest value are routinely collected by state and federal fisheries agencies (See *Commercial Fishing and Shellfishing Data Sources* below). These **fishery dependent data** (i.e., data collected directly from the fishery participants) are typically summarized at the state level. In some cases, fishery landings data such as the number, weight, and value of fish by species, gear type, and ocean area may be available for individual fishing ports. However, the port at which fisheries catches are landed may be geographically far removed from where the fish were actually caught. For purposes of restoration monitoring it is important to make this distinction in order to assess the effectiveness of a restoration effort in increasing fisheries yields.

Fisheries dependent data may not be readily available or summarized in a format useful for small-scale or individual project monitoring. Information collected from fishermen on geographic area of the catch is often not detailed enough to establish a relationship between a given restoration effort and increased fishery productivity. For sedentary species, practitioners can conduct their own surveys of commercial fishermen to track changes in harvest value following a restoration effort. In most commercial fisheries, participants are required to have a license or permit to participate. Practitioners may be able to gain access to these databases from state and federal agencies in order to establish a sampling frame for the collection of commercial fisheries data (Refer to section on page 14.14 titled "Coastal Recreation, Tourism, and Access" for general information on survey methodology).

In addition to measurable parameters based on fisheries dependent data, certain health related measurable parameters may also be directly linked to improved commercial fishing and shellfishing. As the number and severity of fish and shellfish advisories decrease and the level of seafood safety increases, consumers will buy more seafood, thus benefiting the commercial fishing industry. Likewise, water quality improvements resulting from restoration efforts will reduce the number of hypoxia events, thus reducing the magnitude of fish kills and perhaps opening up new areas for commercial fishing and shellfishing.

Commercial Fishing and Shellfishing Data Sources and Web Sites

- Atlantic Coastal Cooperative Statistics Program (ACCSP) web site: http://www.accsp.org/
- Fisheries of the United States, 1977 through 2002 (annual publication). U.S. Dept. Of Commerce, NOAA Fisheries, Washington, D.C. http://www.st.nmfs.gov/st1/fus/current/
- Gulf States Marine Fisheries Commission (GSMFC), Gulf States Fisheries Information Network (Gulf FIN) web site: http://www.gsmfc.org/data.html
- NOAA, National Marine Fisheries Service (NMFS), Commercial Fisheries web site: http://www.st.nmfs.gov/st1/commercial/index.html
- NOAA, National Marine Fisheries Service (NMFS), Social Sciences Branch web site: http://www.nefsc.noaa.gov/read/socialsci/

Figure 32. The Lobstermen's Co-op in Boothbay Harbor, Maine. Photo from William B. Folsom, NMFS, obtained from the NOAA Photo Library. http://www.photolib.noaa.gov/fish/fish0961.htm

- Pacific States Marine Fisheries Commission (PSMFC), Pacific Coast Fisheries Information Network (PacFIN) web site: http://www.psmfc.org/pacfin/index.html
- Pacific States Marine Fisheries Commission (PSMFC), Fisheries Economics Data Program (EFIN) in the Northwest and Alaska web site: http://www.psmfc.org/efin/index.html
- State marine resource agencies are also a good source of commercial fisheries information (too many to list here).

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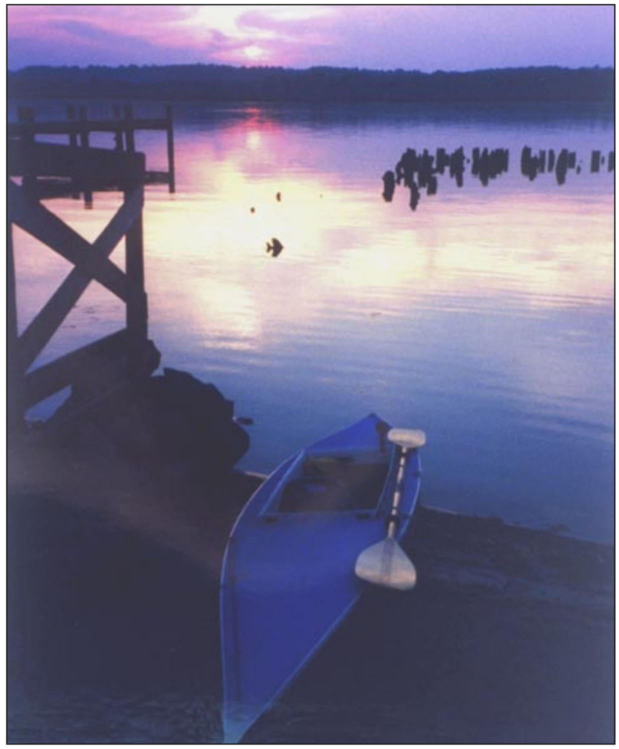

Figure 33. Sunset along the Patuxent River, Maryland. Photo by Mary Hollinger, NODC biologist, NOAA, obtained from the NOAA Photo Library. http://www.photolib.noaa.gov/coastline/line2329.htm

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APPENDIX I: MATRIX OF HUMAN DIMENSIONS GOALS AND MEASURABLE PARAMETERS TO MONITOR

As discussed above under *Project Scale Issues* some of the measurable parameters for assessing human dimensions goals may be difficult to monitor for individual or small-scale projects. The closed circles below (●) indicate, for each particular goal, which parameters restoration practitioners *should* be able to monitor regardless of project size or scope. The open circles (❍) indicate parameters that may be possible to monitor for *some* individual or small-scale projects but in other instances monitoring such parameters may only be feasible at the restoration program level (i.e., estuary, watershed etc.). These circles are intended to provide only broad general guidance and exceptions may exist for any given restoration project. Practitioners are encouraged to consult with human dimensions experts (see Appendix IV) and carefully evaluate the feasibility of monitoring any of these parameters for their particular project.

Parameters for Monitoring Human Dimensions Goals of Coastal Restoration

Parameters for Monitoring	Coastal Recreation, Tourism, and Access Related Goals: Increase Number of Recreational Opportunities (pg 16)	Increase the Level of Recreation Activity (pg 16)	Increase the Quality of Recreational Opportunities (pg 17)	Improve Tourism/Ecotourism (pg 17)	Enhance Access to Coastal Resources (pg 17)	General Social & Non-market Values Related Goals: Enhance Community Investment (pg 23)	Enhance Educational Opportunities (pg 29)	Protect or Improve Human Health (pg 30)	Protect Traditional/Cultural/Historic Values (pg 36)	Enhance Non-Market Values (pg 41)	Improve Aesthetic Values (pg 41)	Market-based Goals: Improve General Market Activity (pg 43)	Reduce Property Damage (pg 46)	Enhance Property Value (pg 46)	Enhance Transportation and Commerce (pg 51)	Improve Commercial Fisheries/ Shellfisheries (pg 54)
Recreation / Tourism Related																
Facilities and Accessibility																
Number of Public Access Points	●			●	●										●	
Number of Private Access Points	●			●	●										●	
Number of Marinas	●			●	●										●	
Number of Boat Slips	●			●	●										●	
Number of Boat Ramps	●			●	●										●	
Trail Miles	●			●	●											
Number of Commercial Providers	●			●	●											
Infrastructure Development	❍			❍	❍										❍	
Functional/Service Capacity	❍			❍	❍											
Level of Facility Maintenance			●													
Perceptions of Conflict and Crowding																
Consumptive users (hunters, anglers, trappers, clamers)			❍													
Non-consumptive users (birders, beach users, divers/snorkelers, boaters, hikers)			❍													
User Satisfaction Rating																
Consumptive users (hunters, anglers, trappers, clamers)			❍	❍												

Parameters for Monitoring Human Dimensions Goals of Coastal Restoration (cont.)

Parameters for Monitoring	Coastal Recreation, Tourism, and Access Related Goals					General Social & Non-market Values Related Goals						Market-based Goals				
	Increase Number of Recreational Opportunities (pg 16)	Increase the Level of Recreation Activity (pg 16)	Increase the Quality of Recreational Opportunities (pg 17)	Improve Tourism/Ecotourism (pg 17)	Enhance Access to Coastal Resources (pg 17)	Enhance Community Investment (pg 23)	Enhance Educational Opportunities (pg 29)	Protect or Improve Human Health (pg 30)	Protect Traditional/Cultural/Historic Values (pg 36)	Enhance Non-Market Values (pg 41)	Improve Aesthetic Values (pg 41)	Improve General Market Activity (pg 43)	Reduce Property Damage (pg 46)	Enhance Property Value (pg 46)	Enhance Transportation and Commerce (pg 51)	Improve Commercial Fisheries/ Shellfisheries (pg 54)
Non-consumptive users (birders, beach users, divers/snorkelers, boaters, hikers)			❍	❍												
Recreational Fishing Catch Indicators																
Catch rates			❍	❍												
Average size per fish			❍	❍												
Availability of preferred target species			❍	❍												
Number of trophy fish caught			❍	❍												
Annual Recreation Visitor Days																
Consumptive days (hunting, fishing, shellfishing, trapping)		❍		❍	❍											
Non-consumptive days (birding, beach use, diving/snorkeling, boating, hiking)		❍		❍	❍											
Watchable Fish and Wildlife Counts	❍			❍							●					
Economic Indicators																
Economic Expenditures		❍		❍								❍				
Economic Impacts		❍		❍								❍				
Employment Impacts		❍		❍								❍				

Parameters for Monitor Human Dimensions Goals of Coastal Restoration (cont.)

Parameters for Monitoring	Coastal Recreation, Tourism, and Access Related Goals					General Social & Non-market Values Related Goals						Market-based Goals				
	Increase Number of Recreational Opportunities (pg 16)	Increase the Level of Recreation Activity (pg 16)	Increase the Quality of Recreational Opportunities (pg 17)	Improve Tourism/Ecotourism (pg 17)	Enhance Access to Coastal Resources (pg 17)	Enhance Community Investment (pg 23)	Enhance Educational Opportunities (pg 29)	Protect or Improve Human Health (pg 30)	Protect Traditional/Cultural/Historic Values (pg 36)	Enhance Non-Market Values (pg 41)	Improve Aesthetic Values (pg 41)	Improve General Market Activity (pg 43)	Reduce Property Damage (pg 46)	Enhance Property Value (pg 46)	Enhance Transportation and Commerce (pg 51)	Improve Commercial Fisheries/ Shellfisheries (pg 54)
Income Level				❍								❍				
Community Related																
Presence in Community Master Plan						●			●							
Component of Town Meetings						●			●							
Attendance at Town Meetings						●										
Community Communications						●										
Volunteerism (number of persons)						●										
NGO Activity						●										
Town Use of Restored Coastal Area		●				●										
Town Portion of Cost Sharing						●										
Corporate Sponsorship						●										
Zoning Changes						●										
Tax Incentives						●										
Community Member Attitudes						●										
Property Damage Related																
Flood Zone Map													●		●	
Number of Losses													❍			
Disaster Relief Costs													❍			
Direct Cost of Damage													❍		❍	

Parameters for Monitor Human Dimensions Goals of Coastal Restoration (cont.)

Parameters for Monitoring	Coastal Recreation, Tourism, and Access Related Goals					General Social & Non-market Values Related Goals						Market-based Goals				
	Increase Number of Recreational Opportunities (pg 16)	Increase the Level of Recreation Activity (pg 16)	Increase the Quality of Recreational Opportunities (pg 17)	Improve Tourism/Ecotourism (pg 17)	Enhance Access to Coastal Resources (pg 17)	Enhance Community Investment (pg 23)	Enhance Educational Opportunities (pg 29)	Protect or Improve Human Health (pg 30)	Protect Traditional/Cultural/Historic Values (pg 36)	Enhance Non-Market Values (pg 41)	Improve Aesthetic Values (pg 41)	Improve General Market Activity (pg 43)	Reduce Property Damage (pg 46)	Enhance Property Value (pg 46)	Enhance Transportation and Commerce (pg 51)	Improve Commercial Fisheries/ Shellfisheries (pg 54)
Insurance Losses													○			
Uninsured Losses													○			
Reduced Insurance Costs													○			
Expenditures on Non-Restoration Projects (e.g., costs associated with coastal armament and channel dredging)													○		○	
Education Related																
Number of Interpretive Centers				●			●									
Number of Interpretive Programs				●			●									
Number of Research Projects							●									
Number of Students Trained							●									
Cost of Research Projects							●									
School Field Trips							●									
Classroom Activities							●									
Association With Museums	●						●									
Informal Education: Media coverage, websites, brochures, kiosks, workshops and public forums				●			●									

Parameters for Monitor Human Dimensions Goals of Coastal Restoration (cont.)

Parameters for Monitoring	Coastal Recreation, Tourism, and Access Related Goals					General Social & Non-market Values Related Goals						Market-based Goals				
	Increase Number of Recreational Opportunities (pg 16)	Increase the Level of Recreation Activity (pg 16)	Increase the Quality of Recreational Opportunities (pg 17)	Improve Tourism/Ecotourism (pg 17)	Enhance Access to Coastal Resources (pg 17)	Enhance Community Investment (pg 23)	Enhance Educational Opportunities (pg 29)	Protect or Improve Human Health (pg 30)	Protect Traditional/Cultural/Historic Values (pg 36)	Enhance Non-Market Values (pg 41)	Improve Aesthetic Values (pg 41)	Improve General Market Activity (pg 43)	Reduce Property Damage (pg 46)	Enhance Property Value (pg 46)	Enhance Transportation and Commerce (pg 51)	Improve Commercial Fisheries/ Shellfisheries (pg 54)
Human Health Related																
Number of Health Advisories																
Fish Advisories								❍								❍
Shellfish Advisories	●		●	●				●								●
Drinking Water Advisories								❍								
Number, Area and Duration of Beach Closures	❍		❍	❍				❍								
Incidence of Disease								❍								
Level of Compliance With Water Quality Standards								❍								
Level of Reduction in BioToxins								❍								
Number of Hazardous Sources								❍								
Number and Area of Algal Blooms								❍								
Duration of Algal Blooms								❍								
Number of Hypoxia Events								❍								❍
Number of Water-Borne Illnesses								❍								
Level of Food Safety								❍								❍
Commercial Fishing Related																
Number of Dock Facilities (commercial)					●										●	●
Total Profits												❍				❍

Parameters for Monitor Human Dimensions Goals of Coastal Restoration (cont.)

Parameters for Monitoring	Coastal Recreation, Tourism, and Access Related Goals					General Social & Non-market Values Related Goals						Market-based Goals				
	Increase Number of Recreational Opportunities (pg 16)	Increase the Level of Recreation Activity (pg 16)	Increase the Quality of Recreational Opportunities (pg 17)	Improve Tourism/Ecotourism (pg 17)	Enhance Access to Coastal Resources (pg 17)	Enhance Community Investment (pg 23)	Enhance Educational Opportunities (pg 29)	Protect or Improve Human Health (pg 30)	Protect Traditional/Cultural/Historic Values (pg 36)	Enhance Non-Market Values (pg 41)	Improve Aesthetic Values (pg 41)	Improve General Market Activity (pg 43)	Reduce Property Damage (pg 46)	Enhance Property Value (pg 46)	Enhance Transportation and Commerce (pg 51)	Improve Commercial Fisheries/ Shellfisheries (pg 54)
Number of Jobs												○				○
Total Value of Harvest												○				○
Sustainability of Fishery																○
Cultural/Historical Heritage Preservation									○							○
Other Social Values																
Property Values																
Appraised Value													●	●		
Market Value													●	●		
Viewscape quality			●	●						●	●			●		
Acres of Land Preserved/Open Space											●					
Preserved Natural/Historic/Cultural Values									○							
Level of Existence Value										●						
Level of Bequest Value										●						
Level of Option Value										●						
Historic Designation				●					●							
Tribal Designation									●							

APPENDIX II: HUMAN DIMENSIONS ANNOTATED BIBLIOGRAPHY

This annotated bibliography contains summaries of selected data sources and human dimensions research that coastal restoration practitioners may find useful in monitoring the human dimensions goals and objectives of a restoration project. Entries are presented from both peer reviewed and gray literature. Entries were selected through extensive literature and Internet searches as well as input from reviewers and workshop participants. This bibliography is not, however, intended to be a complete listing of all the available literature on the human dimensions of coastal restoration. Restoration practitioners and others are encouraged to do their own project specific literature search and to contact human dimensions experts for additional sources of information.

Entries are organized into the following sections:

1. Coastal Recreation Data Sources (National and Regional Surveys, State Level Surveys)
2. Economic Impact and Non-market Valuation Studies
3. Research on Stakeholders' Values, Attitudes and Satisfaction Ratings
4. Commercial Fishing: Human Dimensions Research
5. Education and Outreach Research
6. Socio-Cultural and Anthropological Research
7. Coastal Restoration and Property Damage Reduction
8. Effects of Coastal Restoration on Property Values
9. Human Dimensions Benefits of Improved Water Quality
10. Miscellaneous Human Dimensions of Coastal Restoration Monitoring References

Within each section entries are arranged alphabetically by author (or by data source name in the case of data sources). Wherever possible, web addresses or other contact information has been included in the reference to assist readers in more easily obtaining the original publication or data source. All summaries in this annotated bibliography were taken directly from their original source (i.e., either author abstract, source's web page, or publisher's introduction). In some cases, these original sources were condensed or modified slightly as necessary.

1. Coastal Recreation Data Sources

National and Regional Surveys

- **Marine Recreational Fisheries Statistics Survey (MRFSS)**

This saltwater angler survey has been conducted by NMFS annually since 1979. The MRFSS consists of two independent surveys--a telephone household survey and an intercept survey. Data obtained from the telephone survey are used to generate state-level estimates of fishing effort (measured as number of trips) according to mode (shore, partyboat/charterboat, or privateboat) and wave (2-month sampling period). Data obtained from the intercept survey are used to estimate catch per trip and average weight by species at the state/mode/wave level of detail. Data from the telephone household survey and the intercept survey are combined to provide an estimate of the total catch (number harvested, number released, and total weight) by marine recreational anglers also at the state/mode/wave level. The MRFSS also provides an estimate of the number of marine recreational anglers in the United States by state of residence. The web site below provides instructions for conducting your own data queries online and for downloading raw (unsummarized) telephone and intercept datasets. http://www.st.nmfs.gov/st1/recreational/data.html

- **National Survey of Fishing, Hunting, and Wildlife-Associated Recreation**

The National Survey of Fishing, Hunting, and Wildlife-Associated Recreation has been conducted by the U.S. Fish and Wildlife Service about every five years since 1955. It provides information on the number of participants in fishing, hunting, and wildlife watching (observing, photographing, and feeding wildlife), and the amount of time and money spent on these activities. This survey is one of the nation's most important wildlife recreation databases. It is the only source of comprehensive information on participation and expenditures that is comparable on a state-by-state basis. It is used for estimating the economic impact of wildlife-related recreation for each state; for estimating the value of wildlife resources lost due to pollution or disease such as whirling disease in fish; for use in critical habitat analysis of threatened species; and for preparing environmental impact statements, budgets, and legislative proposals. http://fa.r9.fws.gov/surveys/surveys.html

- **National Survey on Recreation and the Environment**

The National Survey on Recreation (NSRE) was started in 1960 by the congressionally created Outdoor Recreation Resources Review Commission (ORRRC). Since that time, six national surveys have been conducted, in 1965, 1970, 1972, 1977, 1982-83, 1994-95, in addition to the latest 2000 NSRE. One component of the NSRE is the Marine Recreation Participation Module (includes Great Lakes). The main measurements for marine recreation are number of participants and number of days of use in the state in which the activity took place. The relevant population includes all people 16 years of age or older in the civilian non-institutionalized population living in U.S. households. The NSRE 2000 is a rich database that includes full demographic information, information on environmental attitudes, life-styles, and other data to support trip modeling.
http://marineeconomics.noaa.gov/NSRE/NSRE_2.pdf
http://marineeconomics.noaa.gov/NSRE/NSRE_V1-6_May.pdf

- **NOAA Coastal and Ocean Resource Economics Web Page**

The Coastal and Ocean Resource Economics (CORE) Program conducts marine-related socioeconomic research for a wide variety of applications and geographic areas. CORE projects include state-of-the-art socioeconomic monitoring in the Florida Keys National Marine Sanctuary, the first-ever nationwide estimate of participation rates in marine-related recreation activities, an extensive beach valuation effort in Southern California, and many other research activities. http://www.marineeconomics.noaa.gov/welcome.html

- **Saltwater Angler Expenditures in the U.S.**

This three-part National Marine Fisheries Service study on Saltwater Angler Expenditures in the U.S. provides state-level estimates for angler trip and durable good expenditures by fishing mode (party/charter, private/rental boat and shore) and by state resident/non-resident status. With the exception of TX, AK, and HI, estimates are provided for all coastal states. Trip expenditure categories include transportation, food, lodging, fuel, charter and launch fees, equipment rental, bait, and ice. Expenditure categories for durable and semi-durable goods used primarily for saltwater fishing include equipment and tackle, boat purchases, boat expenses, electronics, camping equipment, binoculars, clothing, and more.

Northeast Region: http://www.rbff.org/research/nemarine.pdf
Southeast Region: http://www.rbff.org/research/SEMarine.pdf
Pacific Region: http://www.rbff.org/research/SEMarine.pdf

Selected Examples of State Level Surveys

- **2000 Southeast Alaska Commercial Recreation Survey**

Conducted by the Alaska Division of Community and Business Development, this survey was designed to collect information about SE Alaska that allows businesses, communities, tourism organizations, and land management agencies to:

- Identify the type, quantity, and quality of commercial uses
- Identify sites that have a high degree of potential as future tourism destinations
- Determine the quality of existing services and access points to public lands/waters
- Determine new services and access points needed on public lands/waters
- Identify areas of existing or potential conflict by user groups
- Estimate the impact of the tourism industry on the economy and employment of SE Alaska
- Determine the environmental and social settings that have positive and negative impacts on business
- Identify obstacles to the success of tourism businesses in the region, and
- Identify ways in which federal, state and local governments can better serve the needs of business and augment the recreation experience of their clients.

- **A Baseline Socioeconomic Study of Massachusetts' Marine Recreational Fisheries**

This is a collaborative study conducted by the University of Massachusetts, National Marine Fisheries Service, and Massachusetts Division of Marine Fisheries. This study investigated various socioeconomic attributes of Massachusetts' marine recreational anglers. Separate analyses were conducted for each of three saltwater angler modes of fishing: partyboat, private boat, and shore. Areas of investigation included:

- Evaluation of Massachusetts saltwater anglers' attitudes towards specific fishery management actions and management agencies
- Determination and evaluation of anglers' economic expenditures and economic impacts according to economic sector and fishing mode
- Evaluation of angler species preferences and trends in demand for species-specific fishing activity
- Evaluation of angler switching among fishing modes
- Evaluation of the demand for fishing opportunities and access to fishing locations by fishing mode
- Identification and evaluation of anglers motivations, expectations, and outcomes related to saltwater fishing. http://www.nefsc.noaa.gov/nefsc/publications/tm/tm165/tm165.pdf

- **Southern California Beach Valuation Project**

This multi-agency effort was initiated by two offices in NOAA, The National Ocean Service's Special Projects Office and the

Damage Assessment Center, for the purpose of estimating the market and non-market values of recreation uses of Southern California Beaches, beach visitation, the effect of beach attributes, substitution issues, and profiles of beach users on values. The project will result in a system to use this information to estimate values for any beach in the region. http://marineeconomics.noaa.gov/SCBeach/welcome.html

- **Statewide Comprehensive Outdoor Recreation Plan (SCORP)**

To qualify for Land and Water Conservation Act funds states must prepare a comprehensive plan for outdoor recreation. State agencies rely on survey research to collect information that is used in their plan. SCORPs often include information on outdoor recreation supply and demand, needs analysis, trends, community park and recreation planning, statewide recreation goals and priorities, and other issues. Contact the appropriate natural resource agency for more information on the SCORP in your state. A sample SCORP for the state of Oregon can be found at: http://www.prd.state.or.us/scorp_review.php

2. Economic Impact and Non-market Valuation Studies

Bell, F. W. and V. R. Leeworthy. 1986. An Economic Analysis of the Importance of Saltwater Beaches in Florida. Florida Sea Grant Report 82, pp. 1-166, Florida Sea Grant Program, University of Florida, Gainesville, FL.

To evaluate the economic impact and recreational value of saltwater beaches in Florida, two surveys were conducted over the 1983-84 period. The first surveyed out-of-state tourists as they left the state. Tourists are an important aspect of Florida's economy and thus the role of beaches. The second survey was a telephone survey of Florida residents. The estimated economic impact of tourists while at Florida's saltwater beaches was over $3.4 billion in sales, supporting 142,638 jobs with an annual payroll of $860 million, considering direct and indirect effects. Florida residents spent over $1.1 billion while at the beach, supporting 36,619 jobs with an annual payroll of $240 million. Using the contingent value method (CVM), it was determined that residents were willing to pay $1.31 per day for a visit to the beach.

Bell, F. W. and M. McLean. 1996. The Impact of Manatee Speed Zones on Property Values: A Case Study of Fort Lauderdale, Florida. Florida State University, Department of Economics, Tallahassee, FL; Save the Manatee Club, Maitland, FL.

This study addresses the relationship between manatee speed zones and the market value of property in Fort Lauderdale, Florida. The study used a hedonic property value model that relates the selling price of a piece of property to the property's characteristics including the property's location relative to manatee speed zones. The study found that, contrary to popular belief, manatee speed zones increased property values in Fort Lauderdale, Florida while holding other property characteristics constant. The hedonic property value model found that manatee speed zones increase property values from 15 to 20 percent.

Bell, F. W. and V. R. Leeworthy. 1990. Recreational demand by tourists for saltwater beach days. *Journal of Environmental Economics and Management* 18:189-205.

This analysis addresses tourists (out of state) who come from significant distances for the primary purpose of enjoying the beach resources of Florida. It is argued that those that use the conventional travel cost method do not recognize its potential spatial limitations.

The study concludes that the annual consumer demand by individual tourists for Florida beach days is positively related to travel cost per trip and inversely related to on-site cost per day. Using the on-site cost, the consumer surplus per person per day (i.e., use value) for saltwater beach use was estimated at $34 (in 1984 dollars) without the opportunity cost of time. Using a 10 percent discount rate and an estimated 70 million beach days for the tourist segment of the market for beaches, it was estimated that the asset value (i.e., capitalized value) of Florida's saltwater beaches is $23.74 billion. This does not include the resident part of the asset value.

Bell, F. W. 1992. Actual and Potential Tourist Reaction to Adverse Changes in Recreational Coastal Beaches and Fisheries in Florida. Florida Sea Grant Report TP-64. Florida Sea Grant Program, University of Florida, Gainesville, FL.

This study was designed to test the hypothesis that selected natural resource supply constraints in Florida's coastal zone will moderate the projected growth in Florida tourism. A survey was conducted to determine beach users willingness-to-pay for beach use. The application of the contingent valuation method to estimate use value revealed that tourist saltwater anglers were willing to pay $3.18 per day for their recreational experience.

Bell, F. W. 1995. The Economic Valuation of Saltwater Marsh Supporting Marine Recreational Fishing in the Southeastern United States. Working Paper No. 95-02-02. Florida State University, Department of Economics, Tallahassee, Florida. (Also, see same title in *Ecological Economics* 1997, 21:243-254).

In this study, six proposed methods of wetland valuation are considered and found to be deficient. Following Lynne et al. (1981), a production function approach to valuing the importance of saltwater marshland to marine recreational fisheries has been advocated. To simplify the analysis, the rather complicated production function, which was linked to a demand function for recreational fisheries, was approximated with a Cobb-Douglas form. For 1984, capitalized values of an acre of saltwater to the recreational finfish fishery alone were $6,471 and $981 for the east and west coast of Florida, respectively.

Bell, F. W., M. A. Bonn and V. R. Leeworthy. 1998. Economic Impact and Importance of Artificial Reefs in Northwest Florida. Report prepared for the Office of Fisheries Management and Assistance Service, Florida Department of Environmental Protection, Tallahassee, FL. http://marineeconomics.noaa.gov/Reefs/nwfl.pdf

This study is on the economic impact and economic value of the recreational use of artificial reefs in a five-county area of northwest Florida. Estimates were produced by county, type of user (resident of county versus nonresident of county), boat mode (e.g., own boat, charter boat, party boat or rental boat) and by activity (fishing or diving). For visitors, economic values were estimated using three methods; (1) travel cost demand model, (2) Dichotomous Choice Contingent Valuation Model (probit and logit models) and (3) Turnbull Method – Contingent Valuation. For residents, economic values were estimated using only the two contingent valuation methods that were used for visitors.

Bendle, B. J. and F. W. Bell. 1995. An Estimation of the Total Willingness to Pay by Floridians to Protect the Endangered West Indian Manatee through Donations. Florida Department of Environmental Protection, Economic Analysis Section and Florida

State University, Department of Economics, Tallahassee, FL.

This study uses a variation of one of the existing techniques known as Contingent Valuation by surveying a random sample of 951 Floridians in the winter of 1992/93. The survey elicited information about current donations to several causes, including the plight of the manatee. A contribution continuum method was used for the analysis. This method was reinforced by other empirical techniques. The analysis estimated Floridians' total asset value on protection of the manatee population to be $2.6 billion, or $14.78 per year, per household. Given that there were an estimated 1,800 to 2,000 manatees left in existence, this might be interpreted as meaning that protection of each manatee is conservatively worth $1.5 million to Floridians.

Bhat, M. G. 1999. Valuation of Recreation Benefits of Marine Reserves in the Florida Keys: A Combined Revealed and Stated Preference Approach. Environmental Studies Department, Florida International University, University Park, Miami, FL.

The quality of the coral reefs in the Florida Keys is essential to sustain tourist's interest in the Keys. The recently established marine reserves (MR), are expected to improve the quality and quantity of various attributes of the reefs, including coral and fish abundance and diversity. This study demonstrates how one could measure the recreation benefits of MR-induced quality improvement of the coral reefs. A sample survey was used to obtain data on visitors' travel costs and number of trips under existing reef condition, and their stated preference for trips in response to the MR-related reef improvement. A recreation demand model is derived using the survey data.

Chang, Wen-Huei. 2000. Bibliography of Economic Impacts of Parks, Recreation and Tourism. http://www.msu.edu/user/changwe4/bibli.htm

This bibliography presents diverse applications and concepts of economic impacts studies on recreation and tourism. The sources of this bibliography vary from classic texts to contemporary research. Most of the contemporary studies on economic impacts of recreation and tourism use input-out models, other approaches such as economic base models, econometric techniques, hybrid models, and non-survey methods are also included in this bibliography. Although the primary focus is on park, recreation and tourism related studies, it attempts to cover the major approaches in economic impact analysis, especially the input-output models, for concepts and technical references.

Charbonneau, J. J. 2001. Economic methods used to measure ecological restoration. Abstracts from the 44th Conference on Great Lakes Research, June 10-14, 2001. Great Lakes Science: Making it Relevant. 18 pp.

The primary focus of this paper is to explore the economic methods used to estimate the benefits of restoring the ecosystem components that have been damaged. The examples used come from the Ashtabula River restoration proposal that was submitted to the Corps of Engineers. Traditional economic measures of benefits do not adequately portray all the values associated with a functioning ecosystem. Most economic analyses focus on the goods and services that the public receives and not the infrastructure that produces the goods and services. The many interrelationships between species that are required for a fully functioning ecosystem are not independently recognized and valued by the public. For example, the value of catching game fish has been the focus of many studies, but seldom has the value of the prey species sought by game fish been estimated. In an economic context, the demand for game fish generates a derived demand for the ecosystem components that produce the game fish. It is fairly easy to estimate the economic value of game fishing. It is very difficult to estimate the economic value of the ecological infrastructure that supports game fish.

Crandall, K. B., B.G. Colby and K. A. Rait. 1992. Valuing riparian areas: A Southwestern case study. *Rivers* 3:88-98.

A brief review of economic techniques, including the travel cost method, contingent valuation method, and local economic impact analysis, is presented and applied to sites with instream flows and riparian ecosystems. The paper focuses on a case study of Arizona's Hassayampa River Preserve. An examination of consumer surplus values for the site, with and without perennial stream flows, reveals a large potential loss of user benefits if streamflows diminish from steady perennial flows to intermittent seasonal flows. Results are useful to policymakers and managers of riparian areas and provide economic data to facilitate decisions regarding streamflows, land use alternatives, and riparian habitat preservation.

Douglas, A. J. and D. A. Harpman. 1995. Estimating recreation employment effects with IMPLAN for the Glen Canyon Dam region. *Journal of Environmental Management* 44:233-247.

This study examines the economic implications of water-based recreational activities at the Lee's Ferry site on the Colorado River. Analyses estimate the job impacts of expenditures for recreation trips. Input-output models of water-based recreational activities were used, and conclude that the outdoor recreation sector of the economy is relatively labor intensive.

Green, G., C. B. Moss and T. H. Spreen. 1997. Demand for recreational fishing in Tampa Bay, Florida: A random utility approach. *Marine Resource Economics* 12:293-305.

An estimation of demand for recreational fishing in Tampa Bay, Florida, can facilitate the environmental management of the bay. A nested random utility (RUM) travel cost model was used to estimate access values to Tampa Bay. Average value of welfare losses per resident angler were calculated at $1.68 per trip for the loss of the bay itself and $3.66 for the loss of both the bay and Pinellas County together (expressed in 1992 dollars). Because of large number of substitute water bodies in the west central part of Florida, considered by the RUM model, the trip values per angler to the bay is relatively low compared to other estimates for angling using less flexible techniques.

Hazen and P. C. Sawyer. 1998. Estimated Economic Value of Resources. Report prepared for the Charlotte Harbor National Estuary Program, North Fort Myers, FL.

In preparation for its Comprehensive Conservation and Management Plan (CCMP), Charlotte Harbor NEP commissioned an evaluation of the economic value of resources within the Charlotte Harbor watershed. The study estimated consumer surplus and total income values associated with the natural resources of the Charlotte Harbor watershed. Non-market values of the watershed were estimated using benefits transfer. IMPLAN multipliers were used to estimate total income for the region. The study found that the Charlotte Harbor National Estuary provides about $1.8 billion per year in net value to recreators and Florida households, and was used to produce about $3.2 billion per year in income to the area.

Koberstein, P. 1997. What's a river worth? River Values, 8-12. *American Rivers*.

This article supports the claim that revitalized and protected rivers can produce quantifiable economic benefits. The Missouri, Columbia, and Blackfoot Rivers provide examples of how rivers can attract new small businesses and recreation and tourism dollars to communities. The purpose is to show that rivers provide economic benefits beyond those generated by industrial uses.

Leeworthy, V. R. and J. M. Bowker. 1997. Non-market Economic User Values of the Florida Keys/Key West. June 1995 - May 1996. National Oceanic and Atmospheric Administration, Strategic Environmental Assessments Division, Silver Spring, MD; U.S. Forest Service, Outdoor Recreation and Wilderness Assessment Group, Athens, GA.

This study estimated the use value of various forms of outdoor recreation involving visitors to the Florida Keys/Key West area. Use values were estimated from the basic travel cost model without the value of time using statistical techniques called the truncated Poisson and truncated negative binomial. These values were obtained from a sample of 4,360 visitors over the l995-96 period. Day-trippers to the area were very sensitive to price while others, except Hispanics, were not highly sensitive to price with respect to a reduction. The total annual use value for various recreational activities was estimated at about - $.9 billion dollars. When capitalized at a discount rate of 3%, the asset or capitalized value was about - $30.1 billion for just the visitor segment of use value in the Florida Keys/Key West.

Leeworthy, V. R. 1991. Recreational Use Value for John Pennekamp Coral Reef State Park and Key Largo National Marine Sanctuary, Winter, 1988 - Spring, 1989. National Oceanic and Atmospheric Administration, Rockville, MD.

The purpose of this study was to estimate the use value of John Pennekamp Coral Reef State Park and Key Largo National Marine Sanctuary in Florida, which provides recreational activities including diving, boating and other park-related activities. A sample of 342 visitors (i.e., residents and out-of-state tourists) to this area was analyzed using data from 1989. The travel cost method was used to estimate the use value of this area with and without the value of time. The author feels that a realistic estimate of use value for the park is between $285 and $426 per day or an average of $356, in l989 dollars.

Lin, C-T. J. and W. J. Milon. 1995. Contingent valuation of health risk reductions for shellfish products, In J. A. Caswell (ed.) Valuing Food Safety and Nutrition. Westview Press, Boulder, CO.

Introduces the contingent valuation method for valuing the reductions in heath risks associated with the consumption of shellfish products (in the Southeastern U.S., including Florida). The purpose of the analysis was to investigate 1) the relationship between valuation and the magnitude of foodborne risk reductions and 2) whether risk information presented in relative terms and in absolute terms produces different valuation responses. A survey of 1,094 respondents in the Southeast was conducted in early 1990 that asked respondents about their oyster consumption and preferences. The estimated mean WTP to reduce the heath risk from eating oysters relative to the health risk associated with eating chicken ranged from \$0.54 to \$0.73 depending on the question format and treatment of outliers. The estimated mean WTP to reduce the absolute heath risk from eating oysters ranged from \$0.54 to \$0.80 depending on the treatment of outliers and the level of absolute risk reduction considered.

Liu, B. C., N. Christiansen and J. Jaksch. 1980. Measurement of the socioeconomic impact of lake restoration: An assessment model employing a benefit/cost cross-impact probabilistic approach. *American Journal of Economics and Sociology* 39:227-236.

A number of lake restoration demonstration projects have been launched by the Environmental Protection Agency as a result of Public Law 92-500. To evaluate the cost-effectiveness of these public investment projects requires the development of an assessment model. The proposed Benefit/Cost Cross-Impact Probabilistic Approach is one attempt at assessing the interdependent SE and environmental impacts of the lake restoration project over time, both quantitatively and qualitatively, so that various changes brought about by the project can be investigated and evaluated in two comparative stages for three points in time: before, during, and after project implementation.

Loomis, J. B. 1989. A bioeconomic approach to estimating the economic effects of watershed disturbance on recreational and commercial fisheries. *Journal of Soil and Water Conservation* 44:83-87.

This study estimates changes in value of recreational and commercial fisheries due to timber harvesting and road building in two national forests. A travel-cost method is applied to bioeconomic models of the fisheries in order to examine incremental changes in economic value under different levels of watershed disturbance. Results for the Siuslaw National Forest indicate that the loss of salmon and trout due to clear-cutting on 87 acres of forestland resulted in a \$2 million dollar economic loss to recreational and commercial anglers over a 30-year period. Results indicate that timber harvesting in the Porcupine-Hyalite Wilderness study area in Montana resulted in a loss of \$3.5 million in trout fishing over a 50-year period.

Loomis, J., P. Kent, L. Strange, K. Fausch and A. Covich. 1999. Measuring the total economic value of restoring ecosystem services in an impaired river basin: Results from a contingent valuation survey. *Ecological Economics* 33:103-117.

This paper quantifies willingness to pay for restoration of five ecosystem services: dilution of wastewater, natural water purification, erosion control, habitat for fish and wildlife, and recreation, along a 45-mile stretch of the South Platte River near Denver, Colorado. Household surveys were used to determine willingness to pay by giving individuals the hypothetical option to pay for protection of ecosystem services through higher water bill costs. Results indicate that those surveyed would pay an average increase of \$21 a month (\$252 annually) for the five ecosystem services.

Loomis, J. B. and G. L. Peterson. (Date unknown). Economic Information in River Recreation Management. U.S. Fish & Wildlife Service and U.S. Forest Service, Fort Collins, CO.

This study presents a guide for identifying differences between financial – measurable revenue/sales value, and economic – intrinsic, option, existence and bequest values, of a river.

Identified are economic measures that can be used to address various river management issues. A graphical analysis is used to demonstrate the need for economic efficiency measures, such as willingness to pay and consumer surplus, when evaluating economic Benefit Cost Analyses or in National Forest Planning. The study concludes with a discussion of two commonly used techniques to measure willingness to pay for river recreation and off-site preservation values of rivers.

McDonald, L. A. and G. M. Johns. 1999. Integrating social benefit cost accounting into watershed restoration and protection programs. *Journal of the American Water Resources Association* 35:579-592.

Successful watershed management requires consideration of multiple objectives and the efficient use of scarce public and private resources. One way to address these multi-faceted issues is through Social Benefit-Cost Accounting (SBCA). SBCA is a systematic method of addressing complex social and economic issues relevant to proposed watershed management projects. Benefits of using this technique include: benefits and costs of watershed projects are better understood; politically sensitive issues tend to be put into perspective; and stakeholders' interests are placed on a level playing field. An example from Bogota, Colombia demonstrates how SBCA can be used to value the benefits and costs of a proposed project. By addressing the benefits and costs to all stakeholders, the design of watershed management programs can be improved to achieve goals in a cost-effective manner.

Milon, J. W. 1988. Travel cost methods for estimating the recreational use benefits of artificial marine habitat. *Southern Journal of Agricultural Economics* July:87-101.

Compares and discusses the single and multi-site travel cost demand models used in the study of the economic value of artificial reefs in Dade County, Florida. Theoretical concerns about price and quality effects of substitute sites, corner solutions in site choice and econometric estimation are considered. Results from the case study indicate that benefit estimates are influenced by the way these concerns are addressed, but relatively simple single site models can provide defensible estimates. Practical limitations on data collection and model estimation are also considered.

Milon, J. W. 1989. Contingent valuation experiments for strategic behavior. *Journal of Environmental Economics and Management* 17:293-308.

Elaborates on the contingent valuation methodology used in the study of the economic value of artificial reefs in Dade County, Florida. The paper summarizes the results of an experiment that tested for the effects of variations in the Dade County mail survey form on respondent's willingness to pay for artificial reef use and their ability and willingness to disclose their personal valuation.

Milon, J. W. and A. Rimal. 1997. Substitution, Sequencing and Starting Point Effects in the Valuation of Composite Environmental Goods. Food and Resource Economics Department Staff Paper, University of Florida, Gainesville, FL.

Presents the results from a contingent valuation experiment with survey data from the Indian River Lagoon National Estuary Program and the Coastal Resources Survey. The study estimated willingness to pay for various combinations of six different environmental programs: sea grass restoration and protection, sea turtle protection, coral reef restoration and protection, wetland conservation measures, a wetland restoration trust fund, and stormwater controls. The mean annual willingness to pay for the individual Indian River Lagoon environmental programs ranged from \$58.71 to \$112.05 and from \$79.25 to \$405.02 for the combined programs. Similarly, the mean annual willingness to pay for the individual Coastal Resources Survey environmental programs ranged from \$1.36 to \$65.39 and from \$46.61 to \$216.90 for the combined programs.

National Park Service. 1995. Economic Impacts of Protecting Rivers, Trails, and Greenway Corridors: A Resource Book. National Park Service, Rivers, Trails, and Conservation Assistance Program, Washington, D.C.

This publication is a "how-to" guide that instructs the reader in ways to apply economic rationale and related analyses to support river, trail and greenway projects. Sections address real property values, expenditures by residents, commercial uses, tourism, agency expenditures, corporate relocation and retention, and public cost reduction and benefit estimation. Also included are instructions on how to use a consumer price index and a sample survey for economic studies on property values and user spending.

Qui, Z. and T. Prato. 2001. Physical determinants of economic value of riparian buffers in an agricultural watershed. *Journal of the American Water Resources Association* 37:295-303.

The economic value of riparian buffers presented in this study is based on reducing agricultural nonpoint source pollution and providing stream habitat protection. Physical characteristics (such as hydrologic, topographic, land use, and soil attributes) of the Coldwater Creek watershed, Missouri were studied to determine areas of the watershed where construction of riparian buffers would be most cost-effective. Geographic information systems (GIS) were used to identify these target areas. Findings indicate that riparian buffers have the greatest benefit along streams and rivers in crop production areas. Areas where buffer zones cover longer stream stretches and more acreage tend to have greater benefits than those buffer zones that cover shorter stretches and less acreage, respectively.

Shivlani, M. P., D. Letson and M. Theis. 2003. Visitor preferences for public beach amenities and beach restoration in South Florida. *Coastal Management* 31:367-385.

Coastal erosion threatens many sandy beaches and the ecological, economic, social and cultural amenities they provide. The problem is especially chronic in South Florida. A frequent solution for beach restoration involves sand replacement, or nourishment, but is temporary, expensive, and has usually been funded by governmental sources. However, as such agencies reduce their share and require more local funding, beach nourishment must rely on other funding sources, including beach recreationists. This study characterizes three South Florida beaches and probed visitor willingness-to-pay for beach nourishment. It was found that even beaches within close proximity attract different user types. Users are amenable to higher fees if they lead to greater resource protection.

Southern California Beach Valuation Project - NOAA. http://marineeconomics.noaa.gov/SCBeach/welcome.html

A study initiated by NOAA for the purpose of estimating the market and nonmarket values of recreation uses of Southern California Beaches, beach visitation, the effect of beach attributes, substitution issues, and profiles of beach users on values.

Spurgeon, J. 1999. The socio-economic costs and benefits of coastal habitat restoration and creation. Proceedings of an International Workshop on the Rehabilitation of Degraded Coastal Systems, January 19-24, 1998, no. 20, 133 pp. Special publication. Phuket Marine Biological Center, Phuket, Thailand.

As the number of coastal restoration initiatives increases, so too does the need and ability to determine their true socio-economic costs and benefits. Habitat restoration and creation is certainly in vogue, but does it represent an efficient use of resources? It is only after such initiatives have been undertaken that their full costs can be determined with any accuracy. Costs occur from the initial scoping stages, through the construction phase and continue in the form of on-going management and operational monitoring costs. 'Opportunity costs' (i.e., the benefits foregone from an alternative use) must also be included. Predicting whole life restoration costs is inherently problematic given the complex and dynamic nature of the environment and the many uncertainties involved. Equally, assessing the true socio-economic benefits of restoration schemes is complex and is only now becoming possible as the outcomes of current schemes begin to unfold. Furthermore, the techniques available to place monetary values on the environment are continuing to improve, enabling more comprehensive and accurate estimates of the value of the accruing benefits. Such benefits include, for example, direct (e.g., products and recreation) and indirect (e.g., physical protection) uses, as well as non-use (e.g., existence) values. This paper provides an objective overview of the potential socio-economic costs and benefits relating to the restoration and creation of a diverse range of coastal habitats. The habitats examined include coral reefs, mangroves, sea-grasses, salt marshes, sand dunes, mudflats and lagoons. Factors affecting the magnitude of costs and benefits are highlighted, and the potential significance of different components of costs and benefits for each habitat type are identified. The appropriateness and value of using cost-benefit analysis to help assess and improve the effectiveness of coastal habitat restoration and creation is also discussed.

Spurgeon, J. 1998. The socio-economic costs and benefits of coastal habitat rehabilitation and creation. *Marine Pollution Bulletin* 37:373-382.

This paper provides a comprehensive over-view of the merits and limitations of using an economics-based approach to assess and implement initiatives for coastal habitat rehabilitation and creation. A review of the literature indicates that habitat rehabilitation/creation costs vary widely between and within ecosystems. For coral reefs, costs range from US$ 10,000 to 6.5 million/hectare (ha); for mangroves US$ 3000-510,000/ha; for sea-grasses US$ 9000-680,000/ha and for salt marshes US$ 2000-160,000/ha. A review of the economic benefits derived from various coastal habitats based on a 'Total Economic Value' approach (i.e., accounting for direct and indirect uses, and 'non-uses') reveals that many thousands of US$ per hectare could ultimately accrue from their rehabilitation/creation. The paper concludes that despite its limitations, the 'benefit-cost analysis' framework can play an important role both in assessing the justification of coastal habitat rehabilitation/creation initiatives, and by helping to improve the overall effectiveness of such initiatives.

Spurgeon, J. 2001. Improving the economic effectiveness of coral reef restoration. Proceedings of the International Conference on Scientific Aspects of Coral Reef Assessment, Monitoring, and Restoration. *Bulletin of Marine Science* 69:1031-1045.

This paper provides a brief overview of the economic costs and benefits of coral reef restoration and considers the potential application of benefit-cost analysis. Three coral restoration case studies indicate that restoration costs can vary enormously, from around US$10,000 ha $^{-1}$ to US$5 million ha^{-1}. A brief review of the economic benefits of coral reefs based on a 'total economic value' approach (i.e., accounting for direct and indirect uses, and 'non-uses'), reveals that potentially many thousands of US$ per hectare could accrue from reef restoration. Various parameters are identified which dictate the value of coral benefits, and those factors that can be manipulated through restoration to enhance coral benefits are highlighted. The paper concludes with a number of recommendations. There is scope for greater application of a 'benefit-cost analysis' framework to assess the justification for restoring coral reefs and to improve the overall effectiveness of such initiatives.

Stronge, W. B. and R. R. Schultz. 1997. Broward County Beaches: An Economic Study 1995-96. Technical report 97-03. Prepared for the Broward County, Department of Natural Resource Protection, Biological Resources Division, Ft. Lauderdale, Florida by Regional Research Associates, Inc., Boca Raton, FL.

This report developed estimates of both the market and non-market economic values of Broward County beaches for year 1995-96. Market economic values estimated included direct expenditures, indirect expenditures, tax revenues, and the number of jobs in Broward County, Southeast Florida and all of Florida. In addition, property values related to proximity to the beaches are also estimated. Non-market economic use values are estimated using a contingent valuation question. Overall the study estimated that there were 7,169,447 visits to Broward County beaches that generated a total annual non-market economic user value of $29,677,770. Per visit values, in 1998 dollars, were reported for Delray Beach ($4.94), Anna Marie Island ($41.2) and Captiva Island ($7.00)

Swart, J. A., H. J. Van Der Windt and J. Keulartz. 2001. Valuation of nature in conservation and restoration. *Restoration Ecology* 9:230-238.

Valuation of nature is an important aspect of nature conservation and restoration. Understanding valuation in a broad sense may contribute to conservation strategies since it may lead to better support from society. In this article we propose a model of valuation with respect to conservation and restoration of nature. According to the model, valuation of nature can be characterized by a "valuation approach," consisting of ecological, ethical and aesthetic perspectives. Such an approach includes scientific and normative aspects and leads to a particular claim of conservation. In this paper we discuss different perspectives, and accordingly, we sketch three main types of these valuation approaches. Political and policy issues with respect to nature conservation and restoration are considered in terms of this model.

3. Research on Stakeholders' Values, Attitudes and Satisfaction Ratings

Bright, A. D., S. C. Barro and R. T. Burtz. 2002. Public attitudes toward ecological restoration in the Chicago Metropolitan Region. *Society and Natural Resources* 15:763-785.

This study examined the relationship between attitudes toward urban ecological restoration and cognitive (perceived outcomes, value orientation, and objective knowledge), affective (emotional responses), and behavioral factors using residents of the Chicago Metropolitan

Region. Positive and negative attitudes were both related to perceived outcomes of ecological restoration. In addition, positive attitudes were related to values while negative attitudes were related to emotions. Attitudes of high and low importance groups were connected to perceived outcomes of ecological restoration; however, attitudes of the high importance group were also related to values, emotions, and behavior. Positive and negative attitude groups differed on perceived outcomes, basic beliefs, knowledge, and behavior. Implications lie in understanding of complex attitudes toward natural resource issues and improved communication efforts to influence or educate the public.

Cofer-Shabica, S.V., R. E. Snow and F. P. Noe. 1990. Formulating policies using visitor perceptions of Biscayne National Park and Seashore, pp. 235-254, In P. Fabbri (ed.), Recreational Uses of Coastal Areas. Kluwer Academic Publishers, Norwell, MA.

Visitor surveys were handed to randomly selected visitors to the park in the winter and summer and returned by mail. A mail-out survey was sent to registered boat owners in Dade County. From a park management perspective, Biscayne's data suggest a need for sensitivity to expectations that different ethnic groups brought to the Park when designing services and programs. Data also suggested addressing issues of whether marine recreational areas should have increased development and formal control to maximize visitor satisfaction, or remain undeveloped.

Grese, R. E., R. Kaplan, R., R. L. Ryan and J. Buxton. 2000. Psychological benefits of volunteering in stewardship programs, pp. 265-280, In Gobster, P. H. and R. B. Hull (eds.), Restoring Nature. Island Press, Washington, D.C.

This study explores people's motivations for and benefits derived from volunteer stewardship efforts. Interviews were conducted with Chicago-area participants in the Volunteer Stewardship Network and with leaders of several volunteer programs throughout Michigan. A survey instrument was developed based on these interviews and was distributed to volunteers of different organizations. Volunteers were highly motivated by a desire to help the environment and learn new things. They also may benefit from opportunities to reflect and seek spiritual fulfillment as well as to develop friendship and social networks. Programs that pay attention to these considerations may fare better in attracting and retaining volunteers, issues that are critical to the long-term success of any ecological restoration effort.

Leeworthy, V. R. and P. C. Wiley. 1996. Importance and Satisfaction Ratings by Recreating Visitors to the Florida Keys/ Key West, June 1995 - May 1996. National Oceanic and Atmospheric Administration, Strategic Environmental Assessments Division, Silver Spring, MD.

This report provides an easy-to-use analytical framework for assessing the ratings by visitors in terms of importance and satisfaction with 25 selected natural resource attributes, facilities, and services of the Florida Keys. For 11 of the 25 items, comparisons were made between visitors' current satisfaction ratings and their ratings of these items five years prior. Statistical tests were conducted to highlight significant differences.

Milon, J. W., C. M. Adams and D. W. Carter. 1988. Floridians' Attitudes about the Environment and Coastal Marine Resources. Florida Sea Grant Technical Paper 95, University of Florida, Gainesville, FL.

Provides a description of a research project designed to assess Floridians' attitudes about the environment and coastal marine resources and their support for programs to protect these resources. A statewide survey of nearly 1,800 adult residents elicited information on: preferences for expenditures on various state programs, attitudes about the environment and specific marine resources, participation in coastal recreation activities, and general socioeconomic and demographic characteristics. The survey results indicate that Floridians are broadly committed to an "environmentally oriented world view." They are concerned about the health of coastal resources and the adequacy of existing programs to protect these resources. While there were differences in the intensity of these attitudes across respondents, the consistency of the responses indicates that these attitudes are not random and idiosyncratic, but rather, reflect the personal philosophies, interests, and experiences of the respondents.

Schroeder, H. W. 2000. The restoration experience: Volunteers' motives, values, and concepts of nature, pp. 247-264, In Gobster, P. H. and R. B. Hull (eds.), Restoring Nature. Island Press, Washington, D.C.

The goal of this study was to learn more about restoration volunteers, what their work means to them and what specific motives, values, and rewards have induced them to give so many hours of their free time to restoration activities. The primary source of material for this study was the periodic newsletters distributed by many of the individual stewardship groups. These newsletters, written and edited by the volunteers themselves, contain many passages that express who the volunteers are, what they are trying to achieve, why they are drawn to this kind of work, and what rewards they experience in the course of doing their work. Results suggest that the high level of motivation and enthusiasm for restoration volunteerism stems from three interacting factors: 1) the sense of urgency the feel about the fragility of nature and the impending loss of native sites and species, 2) their belief that they can make an important and real difference in preventing this loss, and 3) the ability to see tangible progress and results from their efforts in a fairly short time span.

Vining, J., E. Tyler and B. Kweon. 2000. Public values, opinions, and emotions in restoration controversies, pp.143-161, In Gobster, P. H. and R. B. Hull (eds.), Restoring Nature. Island Press, Washington, D.C.

This study investigates public values, opinions, and emotions related to ecological restoration. An analysis of new articles and other public documents regarding the Chicago restoration controversy is conducted to develop a comprehensive list of value-based arguments for and against restoration. This information is used to develop and implement a survey of Chicago metropolitan residents' perceptions of restoration practices, as well as their decisions and emotional reactions regarding a restoration scenario in Chicago. Results of this study suggest that ecological restoration specialists, public land managers, decision makers, and social scientists interested in human-environment interactions have a lot to learn from average citizens. Survey respondents strongly identified the need to inform and involve the public in restoration activities, to frame compromise solutions, and to proceed judiciously.

4. Commercial Fishing: Human Dimensions Research

Adams, C. A. 1990. Economic Activities Associated with the Commercial Fishing Industry in Monroe County. Staff Paper SP 92-27. Food and Resource Economics Department, IFAS, University of Florida, Gainesville, FL.

The commercial fishing industry represents an important source of revenue for Monroe County, Florida. This paper estimates (a) economic activity, (b) earnings, and (c) employment generated by the commercial fishing industry in 1990. In 1990, commercial fishermen landed 19.7 million pounds of finfish, shellfish, and other aquatic organisms, valued at $48.4 million dockside. The total wholesale value of the various products landed by the commercial fishing industry in Monroe County was $64 million. The estimated economic impact generated includes economic activity - $90.4 million, earnings - $32.2 million, and employment - 2,230 FTEs.

Anderson, E. 1989. Economic benefits of habitat restoration: Seagrass and the Virginia hard-shell blue crab. *North American Journal of Fisheries Management* 9:140-149.

Since the early 1960s, water pollution has caused the disappearance of much of the seagrass (predominantly eelgrass *Zostera marina*) and other submerged aquatic vegetation in Chesapeake Bay. Seagrass beds appear to serve as preferred habitat for the blue crab *Callinectes sapidus* during early stages of its life history, and there is a statistically significant relationship between the abundance of submerged aquatic vegetation and catch per unit of effort in the Virginia hard-shell blue crab fishery. Virginia seagrass beds might be partially or fully restored through a combination of pollution abatement and replanting. I developed a simple simulation model with minimal data requirements to generate rough estimates of some of the economic benefits that would accrue from seagrass restoration. The estimated net economic benefit to Virginia hard-shell blue crab fishermen of full seagrass restoration is about US $1.8 million per year, and additional annual benefits of about $2.4 million should accrue to U.S. hard-shell blue crab consumers.

Bell, F. W. 1984. Application of Wetland Valuation Theory to Commercial and Recreational Fisheries in Florida. Florida Sea Grant Report No. 95, Florida Sea Grant College Program, University of Florida, Gainesville, FL. (Also see *Ecological Economics* 21 (l997) 243-254 for the recreational segment and the *Journal of Economic Research* 3 (l998) 1-20 for the commercial segment of this report in condensed form).

This paper is concerned with placing an economic value on the contribution of wetlands in supporting both the recreational and commercial marine fisheries in Florida. Production functions linking fishing effort and wetlands to fishery value are used to demonstrate the marginal productivity theory approach to valuing wetlands. Chapter 2 reviews the biological and economic functions of wetlands. Chapter 3 reviews methods for economic valuation of wetlands. Chapter 4 presents the marginal productivity theory approach to valuing wetlands. Chapter 5 examines marginal productivity theory applied to Florida's east and west coast marine fisheries; and Chapter 6 estimates the fishery component of wetlands and the calculated asset values of the wetland resources under alternative discount rates.

NOAA. 1996. An Appraisal of the Social and Cultural Aspects of the Multispecies Groundfish Fishery in New England and the Mid-Atlantic Regions. National Marine Fisheries Service report prepared by Aguirre International under Contract Number 50-DGNF-5-00008 between NOAA and Aguirre International. http://www.nefsc.noaa.gov/read/socialsci/cultural-aspects/50-DGNF-5-00008.pdf

The goals of this study were: (a) to identify fishery-dependent communities throughout the Northeast Region, (b) to provide information on the demographics and numbers of fishermen, fishing craft, and persons involved in fishery-related industries by community, county, and state, (c) to identify existing social science data bases and describe social issues which should be considered in Phase II, and (d) to develop a classification system that would aid in predicting the social impacts of changing fishery regulations on fishery-dependent communities.

Thorhaug, A. 1990. Restoration of mangroves and seagrasses - economic benefits for fisheries and mariculture, pp. 265-281, In Berger, J. J. (ed.), Environmental Restoration: Science and Strategies for Restoring the Earth. Papers from Restoring the Earth Conference, January 1988. Island Press, Washington, D.C.

This paper reviews mangrove and seagrass restoration in terms of its ecological and economic benefit to fisheries and aquaculture. In the tropics and subtropics, mangroves are a critical habitat in the intertidal zone and on the upper shoreline. Seagrasses are a critical habitat from the intertidal zone seaward to the coral reef. Mangroves and seagrasses serve parallel functions as nursery grounds and critical habitats for fish, as a direct food source for fish, and as surfaces for growth of epizonts, which serve as food for fish. This paper contains a review of coastal restoration efforts, including an assessment of development impacts on mangroves and seagrasses. Management solutions to nearshore fisheries problems are also discussed, and general recommendations for using seagrass and mangrove restoration to sustain fisheries are made.

5. Education and Outreach Research

Bowler, P. A., F. G. Kaiser and T. Hartig. 1999. A Role for Ecological Restoration Work in University Environmental Education. *Journal of Environmental Education* 30:19.

The effects of ecological restoration field work and in-class instruction on students' ecological behavior, environmental attitudes, and perceptions of restorative qualities in a natural environment were studied in 3 classes of university undergraduates (N = 488). In 1 class, students (n = 145) carried out ecological restoration work on 8 field trips. Students in 2 control classes (n = 157; n = 186) each made only 1 field trip, to a site where the other class had done restoration work, but did no restoration work. In 1 of the control classes, data were collected from 5 subgroups at different points in the course to examine the effects of cumulating in-class instruction. Ecological restoration work positively affected environmental attitudes and ecological behavior, but within the attitude measures it affected only ecological behavior intention and not environmental knowledge or environmental values. In-class instruction was associated with perceived restorative qualities in the study site; perceptions of Being Away, Coherence, and Fascination increased over the course of instruction.

Burton, S., C. Vickery and K. Weiss. 1994. Public Education Survey for the Indian River Lagoon, National Estuary Program. FAU/FIU Joint Center for Environmental and Urban Problems. U.S. EPA (National Estuary Program), St. John's River Water Management District, FL.

The Indian River Lagoon (IRL) spans some 156 miles along Florida's central east coast. It is listed as an estuary of national significance and included in the National Estuary Program. Results from the survey provided a basis for determining a desirable and acceptable approach to educating the public about the environmental issues of concern and their potential solutions as they relate to the IRL. Furthermore, the survey may also be used to better understand how to target various audiences within the general population for public information and education. Survey information was obtained through telephone interviews with 407 randomly selected residents from the five counties that form the IRL system, Brevard, Indian River, Martin, St. Lucie, and Volusia.

Covington, W. W., P. Z. Fule, T. M. Alcoze and R. K. Vance. 2000. Learning by doing - Education in ecological restoration at Northern Arizona. *Journal of Forestry* 98: 30-34.

In the Southwest, where forest ecosystems have been widely degraded, Northern Arizona University has begun offering an interdisciplinary focus on forest restoration. A course in the principles of restoration addresses such issues as reference conditions, the impact of indigenous peoples on the landscape, and natural variability versus accelerated anthropogenic change. An applications course includes hands-on experience in restoring a ponderosa pine forest and calculating the costs of implementation. Through practical study and applied research, the program is intended to support the preparation of future participants in a growing field.

Geist, C. and M. Galatowitsch. 1999. Reciprocal model for meeting ecological and human needs in restoration projects. *Conservation Biology* 13:970-979.

Research presented concerns a model for ecological restoration that focuses on human relationships to the environment in order to overcome obstacles of time, cost, and labor that often hamper the success of habitat improvement projects. Topics addressed include community participation in restoration projects, and the dynamic relationship between human involvement and project success.

United States General Accounting Office (USGAO). 1995. Restoring the Everglades: Public Participation in Federal Efforts. Resources Community, Economic Development Division. USGAO, Washington, D.C., RCED-96-5.

This document reviews the implications of involving non-federal entities (stakeholders) in the policy development process for specific environmental concerns in South Florida. Constraints imposed by external factors often dictate the extent to which federal agencies can involve nonfederal stakeholders in their activities. Furthermore, although consensus among federal and nonfederal stakeholders is desirable, restoration efforts are inherently contentious, and consensus on solutions that directly affect various interests may not be attainable. In addition, stakeholders express dissatisfaction with the process for nonfederal involvement. In many cases, a public policy decision cannot be disassociated from stakeholder dissatisfaction with the outcome of the process. Therefore, the most that federal agencies may be able to achieve is an open airing and full consideration of all views within the constraints imposed by external factors.

6. Socio-Cultural and Anthropological Research

Wiedman, D. 1976. The individual and innovation in the process of socio-cultural adaptation to frontier situations. *Papers in Anthropology,* University of Oklahoma, Norman, OK, 17:107-116.

This paper outlines a process of human adaptation to new environments. Ethnographic fieldwork and historical data from the Chokoloskee Bay area of Southwest Florida are used in a comparative analysis of three frontier areas of the World. This process is suitable for understanding the various cultural groups as they adapt to South Florida environments.

For example, their settlement patterns, use of resources and technological innovation.

7. Coastal Restoration and Property Damage Reduction

FEMA. Federal Programs Offering Non-Structural Flood Recovery and Floodplain Management Alternatives. Federal Emergency Management Agency Publication #102.

Information to local cooperators and other interested parties about federal programs that support a non-structural approach to floodplain management. Programs are grouped by three primary non-structural strategies: (1) acquisition, relocation, elevation, and flood-proofing of existing structures; (2) rural land easements and acquisitions; and (3) restoration of wetlands.

Loomis, J. B. 1994. Determining Benefits and Costs of Urban Watershed Restoration: Concepts, Techniques and Literature Review. Colorado State University, Department of Agricultural and Resource Economics, Fort Collins, CO.

This study details the economic benefits that natural stream channel restoration can provide, including flood damage reduction, cost savings, and enhancement of the natural environment. Techniques for estimating flood damage reductions are identified.

Olsen, J. R. and P. A. Beling. 1998. Input-output economic evaluation of system of levees. *Journal of Water Resources Planning & Management* 124:237-246.

Presented is a method to estimate the economic effects of flooding over a region of interacting floodplains and other lands by incorporating a Leontief economic input-output model. Authors discuss how the model is used, how to relate flood probabilities to output, and provide application examples.

Property Acquisition Handbook for Local Communities. Federal Emergency Management Agency Publication #317. http://www.fema.gov/fima/handbook/

The Property Acquisition Handbook for Local Communities is a "how to" guide to help communities work through one specific hazard mitigation alternative known as property acquisition (also referred to as "buyout"). The Handbook contains four parts, representing the four phases of the property acquisition process.

8. Effects of Coastal Restoration on Property Values

Brookshire, D. S., M. Thayer, W. D. Schulze and R. C. d'Arge. 1982. Valuing public goods: A comparison of survey and hedonic approaches. *The American Economic Review* 72:165-77.

This 1979 study on the economic benefits of air pollution control includes the empirical results obtained from two experiments to measure the health and aesthetic benefits of air pollution control in the South Coast Air Basin of Southern California. Each experiment involved the same six neighborhood pairs, where the pairings were made on the basis of similarities in housing characteristics, socio-economic factors, distances to beaches and services, average temperatures, and subjective indicators of housing quality. The elements of each pair differed substantially only in terms of air quality. Data on actual residential property transactions and on stated preferences in air quality were collected. The results indicate that air quality deterioration in the Los Angeles area has had substantial negative effects on housing prices and that these effects are comparable in magnitude to what people say they are willing to pay for improved air quality.

Brown, P. J. and C. J. Fausold. 1998. A Methodology for Valuing Town Conservation Land. Lincoln Institute of Land Policy Working Paper. http://www.lincolninst.edu/pubs/pub-detail.asp?id=127

This paper presents a methodology for rating existing or potential conservation land according to ten criteria weighted to reflect the needs of the local community in which the land is located. The ratings may be used to determine priority for public acquisition. The methodology may also be used to establish a dollar "replacement value" for an existing parcel of conservation land, reflecting both its market value as well as its value for other public interests such as conservation, recreation, views, or resource protection. The replacement value may be used as a starting point in negotiations for compensation in the event that the parcel is removed from conservation land status through eminent domain or other mechanism.

Epp, D. J. and K. S. Al-Ani. 1979. The effect of water quality on rural non-farm residential property values. *American Journal of Agriculture and Economics* 61:529-534.

The authors use real estate prices to put a value on improvements in the water quality of small rivers and streams in Pennsylvania. Specific goals are: 1) to estimate the relationship between water quality and value of residential properties adjacent to small rivers and streams, and 2) to estimate the effect of various components of water quality, such as acidity, dissolved oxygen, biochemical demand, and nitrate/phosphate levels on the value of properties adjacent to small streams. Results indicate that water quality has a positive correlation with economic value of adjacent properties.

Kulshreshtha, S. N. and J. A. Gillies. 1993. Economic evaluation of aesthetic amenities: A case study of river view. *Water Resources Bulletin* 29:257-266.

This study employs market and non-market valuation techniques to estimate the value of aesthetic amenities that the South Saskatchewan River provides to residents of Saskatoon, Canada. Two major areas in which greater aesthetic amenities provide greater value are identified: ownership of property, and rental of private property. Findings indicate that aesthetic amenities provided by the river amounted to approximately 10 percent of the annual economic contribution the South Saskatchewan River makes to the city.

Leefers, L. and D. M. Jones. 1996. Assessing Changes in Private Property Values Along Designated Natural Rivers in Michigan. Michigan State University, Department of Forestry, Lansing, MI.

This comprehensive study examines property values and selling prices along areas with 'Natural River' designation in Michigan. The results reveal that property values and selling prices are indeed higher along areas with 'Natural River' designation. The study details the procedures used as well as the methods for data evaluation.

Rosner, M. H. and L. R. Barrows. 1976. Who Pays for the Wild Rivers?: An Analysis of the National Park Service's Wild Rivers Program on Property Taxes in Washburn County, (Cooperative Extension Service no. 110). University of Wisconsin, College of Agricultural and Life Sciences, Madison, WI.

Concern over land acquisition by the National Park Service (NPS) in Washburn County, Wisconsin is addressed. It is generally believed that higher property taxes result when land is removed from the tax base. However, the authors' findings suggest that the impact on property taxes of removing public lands from the tax base is negligible – an increase of only $0.01 per $1000.00. This small increase in property tax is because the tax-loss associated with NPS land acquisition was mostly made up through small increases in income and sales taxes and additional sources of revenue statewide instead of through local property tax increases.

9. Human Dimensions Benefits of Improved Water Quality

Alaouze, C. M. 1999. An economic analysis of the eutrophication problem of the Barwon and Darling Rivers in New South Wales. *Australian Economic Papers* 38:51-63.

This paper focuses on the economic implications of water quality on recreation values. An example of a 1000-km, toxic blue-green algae bloom which afflicted the Barwon and Darling Rivers in 1991 is used for discussion. This bloom occurrence was attributed to increased water use for irrigation, drought, and nutrient pollution (mainly phosphorus) from sewage treatment plants and other point sources. The cost of pollution function is unknown, but results suggest that if marginal costs of phosphorus removal are low, the equilibrium level of phosphorus at each location is likely to be below that which reduces the recreational value of the rivers.

Gramlich, F. W. 1977. The demand for clean water: The case of the Charles River. *National Tax Journal* 30:183-194.

A survey of 165 families' willingness to pay in the metropolitan area of Boston finds that costs and benefits of swimmable water in the Charles River are nearly equal. Determinants of willingness to pay were isolated using regression analysis. An estimate of aggregate benefits from improving water quality was developed from the regressions and compared to resource costs. The range of estimates for aggregate benefits is $8.8-21.9 million, with an average of $15.4 million, with total aggregate costs at $16.7 million. Findings from interviews and questionnaires indicate that family income, education, proximity of home and workplace to the river, graduate student status, and probability of future residence were all positively correlated with willingness to pay. A variety of independent variables were considered for analysis.

Magat, W. A., J. Huber, W. K. Viscusi and J. Bell. 2000. An iterative choice approach to valuing clean lakes, rivers, and streams. *Journal of Risk and Uncertainty* 21:7-43.

This article introduces an iterative choice procedure for valuing the quality of inland waters, which breaks valuation into a series of component tasks. Respondents in Colorado and North Carolina assessed the value of water quality rated "good" by EPA standards, and it was found that the value of water increases with even a 1% increase in water quality. Study results noted differences in valuation of water quality for aquatic environment, edible fish, swimming, and for water that is cloudy, smelly, or polluted by toxins.

Postel, S. L. 1998. Allocating fresh water to aquatic ecosystems: The case of the Colorado River delta. *Water International* 23:119-125.

This is a case study of the potential economic benefits of a revitalized and protected delta ecosystem. The unique biological assets of the Colorado River delta estuary discussed in this paper indicate that efforts to determine and satisfy water needs of a threatened aquatic environment are justified. Ways in which policy and legal reforms, economic incentives, and efficiency investments can help generate water supplies to rejuvenate and maintain a healthier delta ecosystem are discussed. Also discussed are priorities for delta restoration.

Van Den Bergh, J., P. Nunes, H. M. Dotinga, W. Kooistra, E. G. Vrieling and L. Peperzak. 2002. Exotic harmful algae in marine ecosystems: An integrated biological-economic-legal analysis of impacts and policies. *Marine Policy* 26:59-74.

Harmful algal blooms (HABs) are the cause of important damages to marine living resources and human beings. HABs are generated by micro-algae. These marine species are primarily introduced through ballast water of ships and, to a lesser extent, through import of living fish, in particular shellfish. Effective and efficient regulation of HABs requires an integration of insights from biological, economic and legal sciences. Such an integration consists of (a) a clear identification of the bio-ecological pathways and overall consequences related to the damages of HABs; (b) an assessment of monetary costs of HABs; and (c) an understanding of the set of complementary legal-institutional and economic instruments dealing with HABs through prevention, restoration and amelioration. This paper discusses each element in detail, in which biological, economic and legal aspects come together, drawing conclusions for decision making in marine management. In order to move away from the general level of discussion, an example of HABs is presented in which, biological, economic, and legal aspects are combined.

Whitehead, J. C. and P. A. Groothuis. 1992. Economic benefits of improved water quality: A case study of North Carolina's Tar-Pamlico River. *Rivers* 3:170-178.

A contingent valuation survey is used to measure the economic benefits of reduced agricultural non-point source pollution in the Tar-Pamlico River in eastern North Carolina. Surveys show respondents are willing to pay for improved water quality. Survey participants' age, number of children, income, and expected use are related to their willingness to pay. Regression results suggest that for open-ended willingness to pay response data, the Tobit technique is preferred to the ordinary least squares method due to additional information contained in the Tobit decomposition. Results imply that aggregate benefits of improved water quality would be \$1.62 million each year, and the majority of voters would support a program that would raise up to \$1.06 million annually for water quality improvements.

10. Miscellaneous Human Dimensions of Coastal Restoration Monitoring References

Bash, J. S. and C. M. Ryan. 2002. Stream restoration and enhancement projects: Is anyone monitoring? *Environmental Management* 29:877-885.

Declines in salmon stocks and general watershed health in Washington State, USA, have led to an increase in stream restoration and enhancement projects initiated throughout the state. The increasing number of projects has also raised questions regarding the monitoring of these efforts. Project managers receiving hydraulic project approvals (HPAs) were surveyed to determine whether monitoring was taking place on their projects. About half the project managers surveyed reported the collection of baseline data and the use of biological, physical, chemical, or other water quality measures for their projects. Of those who reported collection of monitoring data, only 18% indicated that monitoring was required. Respondents were also asked to rank the importance of various project goals on a Likert scale. Project managers with projects focusing on "engineering" goals (e.g., roadbed stabilization) were less likely than other project managers to collect baseline monitoring data. Project managers with projects focusing on "restoration/ecological" or "fisheries" goals were more likely than other project managers to collect monitoring measures, Although monitoring appears to be taking place in slightly more than half of the projects surveyed, the nature of the data collected varies widely across projects, and in most cases the monitoring effort is voluntary. This suggests that project sponsors, funders, and managers must consider the issues involved in requiring appropriate monitoring, establishing standardized monitoring guidelines, the time frames in which to monitor, providing other incentives for conducting monitoring, and ensuring adequate funding for monitoring efforts.

Cowell. C. M. 1993. Ecological restoration and environmental ethics. *Environmental Ethics* 15:19-32.

Restoration ecology has recently emerged as a branch of scientific ecology that challenges many of the traditional tenets of environmentalism. Because the restoration of ecosystems, 'applied ecology,' has the potential to advance theoretical understanding to such an extent that scientists can extensively manipulate the environment, it encourages increasingly active human participation within ecosystems and could inhibit the preservation of areas from human influences. Despite the environmentally dangerous possibilities that this form of science and technology present, restoration offers an attractive alternative for human interaction with the environment. I outline the primary claims that have been made for ecological restoration, examine inconsistencies with restorationists' philosophical position, and propose a reassessment of the definition of restoration that may aid in the clarification and development of a system of environmental ethics that recognizes human relationships with the environment as potentially symbiotic and positive.

Light, A. and E. S. Higgs. 1996. The politics of ecological restoration. *Environmental Ethics* 18:227-247.

Discussion of ecological restoration in environmental ethics has tended to center on issues about the nature and character of the values that may or may not be produced by restored landscapes. In this paper we shift the philosophical discussion to another set of issues: the social and political context in which restorations are performed. We offer first an evaluation of the political issues in the practice of restoration in general and second an assessment of the political context into which restoration is moving. The former focuses on the inherent participatory capacity at the heart of restoration; the latter is concerned with the commodified use (primarily in the United States) and nationalized use (primarily in Canada) to which restoration is being put. By means of a comparative examination of these two areas of inquiry, we provide a foundation for a critical assessment of the politics of restoration based on the politics in restoration.

APPENDIX III: GLOSSARY OF HUMAN DIMENSIONS TERMS

Adaptive Management - A systematic process for continually improving management policies and practices by learning from the outcomes of operational programs. Its most effective form—"active" adaptive management—employs management programs that are designed to experimentally compare selected policies or practices, by evaluating alternative hypotheses about the system being managed.

Assigned Values - The relative importance or worth of something, usually in economic terms. Natural resource examples include the value of water for irrigation or hydropower, land for development, or forests for timber supply (see held values).

Asset Mapping - A community assessment research method that provides a graphical representation of a community's capacities and assets.

Attitude - An individual's consistent tendency to respond favorably or unfavorably toward a given attitude object. Attitudes can be canvassed through survey research and are often defined utilizing scales ranging from positive to negative evaluations.

Benefit-Cost Analysis - A comparison of economic benefits and costs to society of a policy, program, or action.

Bequest Value - The value that people place on knowing that future generations will have the option to enjoy something.

Causality - Or causation, refers to the relationship between causes and effects - i.e., to what extent does event 'A' (the cause) bring about effect 'B.'

Clustering (Cluster Sample) - A multistage sample in which natural groups (i.e., clusters) are sampled initially, with the members of each selected group being subsampled afterward.

Cognitive Mapping - A community assessment research method used to collect qualitative data and gain insight into how community members perceive their community and surrounding natural environment.

Cohort Studies - Longitudinal research aimed at studying changes in a particular subpopulation or cohort (e.g., age group) over time (see longitudinal studies).

Community - A group of people who interact socially, have common historical or other ties, meet each other's needs, share similar values, and often share physical space; a sense of "place" shaped by either natural boundaries (e.g., watershed), political or administrative boundaries (e.g., city, neighborhood), or physical infrastructure.

Computer-Assisted Telephone Interviewing (CATI) - A system for conducting telephone survey interviews that allows interviewers to enter data directly into a computer database. Some CATI systems also generate phone numbers and dial them automatically.

Concept Mapping - Community assessment research method that collects data about how community members perceive the causes or related factors of particular issues, topics, and problems.

Content Validity - In social science research content validity refers to the extent to which a measurement (i.e., parameter) reflects the specific intended domain of content (i.e., stated goal or objective). That is, how well does the parameter measure whether or not a particular project goal has been met.

Contingent Choice Method - Estimates economic values for an ecosystem or environmental service. Based on the individual's tradeoffs among sets of ecosystems, environmental services or characteristics. Does not directly ask for willingness to pay; inferred from tradeoffs that include cost as an attribute.

Contingent Valuation Method (CVM) - Used when trying to determine the monetary valuation of a resource. The CVM can be used to determine changes in resource value as related to an increase or decrease in resource quantity or quality. Used to measure non-use attributes such as existence and bequest values; market data is not used.

Coverage Error - A type of survey error that can occur when the list – or frame – from which a sample is drawn does not include all elements of the population that researchers wish to study.

Cross-sectional Studies - Studies that investigate some phenomenon by taking a cross section (i.e., snapshot) of it at one time and analyzing that cross section carefully (see Longitudinal Studies).

Crowding - In outdoor recreation, crowding is a form of conflict (see outdoor recreation conflict) that is based on an individual's judgment of what is appropriate in a particular recreation activity and setting. Use level is not interpreted negatively as crowding until it is perceived to interfere with one's objectives or values. Besides use level, factors that can influence perceptions of crowding include participant's motivations, expectations, and experience related to the activity, and characteristics of those encountered such as group size, behavior, and mode of travel.

Culture - A system of learned behaviors, values, ideologies, and social arrangements. These features, in addition to tools and expressive elements such as graphic arts, help humans interpret their universe as well as deal with features of their environments, both natural and social.

Direct Impacts - The changes in economic activity during the first round of spending. For tourism this involves the impacts on the tourism industries (businesses selling directly to tourists) themselves (see Secondary Effects).

Direct Use Values - Refers to the set of values derived from any direct use of natural environments.

Driving Forces - The base drivers that play a large role in people's decision making processes and influence human behavior. Societal forces such as population, economy, technology, ideology, politics and social organizations are all drivers of environmental change.

Economic Impact Analysis - Used to estimate how changes in the flow of goods and services can affect an economy. Measure of the impact of dollars from outside a defined region/area on that region's economy. This method is often used in estimating the value of resource conservation.

Ecosystem Services - The full range of goods and services provided by natural ecological systems that cumulatively function as fundamental life-support for the planet. The life-support functions performed by ecosystem services can be divided into two groups - production functions (i.e., goods) and processing and regulation functions (i.e., services).

Environmental Equity - The perceived fairness in the distribution of environmental quality across groups of people with different characteristics.

Environmental Justice - A social movement focused on the perceived fairness in the distribution of environmental quality among people of different ethnic or socio-economic groups.

Existence Value - The value that people place on simply knowing that something exists, even if they will never see it or use it.

Fishery Dependent Data - Data on fish biology, ecology, and population dynamics that is collected in connection with commercial, recreational, or subsistence fisheries.

Focus Group - A small group of people (usually 8 to 12) that are brought together by a moderator to discuss their opinions on a list of predetermined issues. Focus groups are designed to collect very detailed information on a limited number of topics.

Hedonic Pricing Method - Estimates economic values for ecosystem or environmental services that directly affect market prices of some other good. Most commonly applied to variations in housing prices that reflect the value of local environmental attributes.

Held Values - Conceptual precepts and ideals held by an individual about something. Natural resource examples include the symbolic value of a bald eagle or the aesthetic value of enjoying a beautiful sunset (see assigned values).

Human Dimensions - A multidisciplinary/interdisciplinary area of investigation which attempts to describe, predict, understand, and affect human thought and action toward natural environments in an effort to improve natural resource and environmental stewardship. Disciplines within which human dimensions research is conducted include (but are not limited to) sociology, psychology, resource economics, geography, anthropology, and political science.

Human Dominant Values - This end of the natural resource value continuum emphasizes the use of natural resources to meet basic human needs. These are often described as utilitarian, materialistic, consumptive, or economic in nature.

Human Mutual Values - The polar opposite of human dominant values, this end of the natural resource value continuum emphasizes spiritual, aesthetic, and nonconsumptive values in nature.

IMPLAN - A micro-computer-based input output modeling system(see Input-output model below). With IMPLAN, one can estimate 528 sector I-O models for any region consisting of one or more counties. IMPLAN includes procedures for generating multipliers and estimating impacts by applying final demand changes to the model.

Indirect Impacts - The changes in sales, income, or employment within a region in backward-linked industries supplying goods and services to tourism businesses. For example, the increased sales in linen supply firms resulting from more motel sales is an indirect effect of visitor spending.

Induced Impacts - The increased sales within a region from household spending of the income earned in tourism and supporting industries. Employees in tourism and supporting industries spend the income they earn from tourism on housing, utilities, groceries, and other consumer goods and services. This generates sales, income, and employment throughout the region's economy.

Informed consent - An ethical guideline for conducting social science research. Informed consent emphasizes the importance of both accurately informing research participants as to the nature of the research and obtaining their verbal or written consent to participate.

The purpose, procedures, data collection methods and potential risks (both physical and psychological) should be clearly explained to participants without any deception.

Input-Output Model (I-O) - An input-output model is a representation of the flows of economic activity between sectors within a region. The model captures what each business or sector must purchase from every other sector in order to produce a dollar's worth of goods or services. Using such a model, flows of economic activity associated with any change in spending may be traced either forwards (spending generating income which induces further spending) or backwards (visitor purchases of meals leads restaurants to purchase additional inputs -- groceries, utilities, etc.). Multipliers may be derived from input-output models (see multipliers).

Instrumental Values - The usefulness of something as a means to some desirable human end. Natural resource examples include economic and life support values associated with natural products and ecosystem functions (see non-instrumental values).

Intergenerational Equity - The perceived fairness in the distribution of project costs and benefits across different generations, including future generations not born yet.

Intrinsic Values - Values not assigned by humans but are inherent in the object or its relationship to other objects.

Large-scale Commercial Fishing - Fishing fleets that are owned by corporations with large capital investments, and are highly mobile in their global pursuit of fish populations.

Longitudinal Studies - Social science research designed to permit observations over an extended period of time (see trend studies, cohort studies, and panel studies).

Market Price Method - Estimates economic values for ecosystem products or services that are bought and sold in commercial markets.

Measurement Error - A type of survey error that occurs when a respondent's answer to a given question is inaccurate, imprecise, or cannot be compared to other respondent's answers.

Multipliers - Capture the size of the secondary effects in a given region, generally as a ratio of the total change in economic activity in the region relative to the direct change. Multipliers may be expressed as ratios of sales, income or employment, or as ratios of total income or employment changes relative to direct sales. Multipliers express the degree of interdependency between sectors in a region's economy and therefore vary considerably across regions and sectors.

Non-instrumental Values - Something that is valued for what it is; a good of its own; an end in itself. Natural resource examples include aesthetic and spiritual values found in nature (see instrumental values).

Non-market Goods and Services - Goods and services for which no traditional market exists whereby suppliers and consumers come together and agree on a price. Many ecosystem services and environmental values fall under this category.

Nonresponse Error - A type of survey error that occurs when a significant proportion of the survey sample do not respond to the questionnaire and are different from those who do in a way that is important to the study.

Non-use Values - Also called "passive use" values, these are values that are not associated with current use (see bequest, existence, and option values).

Norms - Perceived standards of acceptable attitudes and behaviors held by a society (social norms) or by an individual (personal norms). Serve as guideposts for what is appropriate behavior in a specific situation.

Opportunity Cost - The cost incurred when an economic decision is made. This cost is equal to the benefit of the most highly valued alternative that would have been gained if a different decision had been made. For example, if a consumer has $2.00 and decides to purchase a sandwich, the economic cost may be that consumer can no longer use that money to buy fruit.

Option Value - The value associated with having the option or opportunity to benefit from some resource in the future.

Outdoor Recreation Conflict - Defined as behavior of an individual or group that is incompatible with the social, psychological or physical goals of another person or group.

Panel Studies - Longitudinal research that studies the same set of people through time in order to investigate changes in individuals over time (see Longitudinal Studies).

Population List - In social science survey research, this is the list from which the sample is drawn. This list should be as complete and accurate as possible and should closely reflect your target population.

Precision - A statistical term that refers to the reproducibility of the result or measurement. Precision is measured by uncertainty and is usually expressed as the standard error or some confidence interval around the estimated mean.

Random Utility Models - A non-market valuation technique that focuses on the choices or preferences of recreationists among alternative recreational sites. Particularly appropriate when substitutes are available to the individual so that the economist is measuring the value of the quality characteristics of one or more site alternatives (e.g., a fully restored coastal wetland and a degraded coastal wetland).

Reliability - The likelihood that a given measurement procedure or technique will yield the same result each time that measure is repeated (i.e., reproducibility of the result).

RVD (recreational visitor day) - One RVD is defined as 12 hours of use in some recreational activity. This could be one person using an area for 12 hours, or 2 people using an area for 6 hours each, or any combination of people and time adding to 12 hours of use.

Sample - In social science survey research, this is a set of respondents selected from a larger population for the purpose of a survey.

Sampling Error - A potential source of survey error that can occur when researchers survey only a subset or sample of all people in the population instead of conducting a census. To minimize this error the sample should be as representative of the population as possible.

Satisfaction - In outdoor recreation, satisfaction is defined as the difference between desired and achieved goals. Can be measured through surveys of recreation participants.

Secondary Data - Information that has already been assembled, having been collected for some other purpose. Sources include census reports, state and federal agency data, and university research.

Secondary Effects - The changes in economic activity from subsequent rounds of re-spending of tourism dollars. There are two types of secondary effects - indirect effects and induced effects.

Sector - A grouping of industries that produce similar products or services. Most economic reporting and models in the U.S. are based on the Standard Industrial Classification system (SIC code). Tourism is more an activity or type of customer than an industrial sector. While hotels (SIC 70) are a relatively pure tourism sector, restaurants, retail establishments and amusements sell to both tourists and local customers. There is therefore no simple way to identify tourism sales in the existing economic reporting systems, which is why visitor surveys are required to estimate tourist spending.

Simple Random Sampling (SRS) - In survey research, when each member of the target population has an equal chance of being selected. If a population list exists, SRS can be achieved using computer-generated random numbers.

Small-scale Commercial Fishing - Fishing operations that have relatively small capital investment and levels of production, and are more limited in terms of mobility and resource options (compared to large-scale operations). Terms that are commonly used to describe small-scale fishermen include artisanal, native, coastal, inshore, tribal, peasant, and traditional.

Social Capital - Describes the internal social and cultural coherence of society, the norms and values that govern interactions among people and the institutions in which they are embedded.

Social Impact Assessment (SIA) - Analysis conducted to assess, in advance, the social consequences that are likely to follow from specific policy actions and alternatives. Social impacts in this context refer to the consequences to human populations that alter the ways in which people live, work, play, relate to one another, organize, and generally cope as members of society.

Social Network Mapping - Community assessment research method used to collect, analyze, and graphically represent data that describe patterns of communication and relationships within a community.

Stakeholders - Individuals, groups, or sectors that have a direct interest in and/or are impacted by the use and management of natural resources in a particular area, or that have responsibility for management of those resources.

Stratification - The grouping of the units composing a population into homogeneous groups (or strata) before sampling. This procedure, which may be used in conjunction with simple random, systematic, or cluster sampling, improves the representativeness of a sample, at least in terms of the stratification variables.

Subsistence - Describes the customary and traditional uses of renewable resources (i.e., food, shelter, clothing, fuel) for direct personal/family consumption, sharing with other community members, or for barter. Subsistence communities are often held together by patterns of natural resource production, distribution, exchange, and consumption which helps maintain a complex web of social relations involving authority, respect, wealth, obligation, status, power and security.

Systematic Sampling - A type of probability sample in which every k^{th} unit in a list is selected for inclusion in the sample - for example, every 10^{th} fisherman on a list of licensed fishermen. The sampling interval, k, is computed by dividing the size of the population by the desired sample size.

Target Population - The subset of people who are the focus of a survey research project.

Travel Cost Method (TCM) - TCM is used to estimate monetary value of a geographical site in its current condition (i.e., environmental health, recreational use capacity, etc.) by site-users. Individuals or groups report travel-related expenditures made while on trips to single and multiple recreational sites. Market values are used.

Trend Studies - Longitudinal research that studies changes within some general population over time (see longitudinal studies).

Utilitarian Value - Valuing some object for its usefulness in meeting certain basic human needs (e.g., food, shelter, clothing). Also see human-dominant values.

Validity - Refers to how close to a true or accepted value a measurement lies.

Weighting - A procedure used in connection with sampling whereby units selected with unequal probabilities are assigned weights in such a manner as to make the sample representative of the population from which it was selected.

Willingness-To-Pay - The amount in goods, services, or dollars that a person is willing to give up to get a particular good or service.

APPENDIX IV: LIST OF HUMAN DIMENSIONS EXPERTS

The experts listed below have provided their contact information so practitioners may contact them with questions pertaining to the human dimensions of restoration monitoring. Contact information is up-to-date as of the printing of this volume. The list below includes only those experts who were: 1) contacted by the authors and 2) agreed to submit their contact information. Some of those listed also reviewed the associated chapter. In addition to these resources, practitioners are encouraged to seek the advice of local human dimensions experts as well as faculty members and researchers at colleges and universities. These people are often extremely knowledgeable in local habitats and their relationship to local communities. They also often have experience in implementing monitoring projects as well as designing and conducting surveys and other data collection techniques. Finally local, state, and Federal environmental agencies also house many experts who monitor and manage coastal habitats and related human dimensions. In addition to the National Oceanic and Atmospheric Administration (NOAA), the Environmental Protection Agency (EPA), the Army Corps of Engineers (ACE), Fish and Wildlife Service (FWS), and the United States Geologic Survey (USGS) are important Federal agencies to contact for assistance in designing restoration and monitoring projects as well as potential sources of funding and permits to conduct work in coastal waterways.

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CHAPTER 15: SELECTION OF REFERENCE CONDITIONS

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INTRODUCTION

The use of reference conditions is a necessary part of any restoration monitoring program. Without the use of appropriate reference conditions for comparison, individuals assigned to monitor restoration sites cannot evaluate, analyze, and/or interpret the data collected from a restored area. This is due to coastal habitats being very dynamic places, subject to a variety of factors that can dramatically influence their structural and functional characteristics. Seasonal and annual differences in rainfall patterns, water levels, the frequency of storms, the introduction of invasive species, and changes in upstream land use, to name just a few, are all factors can directly impact coastal communities and the progress of restoration projects. These factors are often outside of the control of restoration practitioners and their effects may be misinterpreted as resulting from the restoration activity unless data from reference sites under similar influences are available for comparison.

ESTABLISH PROJECT GOALS AND DETERMINE REFERENCE CONDITIONS

Selecting reference conditions should take place early in the planning stages of the restoration project, before any construction or intervention takes place. Once restoration project goals are established and appropriate reference conditions identified, construction documents can then be prepared and practitioners can begin project implementation. The method for selecting reference conditions will vary from one monitoring effort to the next depending upon project goals, level of accuracy desired, the number of potential sites available, and the level of funding allocated to monitoring. In addition, a statistician should be consulted early in the planning process to help practitioners balance statistical needs with logistical constraints and help insure that the appropriate type and amount of information is collected to accurately assess the progress of the restoration project.

DISTINGUISHING BETWEEN 'REFERENCE SITE' AND 'REFERENCE CONDITION'

Before methods to select reference sites or conditions can be discussed, a few definitions need to be established. The terms, 'reference site' and 'reference condition' have been used in many different ways, depending on the literature practitioners have been using. In the habitat assessment literature, for example, the term 'reference site' typically refers to the least impacted examples of a specific habitat[2] within a particular area. In the restoration literature, however, 'reference site' refers to any area to which a restored site is being compared, regardless of the level of impact.

- Reference conditions refer to any historical, predicted, existing condition or site against which a restored area is compared
- A reference domain encompasses all existing sites of a particular habitat type within a defined region (Brinson and Rheinhardt 1996). The full range of impact levels from 'pristine'[3] to degraded is included (see Figure 1).

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[2] Habitat, as defined in Volume One, is the sum total of all the living and non-living factors that surround and potentially influence an organism; a particular organism's environment.

[3] The term pristine is often used in restoration literature with quotes as it is recognized that truly pristine conditions rarely, if ever, exist. Virtually all sites, to some degree have been impacted by human development and can therefore not be considered pristine in the true sense of the word. It is used, however, to relate that these sites are the best-of-the-best available.

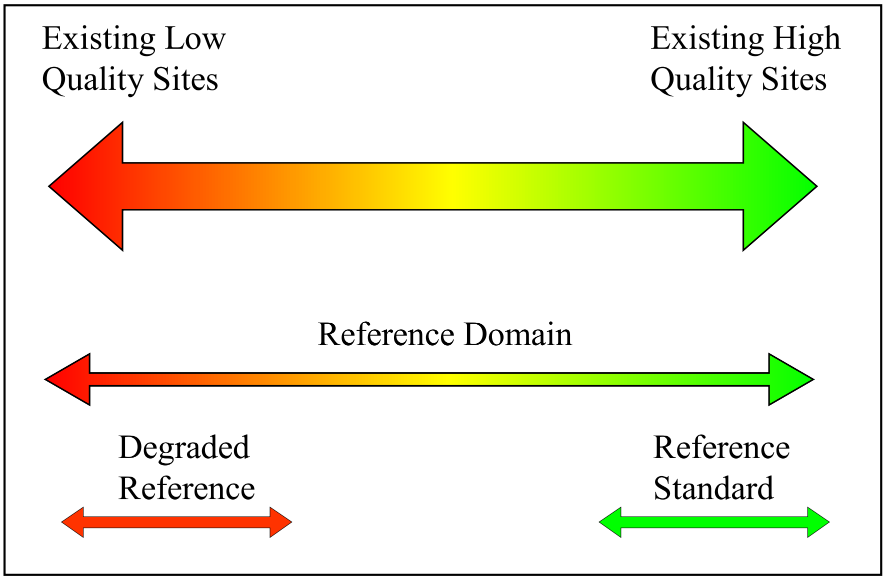

Figure 1. The relationship between different types of existing reference sites. Out of all the existing sites of high and low quality, the reference domain is a subset. The reference domain can be further subdivided into degraded reference sites or reference standards. What type of sites are used for restoration monitoring will depend upon such factors as project goals, available funds, and the availability of different types of sites to name a few. Graphic by David Merkey, NOAA GLERL.

- Reference standards represent all existing sites that are of the highest quality under current conditions. The structural and functional characteristics of reference standards may be used to set goals for restoration projects (Brinson 1993a).
- Degraded reference sites are areas that have undergone similar types and levels of human impact as areas to be restored but are left in an unrestored condition. They are similar to controls used in laboratory experiments.

Reference conditions for use in restoration monitoring projects can be derived from historical information about the site to be restored, existing sites with similar structural characteristics, and predicted conditions based on computer models. Regardless of the type, location, or number of reference sites or conditions the practitioner selects, emphasis must be placed on the similarity of structural characteristics. Structural characteristics are those that define the physical, chemical, and biological composition of a habitat. Without the similarity of primary structural characteristics such as geomorphology, sediment grain size, hydroperiod, and salinity between restored and reference areas, comparison of functional characteristics such as presence and abundance of specific groups of organisms or nutrient cycling dynamics is inappropriate. A complete listing of the primary structural and functional characteristics of marine and freshwater coastal habitats of the United States is provided in Appendix II of *Science-Based Restoration Monitoring of Coastal Habitats, Volume One: A Framework for Monitoring Plans Under the Estuaries and Clean Waters Act of 2000 (Public Law 160-457)*. The importance of these characteristics to restoration monitoring is described for each habitat in *Volume Two: Tools for Monitoring Coastal Habitats*. These lists and descriptions can aid practitioners in determining which site characteristics to use when selecting reference conditions for a restoration project.

This chapter does not present a step-by-step method for selecting reference conditions for a particular restoration project. There is no universal formula to do that. Instead, the strengths, weaknesses, and effectiveness of different approaches to selecting reference conditions and examples of how each has been used in research and restoration efforts are described. Practitioners should be able to build upon this information and, with the help of a statistician and knowledge of the similar coastal habitats as those being restored, select the appropriate type and number of reference conditions for their particular project.

HISTORICAL REFERENCE CONDITIONS

Historical conditions depicted in aerial photos, previous studies, historical accounts such as land surveys, nautical charts, newspaper accounts, or diaries can be useful in making the case for restoration projects (Figure 2). These resources may, however, not be of sufficient detail to set specific restoration targets or success criteria. For example, an aerial photo may show that a marsh once existed in a particular spot but offer little or no information about its hydrodynamic characteristics, substrate elevations, and/or soil chemistry. Without knowing this level of detail about a site, one cannot determine what plant species are appropriate to plant, what density or species of animals should be able to use the marsh, or what water chemistry processes may have occurred. Even in cases where detailed historical data are available, the site may be so altered or degraded that it cannot be restored to some previous condition. The use of historical conditions as reference conditions under these circumstances would not be effective. Therefore, the use of existing reference sites to help set project goals and compare the development of the restoration over time is almost essential.

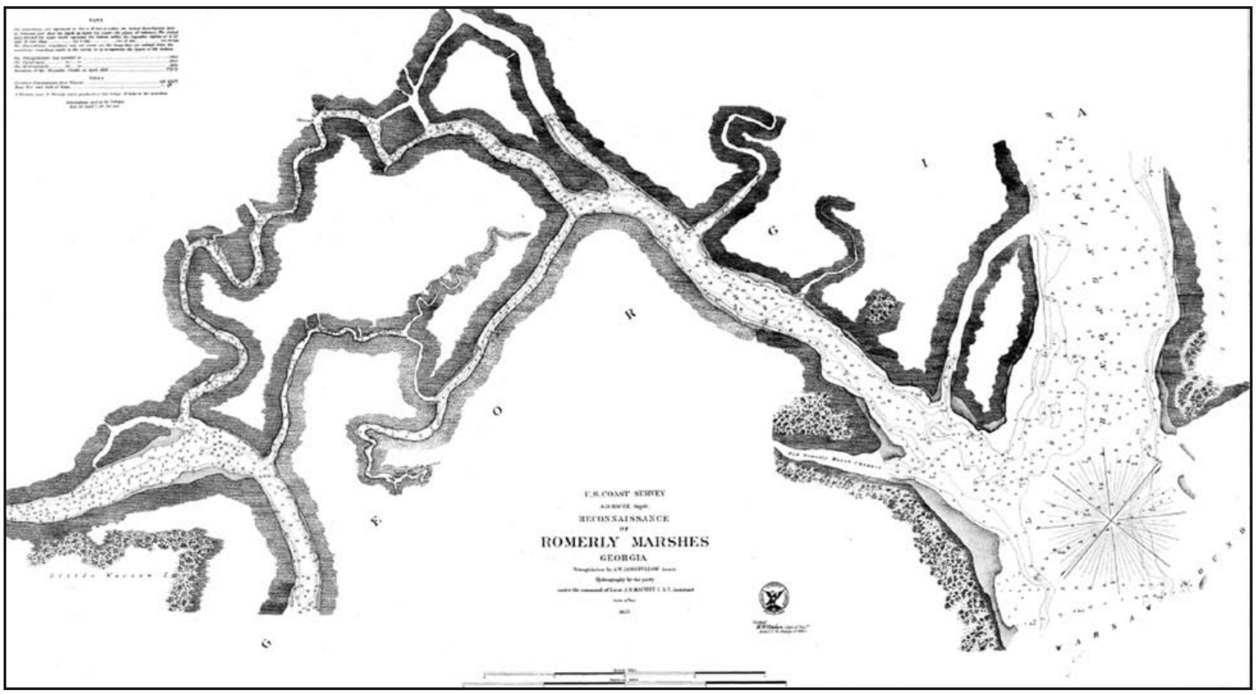

Figure 2. A historical chart of Romerly Marshes in Georgia, circa 1855. Historical documents such as this allow practitioners to begin planning restoration projects by identifying areas were marshes previously occurred. Chart from the NOAA Historical Map and Chart Project Library.

EXISTING REFERENCE SITES

Although historical reference conditions are often used to justify restoration projects, only data collected at the restoration site before and after the project is implemented can be used to demonstrate the effects of a restoration project. Differences in gear required to sample habitats and differences in sampling effort before and after implementation of the restoration project may, however, occasionally make comparison of pre- and post-implementation data difficult (Able et al. 2000). Data should therefore be collected simultaneously from the restored site and one or more reference sites (standard or degraded) whenever possible. Only through the comparison of the restoration site to other existing sites can practitioners document which changes are caused by restoration activities and which are perhaps attributable to natural variability; variability that may be due to broader regional influences or other confounding variables[4]. Confounding variables may include natural, seasonal and annual differences in climate and hydroperiod, changes in water sources, and variability in organism populations, phenomena that are larger than site-scale and often beyond the control of a restoration practitioner. Large scale phenomena such as regional weather patterns and changes in river discharge, for example, have been shown to have tremendous effects on the presence, absence, and community composition of submerged aquatic vegetation (SAV) communities (Carter et al. 1994). Without the use of existing reference sites to compare to the restored site, changes in habitat characteristics caused by these larger-than-site-scale factors could be misinterpreted as resulting from restoration activities.

REFERENCE DOMAIN

The most important factors in selecting reference conditions for a restoration monitoring effort are to ensure that the sites in question are of similar ecological setting and have similar site-level structural characteristics. Depending on the particular goals of the restoration project, ecological settings can be derived through the use of ecoregions or watersheds. Ecoregions are defined as areas within which biotic, abiotic, terrestrial, and aquatic capacities and potentials are similar (Brinson 1993b; McMahon et al. 2001). Among others, Bailey (1983), Omernik (1995), and the Commission for Environmental Cooperation (1997) have presented ecosystem classifications for the United States that can be used for managing natural resources. The North America ecoregions delineated by the Commission for Ecological Cooperation (1997) are shown in Figure 3.

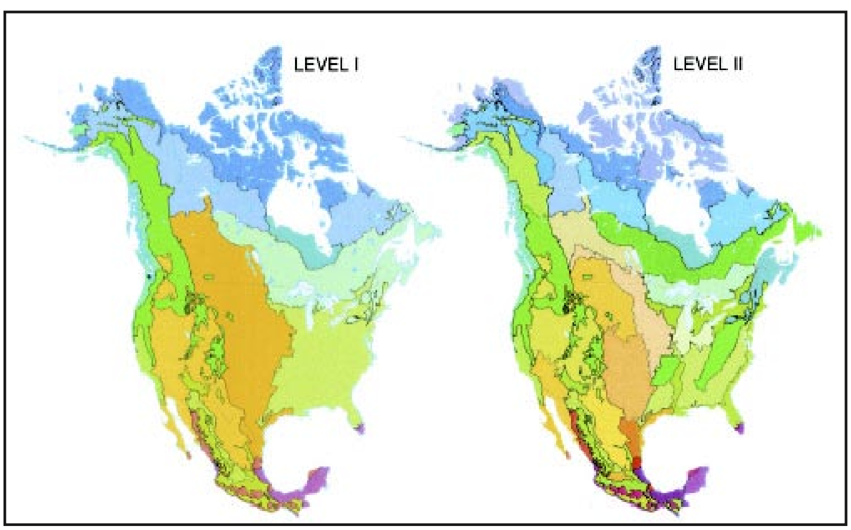

Figure 3. Level I and Level II ecoregions for North America. Taken from Commission for Environmental Cooperation 1997.

[4] Confounding variables are natural phenomena beyond the control of the restoration practitioner that can affect the outcome of the project but are often unseen or unobserved.

One limitation of these regional classifications is that the scale can be quite large for restoration monitoring purposes. Other authors have noted that smaller, state-level ecosystem classifications (e.g., Albert 1995) can be useful in differentiating plant communities in coastal habitats (Minc 1998; Minc and Albert 1998). Albert's (1995) ecosystem classification of Minnesota, Wisconsin, and Michigan is a hierarchical system similar to the ones described by Bailey (1983), Omernik (1995), and McMahon et al. (2001). This similarity occurs at the largest scale (based on climate and geology) but then delineates smaller units based on physiography, soils, and vegetation patterns (Figure 4). Many other states also have finer-scale ecoregion classification systems that practitioners can use to narrow down the search for appropriate reference conditions. Selecting sites within the same watershed or a nearby watershed with similar characteristics such as slope, soil texture, and land cover is another method of ensuring that large-scale external forces influencing reference and restored sites are similar. Once the ecological setting of restored and reference sites has been established, comparison of structural characteristics can be used to further reduce the number of potential reference sites.

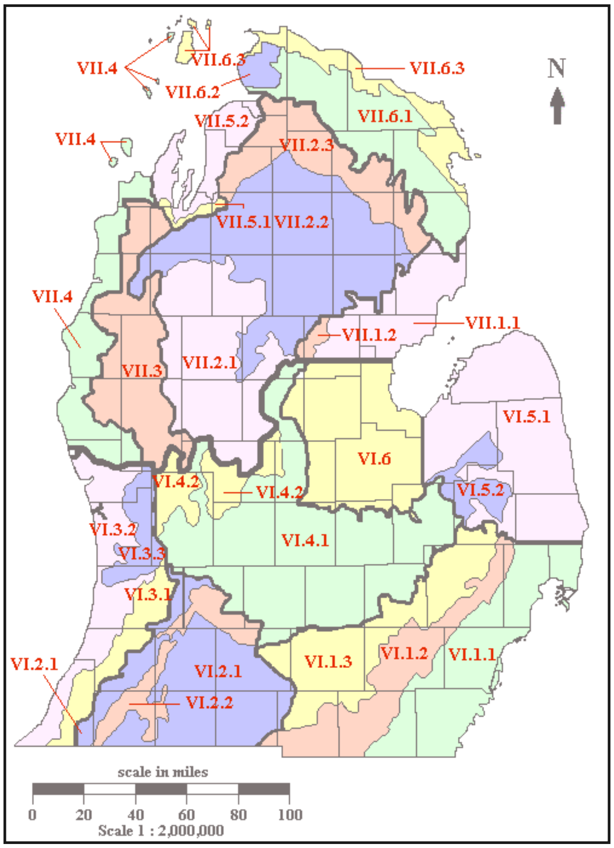

Figure 4. Albert (1995) has devised a classification of regional ecosystems for Michigan (Lower peninsula shown), Wisconsin, and Minnesota. Differences in dominant vegetation of coastal habitats are present between the smallest ecoregions. These smaller scale ecoregions are also used by state resource management agencies for maintaining habitat diversity within the state of Michigan. Taken from Albert 1995.

Adjacent Sites

The similarity of two sites decreases with increasing distance between them (Tobler 1970). Thus many restoration projects have used adjacent areas for comparison to restored sites (Havens et al. 1995; Dawe et al. 2000; Stolt et al. 2000; Tupper and Able 2000; Tanner et al. 2002). Sites that are close to one another also have the advantage of convenience when it comes to fieldwork and data collection. For example, if migratory bird usage is a monitored parameter, there may only be a short period of time when the birds will be present in the restored and reference marshes. Having the marshes in close proximity facilitates completion of sampling within this short time period. If adjacent areas are used as reference sites they should be totally independent of the restored area so that restoration-related activities do not affect their characteristics as well.

Simply using adjacent sites for reference, however, is often not enough. While it is true that adjacent sites should have large-scale influences in common, site-scale structural parameters such as topographic diversity, sediment grain size, salinity levels, water temperature, and wind and wave energy may not be similar. Sites with different structural characteristics are less likely to have similar functional capabilities and should therefore not be used for comparison in restoration monitoring (Brinson 1993a). For example, Havens et al. (1995) compared a created marsh with two other adjacent natural marshes. By using adjacent marshes as references, structural variables such as climate, tidal regime, and access by marine animals were assumed to be similar across all three marshes. While dissolved oxygen concentration and temperature were similar between the three marshes, structural differences in freshwater inputs, substrate topography, surrounding habitats, salinity, soil organic carbon, and vegetation density led to significant differences in marsh functions as measured by zooplankton abundance, and fish, crab, and bird utilization. Thus even though the marshes were in close proximity, differences in structural characteristics lead to differences in functions between the restored and reference marshes.

Multiple Sites

This is not to say that restored and reference sites need to be identical in all biological, geological, and physical aspects. In fact, finding even one or two reference sites with the exact same characteristics as a site being restored is not possible (Hurlbert 1984). The use of a reference domain can help address this problem by describing the range of conditions and natural variability typical of the habitat being restored. The use of multiple sites in the reference domain or reference standard (see below) also allows a 'bound of expectation' to be developed (Weinstein et al. 2000; Weinstein et al. 2001). For example, the goal of a particular restoration effort may be to reintroduce SAV with growth rates comparable to other non-impacted sites in the area (i.e., reference standard sites). Turbidity affects the ability of SAV to grow by altering the amount of light available to plants. An assessment of other SAV beds in the general area may find several that have many structural characteristics in common with the restored area but with higher or lower turbidity levels and corresponding lower or higher levels of SAV growth. This range of conditions could then be used to set up a range of expectations for the restored area. As long as turbidity levels and SAV growth rates are within the range exhibited by the reference standards, the restoration effort could be considered successful. If not, then corrective action can be identified and implemented in an attempt to increase growth rates to the level characteristic of sites in the reference standard.

The selection of a reference domain does not have to be a time consuming and expensive process. Many automated techniques are now available using powerful statistical procedures (Morgan and Short 2002) and geographic information systems (GIS) (Russell et al. 1997; Palik et al. 2000; Wiley et al. 2000) to make selection of potential reference sites more efficient. For example, statistical techniques such as principle components analysis (PCA) or cluster analysis can be used to identify groups of sites. This helps maximize the structural similarity among sites for comparison. Morgan and Short (2002) compared several constructed salt marshes to a large pool of potential reference sites. They used PCA techniques to identify areas that had structural characteristics most similar to the constructed sites and then selected their reference conditions from this smaller number of areas. By using this technique, they were able to minimize the amount of variability among restored and reference sites by comparing only those sites that had the greatest amount of structural similarities. Information about a particular site to be restored can also be entered into a GIS that can then be queried to identify areas with similar attributes to identify reference sites (Russell et al. 1997; Palik et al. 2000; Wiley et al. 2000). The use of these or similar techniques, however, requires access to a sufficiently large, existing database of information on coastal habitats. Research institutions and universities along with federal, state, Tribal, and local units of government assigned to manage coastal resources may be good sources of this information.

REFERENCE STANDARDS

Once a reference domain has been established, reference standards can be selected from it. Reference standards represent the highest quality sites within a reference domain. Once reference standards are identified, their structural and functional characteristics can be used to set a range of acceptable goals for a restoration project. Establishing which specific sites are of the highest quality, however, requires that all of the sites in the reference domain be assessed. Although highly valuable, this can be a costly and time-consuming process and most restoration-monitoring programs are too financially constrained to sample multiple areas. To address this issue, resource managers and scientists have recently started to organize coast-wide data sharing around standardized monitoring protocols (Neckles et al. 2002; Steyer et al. 2003). Sharing information across a variety of sites in an area allows practitioners to incorporate a range of conditions in restoration project planning and goal setting. Thus restoration practitioners can utilize existing information to select an acceptable range of site characteristics without the expense of additional sampling and have access to a suite of reference sites that encompass a range of ecological conditions. Data sharing arrangements of this type have only recently been introduced. Until they are fully functional, restoration practitioners may rely on previous monitoring and assessment efforts conducted by private consultants, universities, non-governmental agencies such as watershed councils, and/or local, state, federal, Tribal, and regional resource management agencies. Each of these parties should have considerable experience in coastal habitats in their region and should be able to help select high quality sites for use as reference standards.

The standardized protocols and data sharing efforts now being planned on coastal and regional scales may also provide restoration practitioners with a readily available list of parameters and monitoring techniques that may be adapted to their own purposes. This data sharing process ensures the comparability of data from one restoration monitoring effort to the next. The National Oceanic and Atmospheric Administration (NOAA) has developed a database of coastal monitoring programs for the entire United States and its protectorates. This searchable web-based database is designed to help restoration practitioners identify and locate other monitoring efforts in their area to facilitate cooperation and collaboration between monitoring efforts. Links to the database can be found at NOAA's restoration monitoring website: http://coastalscience.noaa.gov/ecosystems/estuaries/restoration_monitoring.html or http://restoration.noaa.gov.

NOAA's Restoration Center has also prepared a database of restoration projects for the United States and its protectorates. This online, searchable database can be used to help those interested in planning a restoration project contact others in the area and share information. Individual projects or a description of all restoration efforts in the database can be downloaded from: http://neri.noaa.gov. The U.S. Environmental Protection Agency also maintains a restoration project database (http://yosemite.epa.gov/water/restorat.nsf/rpd-2a.htm). This database, however, is not exclusively devoted to coastal habitat restoration projects. Restoration efforts for inland waterways and terrestrial habitats are also listed there.

DEGRADED REFERENCE SITES

Degraded reference sites may also be used as reference conditions when standards are not available. Degraded sites can be used to describe progress away from the degraded condition and determine which restoration techniques[5] have

[5] Restoration is a relatively young science and many methods and techniques are still experimental. There are also unique aspects to every proposed restoration effort requiring innovative solutions. Experimenting with different techniques and disseminating results is strongly encouraged to further the science and increase the efficiency of future restoration projects

the greatest effect. Ideally, reference sites should be separate and independent of the restored area, however, areas within or near the habitat being restored may be acceptable for use as degraded reference sites when areas to be restored are unique or other acceptable reference sites cannot be identified. This approach was used in the restoration of riverine forests and deepwater swamps along the Pen Branch of the Savannah River (Kolka et al. 2000; Nelson et al. 2000). Vegetation communities along the Savannah River were impacted by hot water discharges from an upstream power plant. No non-impacted riverine forests or deepwater swamps were available in the area for comparison so researchers subdivided the river into a series of cross sections where different planting treatments could be tried and compared to areas left untreated. A variety of structural and functional characteristics were then monitored at the treated and non-treated areas to assess the effects of various restoration techniques (Barton et al. 2000; Bowers et al. 2000; Buffington et al. 2000; Fletcher et al. 2000; Kolka et al. 2000; Lakly and McArthur 2000; Nelson et al. 2000; Paller et al. 2000; Wike et al. 2000).

One draw back of using only degraded sites as the reference condition, is that practitioners may be unable to set appropriate restoration goals. For example, for the Pen Branch project described above, only other impacted areas were used for comparison with the restoration effort. Monitoring results show that some vegetation change occurred in the restored area. Without the benefit of historical data, however, researchers could not determine if the restored area was truly a representative of high quality riverine forest along the Savannah River. Without the use of reference standards to set goals for restoration projects, changes observed in ‘restored’ areas may be just ‘changes’ and not true restoration of the characteristic structures and functions of the habitat.

PREDICTING REFERENCE CONDITIONS

If data from a variety of monitored locations are available, the data can also be used in computer models to predict reference standard conditions given various restoration scenarios. This approach has been successfully demonstrated using hydrologic and fish community data from rivers in southeastern Michigan (Wiley and Seelbach 1997) and could be adapted to coastal areas as well. For a single restoration project this would be an expensive endeavor. On the other hand, it could be useful in areas that have undergone extensive research and assessment such as the Chesapeake Bay, the gulf coast of Louisiana, or the San Francisco and San Pablo Bays.

As young as the science of restoration is, the science of modeling ecosystems is even younger. Although the science is advancing rapidly, current models cannot account for all of the factors that influence habitat development (Oreskes et al. 1994). Natural, random events such as hurricanes, floods, and large fires as well as man-made impacts such as industrial accidents, nutrient enrichment, or introduction of invasive species can have tremendous, and sometimes even devastating, impacts on coastal habitats. These cannot as yet be included reliably in ecosystem modeling. In areas where high quality sites are not available for use as reference standards, however, computer modeling may be the only method available to set realistic restoration project goals.

SOME STATISTICAL ISSUES

As stated previously, the use of a small number of independent, adjacent reference sites minimizes many of the logistical issues associated with monitoring. Shortcomings with this approach, however, do exist. Restoration projects are essentially experiments and for the results of experiments to be statistically valid, they need to be replicated. It has been argued that it is not possible to calculate statistically significant differences between restored and reference sites when only one or two reference sites are used (Hurlbert 1984). Through a variety of statistical techniques, however, is issue may be overcome (Eberhardt 1976; Skalski and McKenzie 1982; Stewart-Oaten et al. 1986; Carpenter 1989; Carpenter et al. 1989; Stewart-Oaten et al. 1992). Through repeated and simultaneous sampling at the restored site and at one or more reference sites, before and after the implementation of the restoration project, effects can be statistically detected (Schroeter et al. 1993). The Before After Control Impact (BACI)[6] study design and the statistical analyses associated with it can be used to statistically assess the effect of impacts and restoration projects on coastal habitats (Schroeter et al. 1993). This further highlights the need for a statistician to be consulted early on in project planning so appropriate statistical practices and models can be incorporated into the sample design.

Statistics alone, however, should never be the used as the sole means for understanding ecological processes and phenomena or for making decisions about restoration progress, particularly where biology is involved. Plants and animals can be remarkably adaptive and resilient to a variety of circumstances. Therefore, a strong understanding of ecology and the use of multiple species and measurements should be a part of any interpretation of statistics derived from restoration monitoring projects before conclusions are drawn (Schroeter et al. 1993).

When monitoring restored and reference sites, it is particularly important to consider temporal variability and monitor sites for several years. Seasonal and annual patterns in climate and water level can change structural and functional characteristics at the site level that may be misinterpreted as restoration-related if monitoring is done without the use of reference sites or only for a short period of time (Simenstad and Thom 1996; Simenstad and Cordell 2000). For example, a monitoring project that only sampled water quality for one year after project construction might conclude that changes in suspended sediment and nutrient concentrations were a result of restoration activities. Yet these changes may be the result of regional hydrologic patterns relatively unaffected by any particular restoration activity. Only through monitoring for multiple years after restoration, within an appropriately selected reference domain, can practitioners distinguish the effects of the restoration activity from the background effect of large-scale, non-restoration related, variables. This is particularly true in highly dynamic environments such as those along the coast of the Great Lakes where annual differences in lake levels can completely alter the dominant vegetation communities (Keddy and Reznicek 1982; Keddy and Reznicek 1986; Wilcox and Whillans 1989; Reznicek 1994; Wilcox et al. 2002). Additional information on the timing and duration of monitoring can be found in *Science-Based Restoration Monitoring of Coastal Habitats: Volume One*.

[6] More thoroughly discussed in several of the citations listed above.

CONCLUSIONS

The specific type and number of reference conditions will vary from one restoration project to another depending upon project goals and constraints, such as available funding. Whether they are in the form of historical records, existing sites, or computer simulations, reference conditions are the guidepost against which the progress of a restoration project is measured. The general scientific consensus is that reference conditions should be developed using multiple existing, independent sites of similar structure to the area to be restored. Use of reference sites and sharing of information with other researchers and restoration practitioners makes sense from the long-term economic view of restoration as well as it increases the efficiency of current and future restoration and monitoring projects (Wilcox, USGS, pers. comm.). That said, constraints dictate that not every restoration project will be able to monitor multiple reference sites as part of their restoration monitoring project. Restoration practitioners should allow an adequate budget for monitoring reference sites or conditions and are encouraged to seek out and create collaborative efforts to share data and information with other affiliated agencies. These efforts will increase the efficiency of restoration and restoration monitoring as well as the over-all amount of information on the structural, functional, ecological, and economic importance of our coastal habitats.

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CHAPTER 16: COST ESTIMATES FOR MONITORING

Perry Gayaldo, NOAA Restoration Center[1]

INTRODUCTION

These cost estimates are presented to aid in the development of monitoring plans. Where applicable, three grades of personnel (labor categories) are identified (e.g., junior, mid-level, senior). In the cases where three grades are not specified, the grades either indicate junior/non-junior or an ungraded category with a single rate. Cost estimates are for 2003-04, and include salary and benefits for the labor categories. It is expected that these examples will vary by region and demand.

Example costs were identified from a variety of sources, including fee schedules from private firms, public documentation, and academic communities. Citable references include:

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[1]1305 East West Highway, Silver Spring, MD 20910.

Supplies/Services	Price	Per Unit
Equipment		
Submersible Data Sonde	$900 – $1250	Month
GPS (handheld)	$100 - $150	Day
GPS (station)	$6000	Month
Doppler Recording Current Meter	$75	Day
Propellor Reading Current Meter	$420	Day
REMOTS Sediment Profiling Camera	$570	Day
Modular Azimuth Position System	$2000 - $2500	Month
Fish Trawler with gear (300 ft.)	$1380 - $4000	Day
Boat Trailer	$50 - $110	Day
Pickup Truck/Van	$50 - $70	Day
Sub-Bottom Profiler / Side-Scan Sonar	$540 - $700	Day
GIS Digitizing System	$210	Day
Large Research Vessel (70-100 ft.)	$2400 - $2800	Day
Sampling Barge w/ Heavy Duty Winch	$300 - $650	Day
Gill Nets (50m)	$50	Day
Clam Dredge	$30	Day
Oyster Dredge	$20	Day
Benthic Box Core Sampler	$35	Day
Benthic Van Veen Sampler	$10	Day
Benthic Smith-McIntyre Sampler	$80	Day
Biological Sieves (0.5 – 2.0 mm)	$10	Day
Electrofishing (backpack)	$60-$100	Day
Electrofishing (boat)	$250-$300	Day
Underwater Video Camera (with cable and light)	$75	Day
Digital Video Camera	$200	Day
Field Laptop Computer	$50-$75	Day
Portable Turbidimeter	$10-$20	Day
Portable Spectrophotometer (and water quality reagents)	$15-$30	Day
Salinometer / Refractometer	$15	Day
D.O. Meter	$25	Day
SUV (for equipment and personnel)	$60	Day
Canoe (minimum 12 ft.)	$35	Day
Electric Outboard Engine (for canoe or inflatable)	$15	Day
4-man Inflatable Boat (with gas-powered outboard motor)	$65	Day
8-man Inflatable Boat (with gas-powered outboard motor and trailer)	$115	Day
Otter Trawl Net (net, bridle, and doors; 24 ft. minimum)	$35 - $50	Day
Plankton Net (1 m mouth diameter)	$35 - $50	Day
Microwave Positioning System	$250 - $300	Day
Computerized Navigation System	$210	Day
Digital Fathometer System (with CTD profiler)	$420 - $500	Day
Ocean Research Vessel (98 ft.)	$3700 - $4500 + fuel	24 Hours
Ocean Research Vessel (55 ft.)	$1300 - $2000	10 Hours
Research Vessel/Work Boat (24 ft.)	$700 - $1000	10 Hours
Research Vessel/Work Boat (16 ft.)	$200 - $500	8 Hours
Crane, Work Boat and 2 crew	$250	Hour
Side-scan Sonar (dual frequency)	$375 - $450	Day
Side-scan Sonar / Magnetometer / Sub-bottom Profiler	$1350 - $1500 + $840 mobil.	Day

Supplies/Services	Price	Per Unit
Services		
Image Analysis System	$160 $200	Hour
Offshore Benthic Box Core Sample Analysis (0.25 m^3, 0.5 mm sieve)	$1600	Each
Inshore Benthic Box Core Sample Analysis (0.25 m^3, 0.5 mm sieve)	$830	Each
Benthic Van Veen Grab Sample Analysis (0.04 m^3, 0.5 mm sieve)	$380	Each
Benthic Smith-McIntyre Grab Sample Analysis (0.1 m^3, 0.5 mm sieve)	$690	Each
Gill Net Fish Catch Analysis (50 m, variable mesh size)	$200 - $300	6-hour deploy
Otter Trawl Fish Catch Analysis	$620-$800	30-minutes
Travel Per Diem	$100 - $200	Day
Labor Category	(junior/mid/senior)	
Marine Ecologist	$46 / $71 /$121	Hour
Aquatic Ecologist	$46 / $71 /$121	Hour
Marine Benthic Ecologist	$50 / $60 / $121	Hour
Wetland Ecologist	$45 / $85 / $105	Hour
Coastal Dune Ecologist	$45 / $85 / $105	Hour
Ornithologist	$50	Hour
Invertebrate Zoologist	$45 / $60 / $105	Hour
Toxicologist	$40 / $75 / $125	Hour
Sedimentologist	$65 / $70 / $95	Hour
Physical Oceanographer	$60 / $70 / $100	Hour
Chemical Oceanographer	$60 / $75 / $100	Hour
Biochemist	$60 / $75 / $100	Hour
Botanist	$55 / $60 / $100	Hour
Limnologist	$50 / $60 / $75	Hour
Ichthyologist	$50 / $60 / $75	Hour
Mammalogist	$45 / $65 / $75	Hour
Wildlife Biologist	$40 / $45 / $50	Hour
Fishery Biologist	$50 / $60 / $75	Hour
Chemist	$55 / $75	Hour
Landscape Architect	$60 / $70 / $85	Hour
Geographer	$55 / $65 / $90	Hour
Land Use Planner	$60 / $100	Hour
Human Dimensions Consultant	$50 / $125	Hour
Planktonist	$55 / $60 / $100	Hour
Hydrologist	$55/ $65 / $90	Hour
Diving (S.C.U.B.A.) Biologist	$35 / $45	Hour
Boat Operator	$50	Hour
Chemical Technician	$45 / $65 / $85	Hour
Biological Technician	$32 / $42	Hour
GIS Specialist	$40 / $60 / $80	Hour
Statistician	$35 / $55 / $70	Hour

CHAPTER 17: REVIEW OF RESTORATION MONITORING PROGRAMS IN THE UNITED STATES

http://www.restoration.noaa.gov/

Amy Nickens, NOAA National Centers for Coastal Ocean Science[1]

INTRODUCTION

A database that indexes coastal monitoring programs in the United States (including the Great Lakes) and its territories has been created to support *Tools for Monitoring Coastal Habitats*, Volume Two of *Science-Based Restoration Monitoring of Coastal Habitats,* and will be available to the public in early 2005. Information on monitoring programs included in this index can be found by querying the database located on the NOAA Restoration Portal (website address provided above). Presented here is the description and purposes of the database, the selection criteria for monitoring programs included in the database, a comparison of what the database is and is not, and other tips on using the database.

DATABASE DESCRIPTION

The database is a review of current and significant coastal habitat monitoring programs in the United States (including the Great Lakes) and its territories. Information provided on each monitoring program in the database includes the name of monitoring program, coordinating entity, region in which monitoring takes place, status and duration of each program, habitat types monitored, contact person, program goals, key parameters measured, and other descriptive notes pertinent to each monitoring program. The database is searchable, allowing users to locate monitoring programs by region, habitat type, or parameter. The database is not meant to be comprehensive, but serves as a list of significant examples of restoration and ecological monitoring programs in the coastal United States. Information presented on each monitoring program is intended to give the general scope of the program. Contact information and URLs for each monitoring program are provided to allow the user to gather more detailed information as needed.

What the Database Is and Is Not

The following comparison of what the database is and is not provides additional insight into the description and goal of the database.

The database ***is****:*

- A reference for those interested in coordinating a monitoring program
- A work in progress to which updates and additions will be made regularly
- A list of significant monitoring programs in the United States (i.e., those programs that are well known among the scientific and non-scientific restoration and monitoring community in the US), and
- A starting point for users that provides appropriate contact information, websites, and references if further detail is needed

The database is ***not****:*

- A comprehensive list or a national repository of all monitoring programs in the US
- A list of only government organized monitoring programs
- A list of only National Oceanic and Atmospheric Administration organized monitoring programs, nor
- A site that holds the data collected by each monitoring program

PURPOSE

The database of monitoring programs allows coastal habitat restoration practitioners to locate regional monitoring programs that may serve as models for the establishment or improvement of

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their own efforts. Restoration practitioners may also find useful historical data on the condition of US coastal areas from the monitoring programs included in the database.

Possible Outcomes of Database

The database of coastal monitoring programs will provide several positive outcomes. Examples of monitoring activities provided by this database may allow coastal habitat restoration practitioners to locate and mimic successful regional monitoring programs, thus improving their own efforts. Lines of communication may be opened among restoration practitioners, generating collaboration and further improving monitoring efforts. This database may allow for more efficient access to resources such as methodologies and protocols, historical data, and monitoring plan design examples. This database may further highlight the importance of monitoring by organizing many monitoring programs nationwide into a centralized and searchable index.

MONITORING PROGRAM SELECTION CRITERIA

The following is a list of criteria used for selection of monitoring programs included in the database. A monitoring program must meet a majority of these criteria and must support the purpose of the database to be included.

- *Current* - Monitoring programs selected for inclusion in the database are currently ongoing or recently concluded (within 10 years). This insures that database users find a representative of the most modern data collection techniques, that the present conditions or health of an area are reflected, and that the program is continuously updated.
- *Easily accessible and well documented procedures and data* - Monitoring programs included in the database provide easily accessible and well-documented information such as site description, protocols, and data. In most cases, this refers to those monitoring programs that are described and documented via the Internet. Program information posted on the Internet may be easily updated by program personnel and quickly accessed by database users. Well documented procedures provide clear examples for restoration practitioners to follow or compare with there own efforts.
- *Extensive or long term* - Programs included in the database should be those that are well established and have been in operation for a significant period of time. These programs are most useful because they provide a wealth of historical information and are comprehensive examples for practitioners to follow when creating a monitoring program.
- *Governmental and non-governmental programs* - Programs included in the database are those coordinated by federal, state or local governments, non-governmental organizations, volunteer groups, educational groups or any combination of these.
- *Restoration and ecological monitoring* - Programs included in the database may fall under either or both of the following two categories. Programs included in the database may be specifically designed to monitor an area before, during, or after a restoration project or series of projects. Programs included in the database may also track the general health or ecological performance of a coastal environment. Data collected in a coastal area over a period of time, whether related directly to a restoration project or not, provide a wealth of information and may act as an example for others interested in creating a monitoring program. In addition, inventories of regional monitoring programs are included in the database.
- *US coastal areas* - Programs included in the database must monitor the condition of United States coastal habitat, including the Great Lakes and the US territories (Puerto Rico, Guam, US Virgin Islands, American Samoa, and the Northern Mariana Islands). Exceptions to this include water bodies (and their coastal habitats) that overlap with other countries. For example, some Canadian Great Lakes monitoring programs may be included in the database because activities in these waters and coasts may affect both Canada and the US
- *Parameters that measure coastal conditions* - Programs included in the database must monitor the condition of US coasts by measuring or tracking the following broad parameters (though programs are not limited to using only these parameters): water quality, contaminants, bacteria, plankton, vegetation, benthos, nekton, other animals (mammals, birds, reptiles, amphibians),

hydrology, sediments, geomorphology, air quality, or human uses or impacts.

Description of Database Website

The database is searchable via the NOAA Restoration Portal (www.restoration.noaa.gov). The database website includes several useful items to orient users to the database, such as the description of the database, the selection criteria for monitoring programs included in the database, and a link to the text of *Volumes One* and *Two* of *Science-Based Restoration Monitoring of Coastal Habitats*. This information is presented to orient the user to the database.

Users may navigate to a search page to query the database. The search page includes a description of the various methods of searching the database's monitoring programs. In addition, search hints give pointers on how to best use each method of searching. After a search is performed the search results are displayed. The results include a list of monitoring programs that fit the search criteria, links to each monitoring programs' primary URL, and the scope of each monitoring program.

CHAPTER 18: REVIEW OF ACTS RELEVANT TO RESTORATION MONITORING

Russel Bellmer, Fish and Wildlife Service[1]

INTRODUCTION

The following summaries of the major Acts mentioned in this Volume, with the exception of the Rivers and Harbors Act of 1899, Magnuson-Stevens Fishery Conservation and Management Act, and the Estuary Restoration Act were obtained from Buck (1995). These Federal Acts may be used to help justify the restoration and monitoring of particular coastal habitats.

ANADROMOUS FISH CONSERVATION ACT

The Anadromous Fish Conservation Act (16 *U.S.C.* 757a-757g, Pub. L. 89-304, as amended) authorizes the Secretary of Commerce, along with the Secretary of Interior, or both, to enter into cooperative agreements to protect anadromous and Great Lakes fishery resources. To conserve, develop, and enhance anadromous fisheries, the fisheries which the United States has agreed to conserve through international agreements, and the fisheries of the Great Lakes and Lake Champlain, the Secretary may enter into agreements with States and other non-Federal interests. An agreement must specify: (1) the actions to be taken, (2) the benefits expected, (3) the estimated costs, (4) the cost distribution between the involved parties, (5) the term of the agreement, (6) the terms and conditions for disposal of property acquired by the Secretary, and (7) any other pertinent terms and conditions.

Pursuant to the agreements authorized under the Act, the Secretary may: (1) conduct investigations, engineering and biological surveys, and research, (2) carry out stream clearance activities, (3) undertake actions to facilitate the fishery resources and their free migration, (4) use fish hatcheries to accomplish the purposes of this Act, (5) study and make recommendations regarding the development and management of streams and other bodies of water consistent with the intent of the Act, (6) acquire lands or interests therein, (7) accept donations to be used for acquiring or managing lands or interests therein, and (8) administer such lands or interest therein in a manner consistent with the intent of this Act. Following the collection of these data, the Secretary makes recommendations pertaining to the elimination or reduction of polluting substances detrimental to fish and wildlife in interstate or navigable waterways. Joint NOAA Fisheries-FWS hold regulations applicable to this program are published in 50 *C.F.R.* Part 401.

CLEAN WATER ACT

The Clean Water Act (CWA, 33 *U.S.C.* 1251-1387, Act of June 30, 1948, as amended) is a very broad statute with the goal of maintaining and restoring waters of the United States. The CWA authorizes water quality and pollution research and monitoring, provides grants for sewage treatment facilities, sets pollution discharge and water quality standards, addresses oil and hazardous substances liability, and establishes permit programs for water quality, point source pollutant discharges, ocean pollution discharges, and dredging or filling of wetlands. The intent of the CWA Section 404 program and its 404(b)(1) "Guidelines" is to prevent destruction of aquatic ecosystems including wetlands, unless the action will not individually or cumulatively adversely affect the ecosystem. NOAA Fisheries provides direct consultations to the Environmental Protection Agency and the U.S. Army Corps of Engineers as to the impacts to living marine resources of proposed activities and to methods for avoiding such impacts.

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ENDANGERED SPECIES ACT

The Endangered Species Act (ESA, 16 *U.S.C.* 1531-1543, Pub. L. 93-205, as amended) was enacted in 1973 to provide for the conservation of species that are in danger of extinction throughout all or a significant portion of their range. "Species" is defined by the Act to mean either a species, a subspecies, or, for vertebrates (i.e., fish, reptiles, mammals) only, a distinct population.

Anyone may petition to have a species considered for listing as endangered or threatened, the action which qualifies it for increased protective measures[2]. NOAA Fisheries regulations concerning ESA listing procedures are published at 50 *C.F.R.* Parts 217-227, with joint NOAA Fisheries-FWS regulations appearing at 50 *C.F.R.* Parts 402 and 424-453. Generally, the U.S. FWS coordinates ESA activities for terrestrial and freshwater species, while NOAA Fisheries is responsible for marine species and Pacific salmon. Within 90 days of a listing petition's filing, an agency decision is made on whether to reject the petition, or accept it for a further intensive status review of the species. If a status review is conducted, it is initiated with a public solicitation of information and data relevant to the species of concern. A species must be listed if it is threatened or endangered because of any of the following five factors: (1) present or threatened destruction, modification, or curtailment of its habitat or range, (2) overutilization for commercial, recreational, scientific, or educational purposes, (3) disease or predation, (4) inadequacy of existing regulatory mechanisms, and (5) other natural or manmade factors affecting its continued existence.

Additional important considerations for an ESA listing decision, especially concerning anadromous fish, include defining population segments that qualify as species, determining the abundance threshold for threatened and endangered status, and determining the causes of decline. NOAA Fisheries will consider listing individual Pacific salmon populations only if they are evolutionarily significant units (ESUs), defined as "substantially reproductively isolated" and "an important component in the evolutionary legacy of the species" (56 *Federal Register* 58612, Nov. 20, 1991).

Economic considerations are not legally relevant to the listing decision, this decision is to be made solely on the basis of the best biological data available. Except for extensions due to consideration of other proposals, a one-year time limit is placed on making the decision to propose listing. If the agency proposes listing, public comments are again solicited on the proposed listing, and a final decision is made within one year after the issuance of the proposal.

Concurrent with the listing decision, critical habitat believed necessary for the continued survival of species is designated. For this decision, economic impacts must be considered. If information is insufficient to designate critical habitat at the time of listing, or if designation of critical habitat would not be "prudent," the Government may take an additional year to identify it[3].

Once a species is listed, recovery plans are prepared which identify mitigation measures to be initiated to improve the species' status. In addition, the ESA Section 7 consultation process requires all Federal agencies to use their authorities to conduct conservation programs (mitigation measures) and to consult with NOAA Fisheries (or the FWS) concerning the potential effects of their actions on any species under the Act's jurisdiction.

[2] However, either NOAA Fisheries or the FWS may initiate a status review for a species without a petition for listing.

[3] If there is substantial disagreement regarding the sufficiency or accuracy of available data, this one-year period may be extended an additional six months.

ESTUARY RESTORATION ACT (ERA), TITLE I OF THE ESTUARIES AND CLEAN WATERS ACT OF 2000

The Estuary Restoration Act (ERA) of 2000, S. 835 was signed into law on November 7, 2000, to authorize expenditure of $275 million over 5 years toward estuary habitat restoration. ERA established an interagency Council, consisting of representatives from the National Oceanic and Atmospheric Administration (NOAA), Environmental Protection Agency (EPA), Natural Resources Conservation Service (NRCS), Fish and Wildlife Service (FWS), and the U.S. Army. The Estuary Habitat Restoration Council meets at least biannually to direct its policy including distribution of the Act's financial and technical assistance program for restoration projects. NOAA, a member of the interagency Council implementing the Estuary Restoration Act, is the lead agency for the restoration project database and monitoring protocols required under the ERA, with the goal of restoring one million acres of estuarine habitat by the year 2010. Backed by a strong federal commitment and allocated resources to restore the Nation's estuarine habitats, the Act covers: the bays, sounds, gulfs, harbors, lagoons, inlets and deltas where fresh water mixes with the salt water of the ocean along all US coasts and protectorates. The Act also includes the US coast of the Great Lakes. As a member of the Estuary Habitat Restoration Council, NOAA, including the National Centers for Coastal Ocean Science is part of an interagency effort to create and maintain effective partnerships for the promotion of estuary habitat restoration, and develop and enhance restoration monitoring and research capabilities.

FISH AND WILDLIFE COORDINATION ACT

The Fish and Wildlife Coordination Act (16 *U.S.C.* 661-666c, Act of March 10, 1934, as amended) requires that wildlife, including fish, receive equal consideration and be coordinated with other aspects of water resource development. This is accomplished by requiring consultation with the FWS and NOAA Fisheries whenever any body of water is proposed to be modified in any way and a Federal permit or license is required. This consultation determines the possible harm to fish and wildlife resources, and the measures that are needed to both prevent the damage to and loss of these resources, and to develop and improve the resources, in connection with water resource development. NOAA Fisheries submits comments and recommendations to Federal licensing and permitting agencies and to Federal agencies conducting construction projects on the potential harm to living marine resources caused by the proposed water development project, and submits recommendations to prevent harm.

MAGNUSON-STEVENS FISHERY CONSERVATION AND MANAGEMENT ACT

The Magnuson-Stevens Fishery Conservation and Management Act (MSFCMA, 16 U.C.S. 1801 et seq.) provides authority to the Secretary, through NOAA Fisheries, to conserve, manage, and monitor fisheries in the exclusive economic zone (EEZ). Fishery Management Plans must include a provision to describe and identify the Essential Fish Habitat (EFH), including adverse impacts, identify adverse impacts from fishing activities, minimize to the extent practicable adverse impacts from fishing, identify non-fishing sources of adverse impacts, and identify actions to encourage the conservation and enhancement of EFH. Federal agencies are required to consult with NOAA Fisheries on all actions that may adversely affect EFH. NOAA Fisheries is required to provide EFH conservation recommendations for any Federal or state activity that may adversely effect EFH. The action agency must respond in writing stating how it will avoid or mitigate adverse impacts on EFH, or explain why it will not follow NOAA Fisheries' recommendations.

Councils may comment on Federal or state actions which may affect the habitat of fishery resources and must comment if there may be substantial adverse effects to anadromous fish habitat.

NATIONAL ENVIRONMENTAL POLICY ACT

The National Environmental Policy Act (NEPA, 42 *U.S.C.* 4321-4347, Pub. L. 91-190, as amended) requires Federal agencies to analyze the potential effects of a proposed Federal action which would significantly affect historical, cultural, or natural aspects of the environment. It specifically requires agencies to use a systematic, interdisciplinary approach in planning and decision-making, to insure that presently unquantified environmental values may be given appropriate consideration, and to provide detailed statements on the environmental impacts of proposed actions including: (1) any adverse impacts, (2) alternatives to the proposed action, and (3) the relationship between short-term uses and long-term productivity. The agencies use the results of this analysis in decision-making. Alternatives analysis allows other options to be considered. NOAA Fisheries plays a significant role in the implementation of NEPA through its consultative functions relating to conservation of marine resource habitats.

NATIONAL MARINE SANCTUARIES ACT (TITLE III OF THE MARINE PROTECTION, RESEARCH, AND SANCTUARIES ACT)

The National Marine Sanctuaries Act (Title III of the Marine Protection, Research, and Sanctuaries Act) requires the Secretary to "assess damages to sanctuary resources." The Act defines natural resource damages to include "the cost of replacing, restoring or acquiring the equivalent of a sanctuary resource, the value of the lost use of the resource pending its restoration, the cost of damage assessments, and reasonable monitoring." The Act further requires the Secretary to conduct "research, monitoring, evaluation, and education programs..."

RIVERS AND HARBORS ACT OF 1899

The Rivers and Harbors Act of 1899, Section 10 (33 *U.S.C.* 403) requires that all obstructions to the navigable capacity of navigable waters of the United States must be authorized by Congress. The Secretary of the Army must authorize any construction outside established harbor lines or where no harbor lines exist. The Secretary of the Army must also authorize any alterations within the limits of any breakwater or channel of any navigable water of the United States.

References

Buck, E.H. 1995. Summaries of major laws implemented by the National Marine Fisheries Service. CRS Report for Congress. Congressional Research Service, Library of Congress, March 24, 1995.

GLOSSARY

Abiotic - non-living

Adaptive management - a systematic process for continually improving management policies and practices by learning from the outcomes of operational programs. Its most effective form–"active" adaptive management– employs management programs that are designed to experimentally compare selected policies or practices, by evaluating alternative hypotheses about the system being managed.

Aerobic - (of an organism or tissue) requiring air for life; pertaining to or caused by the presence of oxygen

Algae - simple plants that are very small and live in water through photosynthesis, algae are the main producers of food and oxygen in water environments

Allochthanous - carbon that is formed outside of a particular area as opposed to an autochthanous carbon that is produced within a given area

Alluvial plain - the floodplain of a river, where the soils are alluvial deposits carried in by overflowing river

Alluvium - any sediment deposited by flowing water, as in a riverbed, floodplain, or delta

Alternate hypothesis - a statement about the values of one or more parameters usually describing a potential change

Anaerobic - living in the absence of air or free oxygen; pertaining to or caused by the absence of oxygen

Anoxic - without oxygen

Anthropogenic - caused by humans; often used when referring to human induced environmental degradation

Apical - the tips of the plants

Aquatic - living or growing in or on water

Asset mapping - a community assessment research method that provide a graphical representation of a community's capacities and assets

Assigned values - the relative importance or worth of something, usually in economic terms. Natural resource examples include the value of water for irrigation or hydropower, land for development, or forests for timber supply (see held values).

Attitude - an individual's consistent tendency to respond favorably or unfavorably toward a given attitude object. Attitudes can be canvassed through survey research and are often defined utilizing scales ranging from positive to negative evaluations.

Backwater - a body of water in which the flow is slowed or turned back by an obstruction such as a bridge or dam, an opposing current, or the movement of the tide

Baseline measurements - a set of measurements taken to assess the current or pre-restoration condition of a community or ecosystem

Basin morphology - the shape of the earth in the area a coastal habitat is found

Benefit-cost analysis - a comparison of economic benefits and costs to society of a policy, program, or action

Benthic - on the bottom or near the bottom of streams, lakes, or oceans

Bequest value - the value that people place on knowing that future generations will have the option to enjoy something

Biogenic - produced by living organisms

Biomass - the amount of living matter, in the form of organisms, present in a particular habitat, usually expressed as weight- per-unit area

Blackwater streams - streams that do not carry sediment, are tannic in nature and flow through peat-based areas

Brackish - water with a salinity intermediate between seawater and freshwater (containing from 1,000 to 10,000 milligrams per liter of dissolved solids)

Calcareous - sediment/soil formed of calcium carbonate or magnesium carbonate due to biological deposition or inorganic precipitation

Canopy formers - plants that form a diverse vertical habitat structure

Carnivores - organisms that feed on animals

Catchment - the land area drained by a river or stream; also known as "watershed" or "drainage basin"; the area is determined by topography that divides drainages between watersheds

Causality - or causation, refers to the relationship between causes and effects: i.e., to what extent does event 'A' (the cause) bring about effect 'B'

Coastal habitat restoration - the process of reestablishing a self-sustaining habitat in coastal areas that in time can come to closely resemble a natural condition in terms of structure and function

Coastal habitat restoration monitoring - the systematic collection and analysis of data that provides information useful for measuring coastal habitat restoration project performance

Cognitive mapping - a community assessment research method used to collect qualitative data and gain insight into how community members perceive their community and surrounding natural environment

Cohort studies - longitudinal research aimed at studying changing in a particular subpopulation or cohort (e.g., age group) over time (see longitudinal studies)

Community - all the groups of organisms living together in the same area, usually interacting or depending on each other for existence; all the living organisms present in an ecosystem

Community (human) - a group of people who interact socially, have common historical or other ties, meet each other's needs, share similar values, and often share physical space; A sense of "place" shaped by either natural boundaries (e.g., watershed), political or administrative boundaries (e.g., city, neighborhood), or physical infrastructure

Computer-assisted telephone interviewing (CATI) - a system for conducting telephone survey interviews that allows interviewers to enter data directly into a computer database. Some CATI systems also generate phone numbers and dial them automatically.

Concept mapping - community assessment research method that collects data about how community members perceive the causes or related factors of particular issues, topics, and problems

Content validity - in social science research content validity refers to the extent to which a measurement (i.e., performance standard) reflects the specific intended domain of content (i.e., stated goal or objective). That is, how well does the performance standard measure whether or not a particular project goal has been met?

Contingent choice method - estimates economic values for an ecosystem or environmental service. Based on individual's tradeoffs among sets of ecosystems, environmental services or characteristics. Does not directly ask for willingness to pay; inferred from tradeoffs that include cost as an attribute.

Contingent valuation method (CVM) - used when trying to determine an individual or individuals' monetary valuation of a resource. The CVM can be used to determine changes in resource value as related to an increase or decrease in resource quantity or quality. Used to measure non-use attributes such as existence and bequest values; market data is not used.

Coral reefs - highly diverse ecosystems, found in warm, clear, shallow waters of tropical oceans worldwide. They are composed of marine polyps that secrete a hard calcium carbonate skeleton, which serves as a base or substrate for the colony.

Coralline algae - algae that contains a coral-like, calcareous outer covering

Cost estimate - estimates on costs of planning and carrying out a project. Examples of items that may be included in a cost estimate for a monitoring plan may be personnel, authority to provide easements and rights-of-way, maintenance, labor, and equipment.

Coulter counter - a device that measures the amount of particles in water

Coverage error - a type of survey error that can occur when the list – or frame – from which a sample is drawn does not include all elements of the population that researchers wish to study

Cross-sectional studies - studies that investigate some phenomenon by taking a cross section (i.e., snapshot) of it at one time and analyzing that cross section carefully (see longitudinal studies)

Crowding - in outdoor recreation, crowding is a form of conflict (see outdoor recreation conflict) that is based on an individual's judgment of what is appropriate in a particular recreation activity and setting. Use level is not interpreted negatively as crowding until it is perceived to interfere with one's objectives or values. Besides use level, factors that can influence perceptions of crowding include participant's motivations, expectations, and experience related to the activity, and characteristics of those encountered such as group size, behavior, and mode of travel.

Cryptofauna - tiny invertebrates that hide in crevices

Cultch - empty oyster shells and other materials that are on the ground and used as a place of attachment

Culture - a system of learned behaviors, values, ideologies, and social arrangements. These features, in addition to tools and expressive elements such as graphic arts, help humans interpret their universe as well as deal with features of their environments, natural and social.

Cyanobacteria - blue-green pigmented bacteria; formerly called blue-green algae

Dataloggers - an electronic device that continually records data over time

Deepwater swamps - forested wetlands that develop along edges of lakes, alluvial river swamps, in slow-flowing strands, and in large, coastal-wetland complexes. They can be found along the Atlantic and Gulf Coasts and throughout the Mississippi River valley. They are distinguished from other forested habitats by the tolerance of the dominant vegetation to prolonged flooding.

Demersal - bottom-feeding or bottom-dwelling fish, crustaceans, and other free moving organisms

Detritivorous - the practice of eating primarily detritus

Detritus - fine particles of decaying organic and inorganic matter fomed by excrement and by plant and animal remains; maybe suspended in water or accumulated on the bottom of a water body

Diatoms - any of a class (Bacillariophyceae) of minute planktonic unicellular or colonial algae with silicified skeletons that form shells.

Direct impacts - the changes in economic activity during the first round of spending. For tourism this involves the impacts on the tourism industries (businesses selling directly to tourists) themselves (see Secondary Effects)

Dissolved oxygen - oxygen dissolved in water and available to aquatic organisms; one of the most important indicators of the condition of a water body; concentrations below 5 mg/l are stressful and may be lethal to many fish and other species

Dominant species - a plant species that exerts a controlling influence on or defines the character of a community

Downwelling - the process of build-up and sinking of surface waters along coastlines

Driving forces - the base drivers that play a large role in people's decision making processes and influence human behavior. Societal forces such as population, economy, technology, ideology, politics and social organizations are all drivers of environmental change.

Duration - a span or interval of time

Ebb - a period of fading away, low tide

Echinoderms - any of a phylum (Echinodermata) of radially symmetrical coelomate marine animals including the starfishes, sea urchins, and related forms

Economic impact analysis - used to estimate how changes in the flow of goods and services can affect an economy. Measure of the impact of dollars from outside a defined region/area on that region's economy. This method is often used in estimating the value of resource conservation.

Ecosystem - a topographic unit, a volume of land and air plus organic contents extended aerially for a certain time

Ecosystem services - the full range of goods and services provided by natural ecological systems that cumulatively function as fundamental life-support for the planet. The life-support functions performed by ecosystem services can be divided into two groups: production functions (i.e., goods) and processing and regulation functions (i.e., services).

Emergent plants - water plants with roots and part of the stem submerged below water level, but the rest of the plant is above water; e.g., cattails and bulrushes

Environmental equity - the perceived fairness in the distribution of environmental quality across groups of people with different characteristics

Environmental justice - a social movement focused on the perceived fairness in the distribution of environmental quality among people of different racial, ethnic or socio-economic groups

Ephemeral - lasting a very short time

Epifaunal - plants living on the surface of the sediment or other substrate such as debris

Epiphytes - plants that grow on another plant or object upon with it depends for mechanical support but not as a source of nutrients

Estuary - a part of a river, stream, or other body of water that has at least a seasonal connection with the open sea or Great Lakes and where the seawater or Great Lakes water mixes with the surface or subsurface water flow, regardless of the presence of man-made structures or obstructions.

Eukaryotic - organisms whose cells have a nucleus

Eulittoral - refers to that part of the shoreline that is situated between the highest and lowest seasonal water levels

Eutrophic - designating a body of water in which the increase of mineral and organic nutrients has reduced the dissolved oxygen, producing an environment that favors plant over animal life

Eutrophication - a natural process, that can be accelerated by human activities, whereby the concentration of nutrients in rivers, estuaries, and other bodies of water increases; over time this can result in anaerobic (lack of oxygen) conditions in the water column; the increase of nutrients stimulates algae "blooms;" as the algae decays and dies, the availability of dissolved oxygen is reduced; as a result, creatures living in the water accustomed to aerobic conditions perish

Evapotranspiration - a term that includes water discharged to the atmosphere as a result of evaporation from the soil and surface-water bodies and by plant transpiration

Existence value - the value that people place on simply knowing that something exists, even if they will never see it or use it

Exotic species - plants or animals not native to the area

Fauna - animals collectively, especially the animals of a particular region or time

Fecal coliforms - any of several bacilli, especially of the genera *Escherichia*, found in the intestines of animals. Their presence in water suggests contamination with sewage of feces, which in turn could mean that disease-causing bacteria or viruses are present. Fecal coliform bacteria are used to indicate possible sewage contamination. Fecal coliform bacteria are not harmful themselves, but indicate the possible presence of disease-causing bacteria, viruses, and protozoans that live in human and animal digestive systems. In addition to the possible health risks associated with them, the bacteria can also cause cloudy water, unpleasant odors, and increased biochemical oxygen demand.

Fetch - the distance along open water or land over which the wind blows

Fishery dependent data - data on fish biology, ecology and population dynamics that is collected in connection with commercial, recreational or subsistence fisheries.

Flooding regime - pattern of flooding over time

Floodplain - a strip of relatively flat land bordering a stream channel that may be overflowed at times of high water; the amount of land inundated during a flood is relative to the severity of a flood event

Flora - plants collectively, especially the plants of a particular region or time

Fluvial - of, relating to, or living in a stream or river

Focus group - a small group of people (usually 8 to 12) that are brought together by a moderator to discuss their opinions on a list of predetermined issues. Focus groups are designed to collect very detailed information on a limited number of topics.

Food chain - interrelations of organisms that feed upon each other, transferring energy and nutrients; typically solar energy is processed by plants who are eaten by herbivores which in turn are eaten by carnivores: sun –> grass –> mouse –> owl

Food webs - the combined food chains of a community or ecosystem

Frequency - how often something happens

Fronds - leaf-like structures of kelp plants

Function - refers to how wetlands and riparian areas work – the physical, chemical, and biological processes that occur in these settings, which are a result of their physical and biological structure

Functional habitat characteristics - characteristics that describe what ecological service a habitat provides to the ecosystem

Gastropods - any of a large class (Gastropoda) of mollusks (as snails and slugs) usually with a univalve shell or none and a distinct head bearing sensory organs

Geomorphic - pertaining to the form of the Earth or of its surface features

Geomorphology - the science that treats the general configuration of the Earth's surface; the description of landforms

Habitat - the sum total of all the living and non-living factors that surround and potentially influence an organism; a particular organism's environment

Hard bottom - the floor of a water body composed of solid, consolidated substrate, including reefs and banks. The solid floor typically provides an attachment surface for sessile organisms as well as a rough three-dimensional surface that encourages water mixing and nutrient cycling.

Hedonic pricing method - estimates economic values for ecosystem or environmental services that directly affect market prices of some other good. Most commonly applied to variations in housing prices that reflect the value of local environmental attributes.

Held values - conceptual precepts and ideals held by an individual about something. Natural resource examples include the symbolic value of a bald eagle or the aesthetic value of enjoying a beautiful sunset (see assigned values).

Herbivory - the act of feeding on plants

Holdfasts - a part by which a plant clings to a flat surface

Human dimensions - an multidisciplinary/interdisciplinary area of investigation which attempts to describe, predict, understand, and affect human thought and action toward natural environments in an effort to improve natural resource and environmental stewardship. Disciplines within human dimensions research is conducted include (but are not limited to) sociology, psychology, resource economics, geography, anthropology, and political science.

Human dominant values - this end of the natural resource value continuum emphasizes the use of natural resources to meet basic human needs. These are often described as utilitarian, materialistic, consumptive or economic in nature.

Human mutual values - the polar opposite of human dominant values, this end of the natural resource value continuum emphasizes spiritual, aesthetic, and nonconsumptive values in nature

Hydric soil - a soil that is saturated, flooded, or ponded long enough during the growing season to develop anaerobic conditions that favor the growth and regeneration of hydrophytic vegetation; field indicators of hydric soils can include: a thick layer of decomposing plant material on the surface; the odor of rotten eggs; and colors of bluish–gray, gray, black, or sometimes gray with contrasting brighter spots of color

Hydrodynamics - the motion of water that generally corresponds to its capacity to do work such as transport sediments, erode soils, flush pore waters in sediments, fluctuate vertically, etc. Velocities can vary within each of three flow types: primarily vertical, primarily bidirectional and horizontal, and primarily unidirectional and horizontal. Vertical fluxes are driven by evapotranspiration and precipitation. Bidirectional flows are driven by astronomic tides and wind-driven seiches. Unidirectional flows are downslope movement that occurs from seepage slopes and floodplains.

Hydrogeomorphology - a branch of science (geology) that studies the movement of subsurface water through rocks, either as underground streams or percolating through porous rocks.

Hydrology - the study of the cycle of water movement on, over and through the earth's surface; the science dealing with the properties, distribution, and circulation of water

Hydroperiod - depth, duration, seasonality, and frequency of flooding

Hydrostatic pressure - the pressure water exerts at any given point when a body of water is in a still motion

Hypersaline - extremely saline, generally over 30 ppt salinity (average ocean water salinity)

Hypoxic - waters with dissolved oxygen less than 2 mg/L

IMPLAN - a micro-computer-based input-output (IO) modeling system (see Input-output model below). With IMPLAN, one can estimate 528 sector I-O models for any region consisting of one or more counties. IMPLAN includes procedures for generating multipliers and estimating impacts by applying final demand changes to the model.

Indirect impacts - the changes in sales, income or employment within the region in backward-linked industries supplying goods and services to tourism businesses. The increase in sales of linen supply firms that result from more motel sales is an indirect effect of visitor spending.

Induced impacts - the increased sales within the region from household spending of the income earned in tourism and supporting industries. Employees in tourism and supporting industries spend the income they earn from tourism on housing, utilities, groceries, and other consumer goods and services. This generates sales, income and employment throughout the region's economy.

Infauna - plants that live in the sediment

Informed consent - an ethical guideline for conducting social science research. Informed consent emphasizes the importance of both accurately informing research participants as to the nature of the research and obtaining their verbal or written consent to participate. The purpose, procedures, data collection methods and potential risks (both physical and psychological) should be clearly explained to participants without any deception.

Infralittoral - a sub-area of the sublittoral zone where upward-facing rocks are dominated by algae, mainly kelp

Input-output model (I-O) - an input-output model is a representation of the flows of economic activity between sectors within a region. The model captures what each business or sector must purchase from every other sector in order to produce a dollar's worth of goods or services. Using such a model, flows of economic activity associated with any change in spending may be traced either forwards (spending generating income which induces further spending) or backwards (visitor purchases of meals leads restaurants to purchase additional inputs -- groceries, utilities, etc.). Multipliers may be derived from an input-output models (see multipliers).

Instrumental values - the usefulness of something as a means to some desirable human end. Natural resource examples include economic and life support values associated with natural products and ecosystem functions (see non-instrumental values).

Intergenerational equity - the perceived fairness in the distribution of project costs and benefits across different generations, including future generations not born yet

Interstices - a space that intervenes between things; especially one between closely spaced things

Intertidal - alternately flooded and exposed by tides

Intrinsic values - values not assigned by humans but are inherent in the object or its relationship to other objects

Invasive species - a species that does not naturally occur in a specific area and whose introduction is likely to cause economic or environmental harm

Invertebrate - an animal with no backbone or spinal column; invertebrates include 95% of the animal kingdom

Irregularly exposed - refers to coastal wetlands with surface exposed by tides less often than daily

Lacunar - a small cavity, pit, or discontinuity

Lacustrine - pertaining to, produced by, or formed in a lake

Lagoons - a shallow stretch of seawater (or lake water) near or communicating with the sea (or lake) and partly or completely separated from it by a low, narrow, elongate strip of land

Large macroalgae - relatively shallow (less then 50 m deep) subtidal algal communities dominated by very large brown algae. Kelp and other large macroalgae grow on hard or consolidated substrates forming extensive three-dimensional structures that support numerous flora and fauna assemblages.

Large-scale commercial fishing - fishing fleets that are owned by corporations with large capital investments, and are highly mobile in their global pursuit of fish populations

Littoral - refers to the shallow water zone (less than 2 m deep) at the end of a marine water body, commonly seen in lakes or ponds

Longitudinal studies - social science research designed to permit observations over an extended period of time (see trend studies, cohort studies, and panel studies)

Macrofauna - animals that grow larger than 1 centimeter (e.g., animals exceeding 1 mm in length or sustained on a 1 mm or 0.5 mm sieve)

Macroinvertebrate - animals without backbones that can be seen with the naked eye (caught with a 1 mm^2 mesh net); includes insects, crayfish, snails, mussels, clams, fairy shrimp, etc

Macrophytes - plant species that are observed without the aid of an optical magnification e.g., vascular plants and algae

Mangroves - swamps dominated by shrubs that live between the sea and the land in areas that are inundated by tides. Mangroves thrive along protected shores with fine-grained sediments where the mean temperature during the coldest month is greater than 20º C, which limits their northern distribution.

Marine polyps - refer to the small living units of the coral that are responsible for secreting calcium carbonate maintaining coral reef shape

Market price method - estimates economic values for ecosystem products or services that are bought and sold in commercial markets

Marshes (marine and freshwater) - coastal marshes are transitional habitats between terrestrial and aquatic systems where the water table is usually at or near the surface, or the land is covered by shallow water tidally or seasonally. Freshwater species are adapted to the short- and long-term water level fluctuations typical of freshwater ecosystems.

Mast - the nuts of forest trees accumulated on the ground

Measurement error - a type of survey error that occurs when a respondent's answer to a given question is inaccurate, imprecise, or cannot be compared to other respondent's answers

Meiofauna - diverse microorganisms that are approximately between .042 mm and 1 mm in size

Meristematic - the ability to form new cells that separate to form new tissues

Mesocosm - experimental tanks allowing studies to be performed on a smaller scale

Metadata - data that describes or provides background information on other data

Microfauna - animals that are very small and best identified with the use of a microscope, such organisms include protozoans and nematodes

Microinvertebrates - invertebrate animals that are so small they can only be observed with a microscope

Micro-topography - very slight changes in the configuration of a surface including its relief and the position of its natural and man-made features

Migratory - a creature that moves from one region to another when the seasons change

Morphology - the study of structure and form, either of biological organisms or features of the earth surface

Mottling - contrasting spots of bright colors in a soil; an indication of some oxidation or ground water level fluctuation

Mudflat - bare, flat bottoms of lakes, rivers and ponds, or coastal waters, largely filled with organic deposits, freshly exposed by a lowering of the water level; a broad expanse of muddy substrate commonly occurring in estuaries and bays

Multipliers - capture the size of the secondary effects in a given region, generally as a ratio of the total change in economic activity in the region relative to the direct change. Multipliers may be expressed as ratios of sales, income or employment, or as ratios of total income or employment changes relative to direct sales. Multipliers express the degree of interdependency between sectors in a region's economy and therefore vary considerably across regions and sectors

Nanoplankton - plankton of minute size, generally size range is from 2 to 20 micrometers

Native - an animal or plant that lives or grows naturally in a certain region

Nearshore - nearshore waters begin at the shoreline or the lakeward edge of the coastal wetlands and extend offshore to the deepest lakebed depth contour, where the thermocline typically intersects with the lake bed in late summer or early fall

Nekton - free-swimming aquatic animals (such as fish) essentially independent of wave and current action

Non-instrumental values - something that is valued for what it is; a good of its own; an end in itself. Natural resource examples include aesthetic and spiritual values found in nature (see instrumental values)

Non-market goods and services - goods and services for which no traditional market exists whereby suppliers and consumers come together and agree on a price. Many ecosystem services and environmental values fall under this category

Non-point source - a source (of any water–carried material) from a broad area, rather than from discrete points

Nonresponse error - a type of survey error that occurs when a significant proportion of the survey sample do not respond to the questionnaire and are different from those who do in a way that is important to the study

Non-use values - also called “passive use” values, or values that are not associated with actual use, or even the option to use a good or service

Norms - perceived standards of acceptable attitudes and behaviors held by a society (social norms) or by an individual (personal norms). Serve as guideposts for what is appropriate behavior in a specific situation.

Nuisance species - undesirable plants and animals, commonly exotic species

Null hypothesis - a statement about the values of one or more parameters usually describing a condition of no change or difference

Nutria - a large South American semiaquatic rodent (*Myocastor coypus*) with webbed hind feet that has been introduced into parts of Europe, Asia, and North America

Nutrient - any inorganic or organic compound that provides the nourishment needed for the survival of an organism

Nutrient cycling - the transformation of nutrients from one chemical form to another by physical, chemical, and biological processes as they are transferred from one trophic level to another and returned to the abiotic environment

Octocorals - corals with eight tentacles on each polyp. There are many different forms that may be soft, leathery, or even those producing hard skeletons.

Oligohaline - an area of an estuary with salinities between 0.5 and 5.0 ppt

Oligotrophic - a water body that is poor in nutrients. This refers mainly to lakes and ponds

One-hundred year flood - refers to the floodwater levels that would occur once in 100 years, or as a 1.0 percent probability per year

Opportunity cost - the cost incurred when an economic decision is made. This cost is equal to the benefit of the most highly valued alternative that would have been gained if a different decision had been made. For example, if a consumer has $2.00 and decides to purchase a sandwich, the economic cost may be that consumer can no longer use that money to buy fruit.

Option value - the value associated with having the option or opportunity to benefit from some resource in the future

Organic - containing carbon, but possibly also containing hydrogen, oxygen, chlorine, nitrogen, and other elements

Organic material - anything that is living or was living; in soil it is usually made up of nuts, leaves, twigs, bark, etc.

Osmotic stress - water stresses due to differences in salinity between an organism and its aquatic environment

Outdoor recreation conflict - defined as behavior of an individual or group that is incompatible with the social, psychological or physical goals of another person or group

Oyster beds - dense, highly structured communities of individual oysters growing on the shells of dead oysters

Panel studies - longitudinal research that studies the same set of people through time in order to investigate changes in individuals over time (see longitudinal studies)

Pelagic - pertaining to, or living in open water column

Personal area network (PAN) - a computer network used for communicating between computer devices (including telephones and personal digital assistants) and a person

Petiole - the stalk of a leaf, attaching it to the stem

pH - a measure of the acidity (less than 7) or alkalinity (greater than 7) of a solution; a pH of 7 is considered neutral

Phenology - refers to the life stages a plant/algae experiences (e.g., shoot development in kelp)

Physiographic setting - the location in a landscape, such as stream headwater locations, valley bottom depression, and coastal position. Similar to geomorphic setting.

Physiography - a description of the surface features of the Earth, with an emphasis on the mode or origin

Phytoplanktivores - animals that eat planktonic small algae that flow in the water column

Phytoplankton - microscopic floating plants, mainly algae that are suspended in water bodies and are transported by wave currents because they cannot move by themselves swim effectively against a current.

Piscivorous - feeding on fish

Planktivorous - eating primarily plankton

Plankton - plant and animal organisms, generally microscopic, that float or drift in water

Pneumatocysts - known as gas bladders or floaters that help the plant stay afloat such as the bladders seen in the brown alga *Macrocystis*

Pneumatophores - specialized roots formed on several species of plants occurring frequently in inundated habitats; root is erect and protrudes above the soil surface

Polychaete - a group of chiefly marine annelid worms armed with setae, or bristles, extending from most body segments

Population - a collection of individuals of one species or mixed species making up the residents of a prescribed area

Population list - in social science survey research, this is the list from which the sample is drawn. This list should be as complete and accurate as possible and should closely reflect the target population.

ppt - parts per thousand. The salinity of ocean water is approximately 35 ppt

Precision - a statistical term that refers to the reproducibility of the result or measurement. Precision is measured by uncertainty and is usually expressed as the standard error or some confidence interval around the estimated mean.

Prop roots - long root structures that extend midway from the trunk and arch downward creating tangled branching roots above and below the water's surface, such as the mangrove *Rhizophora*

Propagules - a structure (cutting, seed, spore, rhizome, etc.) that causes the continuation or increase of a plant, by sexual or asexual reproduction

Protodeltaic - similar in form to the early stages of delta formation

Pseudofeces - material expelled by the oyster without having gone through the animal's digestive system

Quadrats - are rectangular, or square shaped instruments used to estimate density, cover and biomass of both plants and animals

Quality assurance/quality control plan - a detailed plan that describes the means of data collection, handling, formatting, storage, and public accessibility for a project

Random utility models - a non-market valuation technique that focuses on the choices or preferences of recreationists among alternative recreational sites. Particularly appropriate when substitutes are available to the individual so that the economist is measuring the value of the quality characteristics of one or more site alternatives (e.g., a fully restored coastal wetland and a degraded coastal wetland).

Receiving water bodies - lakes, estuaries, or other surface waters that have flowing water delivered to them

Recruitment - the process of adding new individuals to a population or subpopulation (as of breeding individuals) by growth, reproduction, immigration, and stocking; also a measure (as in numbers or biomass) of recruitment

Redox potential - oxidation-reduction potential; often used to quantify the degree of electrochemical reduction of wetland soils under anoxic conditions

Reference condition - set of selected measurements or conditions of minimally impaired waterbodies characteristic of a waterbody type in a region

Reference site - a minimally impaired site that is representative of the expected ecological conditions and integrity of other sites of the same type and region

Reflectance - The ratio of the light that radiates onto a surface to the amount that is reflected back

Regime - a regular pattern of occurrence or action

Reliability - the likelihood that a given measurement procedure or technique will yield the same result each time that measure is repeated (i.e., reproducibility of the result) (see Precision)

Remote sensing - the process of detecting and monitoring physical characteristics of an area by measuring its reflected and emitted radiation and without physically contacting the object

Restoration - the process of reestablishing a self-sustaining habitat that in time can come to closely resemble a natural condition in terms of structure and function

Restoration monitoring - the systematic collection and analysis of data that provides information useful for measuring restoration project performance at a variety of scales (locally, regionally, and nationally)

Rhizome - somewhat elongate usually horizontal subterranean plant stem that is often thickened by deposits of reserve food material, produces shoots above and roots below, and is distinguished from a true root in possessing buds, nodes, and usually scale-like leaves

Riparian - a form of wetland transition between permanently saturated wetlands and upland areas. These areas exhibit vegetation or physical characteristics reflective of permanent surface of subsurface water influence. Lands along, adjacent to, or contiguous with perennially and intermittently flowing rivers and streams, glacial potholes, and the shores of lakes and reservoirs with stable water levels are typically riparian areas. Excluded are such sites as ephemeral streams or washes that do not exhibit the presence of vegetation dependent upon free water in the soil.

Riverine - of, or associated with rivers

Riverine forests - forests found along sluggish streams, drainage depressions, and in large alluvial floodplains. Although associated with deepwater swamps in the SE United States, riverine forests are found throughout the US and do not exhibit prolonged flooding.

Rocky shoreline - extensive hard bottom littoral habitats on wave-exposed coasts

RVD (recreational visitor day) - one RVD is defined as 12 hours of use in some recreational activity. This could be one person using an area for 12 hours, or 2 people using an area for 6 hours each, or any combination of people and time adding to 12 hours of use.

Salinity - the concentration of dissolved salts in a body of water; commonly expressed as parts per thousand

Salt pans - an undrained natural depression in which water gathers and leaves a deposit of salt on evaporation

Sample - in social science survey research, this is a set of respondents selected from a larger population for the purpose of a survey

Sampling designs - the procedure for selecting samples from a population and the subsequent statistical analysis

Sampling error - a potential source of survey error that can occur when researchers survey only a subset or sample of all people in the population instead of conducting a census. To minimize this error the sample should be as representative of the population as possible.

Satisfaction - in outdoor recreation, satisfaction is defined as the difference between desired and achieved goals. Can be measured through surveys of recreation participants.

SAV (submerged aquatic vegetation) - marine, brackish, and freshwater submerged aquatic vegetation that grows on soft sediments in sheltered shallow waters of estuaries, bays, lagoons, and lakes

Seasonality - the change in naturally cycles, such as lunar cycles and flooding cycles, from one season to the next

Secondary data - information that has already been assembled, having been collected for some other purpose. Sources include census reports, state and federal agency data, and university research.

Secondary effects - the changes in economic activity from subsequent rounds of re-spending of tourism dollars. There are two types of secondary effects: indirect effects and induced effects.

Sector - a grouping of industries that produce similar products or services. Most economic reporting and models in the U.S. are based on the Standard Industrial Classification system (SIC code). Tourism is more an activity or type of customer than an industrial sector. While hotels (SIC 70) are a relatively pure tourism sector, restaurants, retail establishments and amusements sell to both tourists and local customers. There is therefore no simple way to identify tourism sales in the existing economic reporting systems, which is why visitor surveys are required to estimate tourist spending.

Sediment porewater - water in the spaces between individual grains of sediment

Seiches - a sudden oscillation of the water in a moderate-size body of water, caused by wind

Seine - a net weighted at the bottom with floats at the top so it remains vertical in the water. A seine can be towed behind a boat or smaller versions, attached to poles, may be operated by hand.

Senescence - the growth phase in a plant or plant part (as a leaf) from full maturity to death, also applies to winter dormancy

Sessile - plants that are permanently attached or established; animals that do not freely move about

Simple random sampling (SRS) - in survey research, when each member of the target population has an equal change of being selected. If a population list exists, SRS can be achieved using a computer-generated random numbers.

Small-scale commercial fishing - fishing operations that have relatively small capital investment and levels of production, and are more limited in terms of mobility and resource options (compared to large-scale operations). Terms that are commonly used to describe small-scale fishermen include native, coastal, inshore, tribal, peasant, artisanal, and traditional.

Social capital - describes the internal social and cultural coherence of society, the norms and values that govern interactions among people and the institutions in which they are embedded

Social impact assessment (SIA) - analysis conducted to assess, in advance, the social consequences that are likely to follow from specific policy actions and alternatives. Social impacts in this context refers to the consequences to human populations that alter the ways in which people live, work, play, relate to one another, organize and generally cope as members of society.

Social network mapping - community assessment research method used to collect, analyze, and graphically represent data that describe patterns of communication and relationships within a community

Socioeconomic monitoring - tracking of key indicators that characterize the economic and social state of a community

Soft bottom - loose, unconsolidated substrate characterized by fine to coarse-grained sediment

Soft shoreline - sand beaches, dunes, and muddy shores. Sandy beaches are stretches of land covered by loose material (sand), exposed to and shaped by waves and wind.

Stakeholders - individuals, groups, or sectors that have a direct interest in and/or are impacted by the use and management of natural resources in a particular area, or that have responsibility for management of those resources

Statistical protocol - a method of a analyzing a collection of observed values to make an inference about one or more characteristic of a population or unit

Strands - a diffuse freshwater stream flowing through a shallow vegetated depression on a gentle slope

Structural habitat characteristics - characteristics that define the physical composition of a habitat

Subsistence - describes the customary and traditional uses of renewable resources (i.e., food, shelter, clothing, fuel) for direct personal/family consumption, sharing with other community members, or for barter. Subsistence communities are often held together by patterns of natural resource production, distribution, exchange, and consumption that helps maintain a complex web of social relations involving authority, respect, wealth, obligation, status, power and security.

Subtidal - continuously submerged; an area affected by ocean tides

Supralittoral region - is that area which is above the high tide mark receiving splashing from waves

Target population - the subset of people who are the focus of a survey research project

Taxa - a grouping of organisms given a formal taxonomic name such as species, genus, family, etc. (singular form is taxon)

Temporal - over time

Thermocline - the region in a thermally stratified body of water which separates warmer oxygen-rich surface water from cold oxygen-poor deep water and in which temperature decreases rapidly with depth

Tide - the rhythmic, alternate rise and fall of the surface (or water level) of the ocean, and connected bodies of water, occurring twice a day over most of the Earth, resulting from the gravitational attraction of the Moon, and to a lesser degree, the Sun

Topography - the general configuration of a land surface or any part of the Earth's surface, including its relief and the position of its natural and man–made features

Transect - two types of transects, point and line. Point intercept transect methods is performed by placing a point frame along a set of transect lines. Line transects are when a line is extended from one point to the next within the designated sample area

Transient - passing through or by a place with only a brief stay or sojourn

Transit - a surveying instrument for measuring horizontal and vertical angles; appropriate to help determine actual location of whale surfacing. It contains a small telescope that is placed on top of a tripod.

Travel cost method (TCM) - TCM is used to estimate monetary value of a geographical site in its current condition (i.e., environmental health, recreational use capacity, etc.) by site-users. Individuals or groups report travel-related expenditures made while on trips to single and multiple recreational sites. Market values are used.

Trend studies - longitudinal research that studies changes within some general population over time (see longitudinal studies)

Trophic - refers to food, nutrition, or growth state

Trophic level - a group of organisms united by obtaining their energy from the same part of the food web of a biological community

Turf - cover (the ground) with a surface layer of grass or grass roots

Unconsolidated - loosely arranged

Utilitarian value - valuing some object for its usefulness in meeting certain basic human needs (e.g., food, shelter, clothing). Also see human-dominant values

Validity - refers to how close to a true or accepted value a measurement lies

Vibracore - refers to a high frequency, low amplitude vibration, coring technique used for collecting sediment samples without disrobing the sample

Viviparous - producing living young instead of eggs from within the body in the manner of nearly all mammals, many reptiles, and a few fishes; germinating while still attached to the parent plant

Water column - a conceptual volume of water extending from the water surface down to, but not including the substrate. It is found in marine, estuarine, river, and lacustrine systems.

Watershed - surface drainage area that contributes water to a lake, river, or other body of water; the land area drained by a river or stream

Willingness-to-pay - the amount in goods, services, or dollars that a person is willing to give up to get a particular good or service

Zonation - a state or condition that is marked with bands of color, texture, or plant species

Zooplanktivorus - animals that feed upon zooplankton

Zooplankton - free-floating animals that drift in the water, range from microscopic organisms to larger animals such as jellyfish

References

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