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# Use of Natural and Nature-Based Features (NNBF) for Coastal Resilience

Final Report

Todd S. Bridges, Paul W. Wagner, Kelly A. Burks-Copes, Matthew E. Bates, Zachary A. Collier, Craig J. Fischenich, Joe Z. Gailani, Lauren D. Leuck, Candice D. Piercy, Julie D. Rosati, Edmond J. Russo, Deborah J. Shafer, Burton C. Suedel, Emily A. Vuxton, and Ty V. Wamsley

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# Abstract

Coastal systems are increasingly vulnerable to flooding due to the combined influence of coastal storms, development and population growth, geomorphic change, and sea level rise. This reality has given rise to efforts to make greater use of ecosystem-based approaches to reduce risks from coastal storms, approaches which draw from the capacity of wetlands, beaches and dunes, biogenic reefs, and other natural features to reduce the impacts of storm surge and waves. This report offers details regarding the use of natural and nature-based features (NNBF) to improve coastal resilience and was designed to support post-Hurricane Sandy recovery efforts under the North Atlantic Coast Comprehensive Study (NACCS). An integrative framework is offered herein that focuses on classifying NNBF, characterizing vulnerability, developing performance metrics, incorporating regional sediment management, monitoring and adaptively managing from a systems perspective, and addressing key policy challenges. As progress is made on these and other actions across the many organizations contributing to the use of NNBF, implementation of the full array of measures available will reduce the risks and enhance the resilience of the region's coastal systems.

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# Preface

This report offers details regarding the use of natural and nature-based features to improve coastal resilience and was designed to support efforts under the North Atlantic Coast Comprehensive Study (NACCS) (USACE 2015). The report was prepared jointly by staff from the U.S. Army Engineer and Research Development Center (CEERD) and the Institute of Water Resources (CEIWR) at the request of the U.S. Army Corps of Engineers, National Planning Center for Coastal Storm Risk Management. Contributors to the report include the following:

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# Executive Summary

Natural, nature-based, nonstructural, and structural are terms used to describe the full array of measures that can be employed to support coastal resilience and risk reduction (U.S. Army Corps of Engineers (USACE) 2013). By definition, natural features are created and evolve over time through the actions of physical, biological, geologic, and chemical processes operating in nature. Natural coastal features take a variety of forms, including reefs (e.g., coral and oyster), barrier islands, dunes, beaches, wetlands, and maritime forests. The relationships and interactions among the natural and built features comprising the coastal system are important variables determining coastal vulnerability, reliability, risk, and resilience. Conversely, nature-based features are those that may mimic characteristics of natural features, but are created by human design, engineering, and construction to provide specific services such as coastal risk reduction. The built components of the system include nature-based and other structures that support a range of objectives, including erosion control and storm risk reduction (e.g., seawalls, levees), as well as infrastructure providing economic and social functions (e.g., navigation channels, ports, harbors, residential housing). An integrated approach to coastal resilience and risk reduction will employ the full array of measures, in combination, to support coastal systems and communities. In order to pursue an integrated approach to coastal resilience, the North Atlantic Coast Comprehensive Study (NACCS) formed a team to develop a framework for identifying and evaluating opportunities for integrating natural and nature-based features (NNBF) (USACE 2015).

NNBF can be used to enhance the resilience of coastal areas threatened by sea level rise and coastal storms. For example, beaches are natural features that can provide coastal storm risk reduction and resilience where their sloping nearshore bottom causes waves to break—dissipating wave energy over the surf zone. Dunes that back a beach can act as physical barriers that reduce inundation and wave attack to the coast landward of the dune. Coastal wetlands can attenuate waves and stabilize sediments, thereby providing coastal storm protection.

Nature-based features are acted upon by processes operating in nature, and as a result, generally must be maintained by human intervention to

provide the functions and services for which they were built. Coastal systems are naturally dynamic, and NNBF respond in many ways to storms—with some responses being temporary and others permanent. Storm effects on wetlands often include erosion, stripped vegetation, and salinity burn—all of which can decrease long-term productivity. Storms, however, also introduce mineral sediments that contribute to long-term sustainability with respect to sea level rise.

In addition to providing engineering functions related to reducing risks from coastal storms, NNBF can provide a range of additional ecosystem services, including those supporting coastal ecosystems and communities. A true systems approach to coastal risk reduction and resilience requires consideration of the full range of functions, services, and benefits produced by coastal projects and NNBF. These include benefits related to commercial and recreational fisheries, tourism, provisioning of clean water, habitat for threatened, endangered, and sensitive species (TES), and support for cultural practices. Developing a more complete understanding of the ecosystem goods and services provided by the full range of coastal features, individually and in combination, will help to inform plan formulation and benefit determination for risk reduction strategies.

Knowledge about the performance of natural, nature-based, nonstructural, and structural features varies, as do the methods to calculate and measure performance. The dynamic behavior and response of NNBF to threats such as coastal storms and development can affect their performance with respect to system-level risk reduction and resiliency objectives. Moreover, it is important to design nature-based features in such a way that they will establish and/or re-establish natural processes and become as self-sustaining as possible. Federal investment in the use of NNBF intended to provide ecosystem goods and services, including coastal risk reduction and resiliency, should be based upon solid scientific and engineering evidence about the function and performance of these features. As with structural measures, some nature-based features will require routine maintenance and these costs should be factored into analyses.

## Purpose of this study

The purpose of this study was to fill knowledge gaps and produce relevant information to support the identification, evaluation and integration of NNBF with structural and non-nonstructural measures in order to support coastal risk reduction and resilience. Developing a comprehensive framework was viewed as an important next step in coordinating the advancement of NNBF among the many organizations and stakeholders engaged in the management of coastal systems. The framework includes a range of activities relevant to the use of NBF and is divided into three categories of activities: Organizational Alignment, Evaluation and Implementation. Steps in the framework are enumerated here and briefly described below:

1. Classifying, mapping, and characterizing NNBF
2. Developing vulnerability metrics
3. Developing performance metrics
4. Assessing and ranking proposed alternatives
5. Considering sediment as a resource for NNBF
6. Monitoring and assessing NNBF to support adaptive management
7. Considering policy challenges and implications.

## Classification, mapping, and feature characterization

A classification system was developed for NNBF that applies two existing systems that are widely used both nationally and internationally. The first is a geomorphologic classification system of coastline types based on Shepard (1973), and illustrated in the Coastal Engineering Manual (USACE 2002). For each of the geomorphologic classes present within the study area, one or more profiles were generated to illustrate the typical arrangement of geomorphic features, including those potentially identified as NNBF. The profiles can be used to illustrate the types of NNBF that could be expected to occur or be used in the landscape, as well as how combinations of multiple features could be applied to increase the level of coastal protection afforded. Geomorphic features typical of each coast type are described in detail. Many features are coincident and/or provide similar functions in the landscape and are described together. The driving processes that describe each feature are identified; information on processes is detailed separately to avoid repetition. These processes (e.g., wave attack, erosion, sediment transport, changes in sea level, glaciation) also continue to act on and shape NNBF in the coastal environment. Understanding these processes will be important to engineers and scientists involved in the design and construction of NNBF. Morphological and physical attributes of each feature type are tabulated for each coast type.

The approach applied to NNBF is the U.S. National Vegetation Classification (USNVC) (Grossman 1998). This system delivers a comprehensive single-factor approach to hierarchical classification of ecological communities based on vegetation. A major advantage of this system is that geospatial mapping layers are available for the study area, and detailed descriptions of the plant communities are available for each State through the State Natural Heritage programs. The detailed descriptions of the plant community associations can be used in a variety of ways. For example, knowledge of the species composition and structural characteristics of the vegetation can be used to estimate the degree of surface roughness and impedance to the flow of water during storm events. The descriptions of the species associations can also be used as a planting guide to select the most appropriate suite of plant species for the NNBF under consideration. Mapping layers of the vegetation classes can also be used to identify NNBF characteristics in relation to conservation and preservation goals.

## Approach for developing coastal vulnerability metrics

Coastal areas of the U.S. are threatened by erosion and damage due to storm waves, wind, and surge. Evaluation of the role of NNBF, in the context of coastal zone management and storm damage risk reduction, requires the assessment of vulnerability in natural and human environments. Vulnerability is conceptualized in many different ways and depends on the scientific background of those assessing vulnerability. Here is defined an approach to assessing vulnerabilities in order to identify beneficial applications of NNBF.

A comparison was made of previous approaches to assessing vulnerability, which demonstrated the subjective nature of developing vulnerability metrics. The various approaches differ in how vulnerability is measured as they depend on the purpose of the vulnerability assessment, the spatial and temporal scale for which the assessment is being conducted, the specific coastal characteristics for the area of interest, and data availability. Metrics can be both quantitative and qualitative. While qualitative metrics are non-numerical, they may still reflect measurable characteristics such as the relative resistance of a given landform to erosion. Comprehensive approaches recognize that overall vulnerability is determined by physical coastal characteristics (e.g., geology, elevation), coastal forcing (e.g., tide range, wave height, storm frequency), and socioeconomic characteristics (e.g., population, cultural heritage, land use). Finally, it is also recognized that assessment of vulnerability can be improved through process parameterization or modeling.

Vulnerability is a function of the hazard to which a system is exposed, the sensitivity of the system to the hazard, and the system's adaptive capacity. A satisfactory conceptual approach for identifying and defining meaningful metrics must consider all three of these components to be complete. The approach that was developed was designed to ensure a set of metrics is developed for a complete assessment of vulnerability for a wide range of systems and hazards at multiple scales, with specific emphasis on NNBF.

Metrics for application in assessing vulnerability for multiple coastal landscapes are developed. The vulnerability of anything on the landscape is directly linked to natural coastal landscape and NNBF vulnerability. The metrics developed are specifically intended for assessing relative vulnerability of coastal landscapes along the northern Atlantic coast, understanding how NNBF influence vulnerability of a coastal landscape, and understanding vulnerability of specific NNBF. The metrics presented are not all of equal importance, nor are they mutually exclusive. The actual selection of metrics to apply for a given vulnerability assessment will depend on many factors, most notably the purpose and scale of the vulnerability assessment and data availability.

## Performance metrics for ecosystem goods and services generated by NNBF

Identifying appropriate and effective applications of NNBF will be guided by the benefits and services these features can provide. A comprehensive set of relevant performance metrics for NNBF was developed, expressed in terms of ecosystem goods and services, that can be used to characterize (either qualitatively or quantitatively) the benefits generated by these features. Twenty-one ecosystem-based goods and services were developed along with 72 quantitative performance metrics that capture a full suite of social, environmental, and economic benefits generated by 30 NNBF and structural features, implemented individually and in combination, to promote flood risk reduction and improve ecosystem resilience. A general methodology was developed to qualitatively analyze these services for NNBF applications.

Each NNBF (e.g., dune-swale complex) was decomposed into its critical components (i.e., physical characteristics such as soils and vegetative properties), and the ecosystem functions and processes associated with these components were linked through causal pathways to the goods or services the feature would provide (e.g., aesthetics, habitat provisioning, wave-attack reduction). From there, benefits were derived (e.g., scenic beauty, TES protection, flood risk reduction) and a metric for each line of evidence was developed (e.g., vegetative cover visible to local community, habitat suitability indices, and flood-prone-area reduction).

Three methodologies were developed to analyze ecosystem goods and services for NNBF applications. A matrix was developed aligning NNBF with the various services they provide, and a qualitative ranking system was produced to elicit stakeholder preferences with regards to NNBF applications. A second, semi-quantitative method was developed to expose lines of evidence linking features to benefits through causal pathways. This approach can be operationalized in the future using scientific evidence and quantifications to measure recovery plan performance with respect to NNBF inputs. The third approach focused on the development of quantifiable metrics using readily available geographic information system (GIS)-based data to characterize landscape-level performance of NNBF using a variety of geoprocessing techniques documented in the relevant scientific literature. In addition, a Benefit Transfer Table was developed using literature-based values in order to provide an alternative means for characterizing the goods and services in a quantitative fashion.

## Framework for assessing and ranking NNBF alternatives

A flexible, tiered evaluation framework was developed for analyzing the contribution of NNBF to system resilience, while accounting for other services generated by NNBF. The framework uses a structured decision-making process, performance metrics, and available data to guide the identification of appropriate applications of NNBF. The tiers of analysis, beginning with evaluation based on expert elicitation, will progress through stages employing greater levels of quantitative and engineering analysis. Each successive tier is more quantitative (to resolve uncertainties) and can build on previous tiers. The framework is compatible with alternative screening, prioritization, and benefit and cost analyses, depending on the tier. The framework includes how to use stakeholder preferences, how consequence tables can be derived consistently across the tiers, and the inherent characteristics that make the framework suitably appropriate and flexible. The evaluation framework includes processes for engaging stakeholder preferences regarding objectives in order to explore trade-offs among alternative configurations and uses of NNBF. The framework can be used to assess NNBF in a categorical fashion, as specific projects, or as groups of projects reflecting a particular alternative. NNBF alternatives, alone or in combination with structural features, are evaluated against an explicit set of the performance metrics. Performance may be determined using the expert opinion (in the first tier of analysis) or through application of detailed modeling and technical analyses (in subsequent tiers of analysis), or through a combination of inputs. Thus, the framework can be implemented, initially, with limited information and can be progressively applied through stages employing greater levels of quantitative and engineering analysis. A narrative describing how the approach applies, how to use stakeholder preferences and how the consequence tables can be derived at each of three tiers, and the inherent characteristics that make the framework suitably appropriate and flexible is presented using several examples.

## Regional sediment management (RSM) to support NNBF

A life-cycle RSM strategy for placing dredged sediments beneficially in the study area was developed to support and sustain the use and value of NNBF. The intent was to have a means for comprehensively developing dredging and placement options in a technically appropriate and consistent manner in the context of stakeholder objectives. Relevant information and input was gathered from subject matter experts (SME) in the field of dredging and sediment management. A case-study application was developed using data and information from Long Island Sound (LIS).

Beneficial use of dredged material has been a long-established practice within the study region. In the context of this practice, the developed strategy defines and distinguishes practices related to strategic placement of sediment, natural systems approaches, and Engineering with Nature (EWN). The results of a detailed literature review served as the basis for identifying and inventorying past best practices, underpinning technical information, and using evaluation tools to support the development of a Screening Methodology for Strategic Placement (SMSP). Field site visits to the region were used to gain firsthand information about current practices and to engage SME on dredging operational practices.

The initial phase of the SMSP methodology concerns the identification of NNBF opportunities, which includes

- identification of coastal geomorphic landscape features
- condition assessment of features

- assessment of the benefit of dredged sediment applicability
- identification of dredging/placement techniques compatible with the settings.

Next, navigation channel Operations and Maintenance (O&M) sediment sources were estimated. This involved forecasting shoaling and dredging requirements, assessing the properties of materials to be dredged, and identifying dredging/placement techniques compatible with dredged sediments. With the foregoing information sets prepared, technically defensible options were inventoried for sediment source matching with beneficial use placement opportunities. A dredging/placement technique library was created and was related to forecasts of dredging/sediment placement activities in order to identify compatibilities.

A case-study application of the SMSP was developed for Long Island Sound (LIS) in order to produce an example of strategic placement designs and costs for sediments that are forecasted to be dredged. In a separate effort, stakeholders engaged through the New England District of USACE had collaborated to define a set of problems, needs, and opportunities for dredged-material management in the region. Through this engagement, performance objectives, constraints, driving scenarios, and potential dredged-sediment management measures were summarized to inform the demonstration.

Optimization of dredged-sediment management options with respect to life-cycle performance and cost was analyzed using an existing USACE modeling tool (D2M2[1]). Using existing data and following the themes of the prior stakeholder preference elicitation, this tool was used to perform a trade-off analysis. The LIS case-study application of the SMSP was developed to provide a template for scoping comprehensive analyses that could be performed over the entire study area. Key elements along the path to wider application of the SMPS include

- *bench-scale* testing the methodology for engaging stakeholders to identify dredged-sediment sources and placement options at multiple locations in the Study Area
- critically reviewing bench-scale testing of the engagement methodology
- refining the method based on critical review

[1] http://el.erdc.usace.army.mil/dots/models.html

- applying refined method for the entire NACCS study area.

## Ecosystem service benefits of existing NNBF–A Hurricane Sandy case study

An evaluation of ecosystem goods and services (EGS) produced by three coastal ecosystem restoration sites (Jamaica Bay, NY; Cape May Meadows, NJ; and Cape Charles, VA) within the study area was performed. The sites were distributed to provide geographic coverage of the study area; the sites also differed in terms of their objectives and construction details. To examine performance during extreme events, when some benefits of coastal ecosystem restoration would be expected to be at their peak, outcomes in restored and un-restored areas during Hurricane Sandy were compared. For all analyses, available data was used, including data that had been collected to document Hurricane Sandy impacts. The results of the evaluation indicate that the benefits provided by these projects were moderate to substantial in nature, particularly in terms of beneficial effects on rare species habitats and property value enhancements. The results of the evaluations indicate that with relatively cost-effective analysis methods, the changes in ecosystem goods and services as a result of ecological restoration projects can be quantified in terms that are meaningful to the public. Further, some of those changes could be translated into social values using damage costs avoided and benefit-transfer methods. The case-study evaluations allowed the identification of opportunities for improving and strengthening monitoring and performance evaluation of NNBF.

## Institutional barriers and opportunities related to NNBF

Advancing practice related to NNBF will involve making changes to institutional practices across Federal, State, and local government levels, as well as other organizations. In order to inform the efforts of the NACCS, a workshop was conducted with the purpose of assessing the policy challenges that exist that may impair the implementation and use of NNBF to create coastal resilience and reduce coastal risk. Specifically, the identification of the policy challenges that exist within and among Federal agencies that have a role in the implementation of these features was sought. Thirty-four individuals from the Bureau of Ocean Energy Management, CDM Smith, the Department of Homeland Security (DHS), the USACE, the U.S. Environmental Protection Agency (USEPA), the U.S. Fish and Wildlife Service (USFWS), the U.S. Forest Service (USFS), the U.S. Geological Survey (USGS), HR Wallingford, the National Park Service (NPS), the

National Ocean and Atmospheric Administration (NOAA), the National Wildlife Federation (NWF), and the Water Institute of the Gulf participated in the workshop.

Several opportunities for addressing the challenges were identified and categorized as follows:

- Science, Engineering, and Technology
    - Create NNBF demonstration projects to learn the best practices and uses of NNBF.
    - Generate a compilation of information on the ecosystem goods and services provided by NNBF.
    - Develop risk and resiliency performance metrics for NNBF.
    - Initiate a wiki-type repository of knowledge adjacent to a data portal that could include contact information of people involved in NNBF efforts in different organizations and agencies.
- Leadership and Institutional Coordination
    - Improve regional coordination through existing mechanisms such as Silver Jackets, NOAA's Sea Grant, and U.S. Department of Agriculture (USDA) extension offices.
    - Utilize public/private partnerships to implement NNBF.
    - Initiate the development of guidance and policies to achieve robust coordination and data sharing among resource and planning agencies.
    - Incorporate NNBF into existing decision support and communication tools.
    - Leverage partnerships and funding to promote NNBF in support of community resilience.
    - Develop a guidebook with information on NNBF that could be implemented during the recovery process following a disaster.
- Communication and Outreach
    - Develop a policy digest with relevant definitions of NNBF, as well as the authorities, roles, and responsibilities of Federal, State, and local agencies that have jurisdiction or interest in the implementation of NNBF.
    - Form an NNBF community-of-practice.

## Looking forward

U.S. coastlines provide social, economic, and ecological benefits to the nation, but are especially vulnerable to risks from the combination of changing climate and geological processes and continued urbanization and economic investment. NNBF can help reduce coastal risks as a part of an integrated approach that draws together the full array of coastal features that contribute to enhancing coastal resilience. By employing sound science and engineering practices, collaborating organizations will be able to identify timely opportunities, formulate and evaluate robust alternatives, and implement feasible approaches for making use of NNBF to enhance the resilience of social, economic, and ecological systems in coastal environments.

# Unit Conversion Factors

| Multiply | By | To Obtain |
|---|---|---|
| acres | 4,046.873 | square meters |
| cubic yards | 0.7645549 | cubic meters |
| feet | 0.3048 | meters |
| hectares | 1.0 E+04 | square meters |
| horsepower (550 foot-pounds force per second) | 745.6999 | watts |
| inches | 0.0254 | meters |
| miles (U.S. statute) | 1,609.347 | meters |
| miles per hour | 0.44704 | meters per second |
| square miles | 2.589998 E+06 | square meters |

# Acronyms

| | |
|---|---|
| ADCIRC | ADvanced CIRCulation Model |
| ASCE | American Society of Civil Engineers |
| AZGF | Arizona Game and Fish Department |
| BoR | Bureau of Reclammation |
| BUDM | Beneficial Use of Dredged Materials |
| CAP | NOAA's Coastal Change Analysis Program |
| CARRI | Community and Regional Resilience Institute |
| CDM | Commander |
| CELCP | Coastal and Estuarine Land Conservation Program |
| CERB | Coastal Engineering Research Board |
| CF | Critical Facilities |
| CI | Critical Infrastructure |
| CO-OPs | NOAA's Center for Operational and Oceanographic Products and Services |
| CPI | Consumer Price Index |
| CRM | Community Resilience Metric |
| CRS | Community Rating System Program |
| CRSB | Conceptual Regional Sediment Budget |
| CSTORM-MS | Coastal Storm Modeling System |
| CVI | Coastal Vulnerability Index |
| CWCCIS | Civil Works Construction Cost Index System |
| D2M2 | Dredged material Management Decisions Model |
| DHS | U.S. Department of Homeland Security |
| DIS | Dredging Information System |
| DMMP | Dredged Materials Management Plan |
| DOER | Dredging Operations and Environmental Research Programs |

| | |
|---|---|
| DSAS | Digital Shoreline Analysis System |
| EA | Environmental Assessment |
| EAA | European Environment Agency |
| EGS | Ecosystem Goods and Services |
| ERDC | U.S. Army Engineer Research and Development Center (CEERD) |
| ESI | NOAA'S Environmental Sensitivity Index |
| ESMF | Earth System Modeling Framework |
| EWN | Engineering With Nature |
| FEMA | Federal Emergency Management Agency |
| FIFM-TF | Federal Interagency Floodplain Management Task Force |
| GAP | USGS Gap Analysis Program |
| GHG | Greenhouse Gases |
| GEV | Generalized Extreme Value |
| GIS | Geographic Information Systems |
| GNRA | Gateway National Recreation Area |
| HUC | Hydrologic Unit Code |
| HUD | U.S. Department of Housing and Urban Development |
| INA | International Navigation Association |
| IPCC | Intergovernmental Panel on Climate Change |
| IWR | U.S. Army Engineers, Institute of Water Resources (CEIWR) |
| JALBTCX | Joint Airborne Lidar Bathymetry Technical Center of Expertise |
| LIS | Long Island Sound |
| MASGC | Mississippi-Alabama Sea Grant Consortium |
| MHHW | Mean Higher High Water |
| MOA | Memorandum of Agreement |
| MOU | Memorandum of Understanding |

| | |
|---|---|
| MRLC | Multi-Resource Land Characteristics Consortium |
| MSL | Mean Sea Level |
| MSPA | Morphological Spatial Pattern Analysis |
| NACCS | North Atlantic Coast Comprehensive Study |
| NCMP | National Coastal Mapping Program |
| NDBC | National Data Buoy Center |
| NFIP | National Flood Insurance Program |
| NGO | Non-Governmental Organization |
| NJOCM | NJ Office of Coastal Management |
| NLCD | National Land Cover Dataset |
| NNBF | Natural and Nature-based Features |
| NOAA | National Oceanic and Atmospheric Administration |
| NPP | Net Primary Productivity |
| NPS | National Park Service |
| NSRE | National Survey on Recreation and the Environment |
| NVC | National Vegetation Classification |
| NWI | National Wetlands Inventory |
| O&M | Operation and Maintenance |
| PCA | Principle Components Analysis |
| PDT | Project Delivery Team |
| PIANC | Permanent International Association of Navigation Congresses |
| PWDCA | Priority Wildlife Diversity Conservation Areas |
| RG | Recovery Goal |
| RSM | Regional Sediment Management |
| SAME | Society of Military Engineers |
| SBAS | Sediment Budget Analysis System |
| SEDMAN | Sediment Management Technologies |
| SH | Stakeholder |
| SME | Subject Matter Experts |

| | |
|---|---|
| SMSP | Screening Methodology for Strategic Placement |
| STWAVE | Steady-state Spectral Wave Model |
| SWAP | NY State Wildlife Action Plan |
| SWReGAP | Southwest Regional Gap Analysis Project |
| TES | Threatened, Endangered, and Sensitive Species |
| TNC | The Nature Conservancy |
| USACE | U.S. Army Corps of Engineers |
| USBLS | U.S. Bureau of Labor Statistics |
| USDA | U.S. Department of Agriculture |
| USEPA | U.S. Environmental Protection Agency |
| USFWS | U.S. Fish and Wildlife Service |
| USGS | U.S. Geological Survey |
| USNVC | U.S. National Vegetation Classification |
| VEVA | Coastal Virginia Ecological Value Assessment |
| VDGIF | Virginia Department of Game and Inland Fisheries |
| WAM | WAve Prediction Model |
| WAPA | Western Area Power Administration |
| WIS | Wave Information Studies |

# 1 An Introduction to Natural and Nature-Based Features (NNBF) and Their Use in Coastal Systems

## Overview

Coastal systems are increasingly vulnerable to flooding due to the combined influence of coastal storms, development and population growth, geomorphic change, and sea level rise (Woodruff et al. 2013). This reality has given rise to efforts to make greater use of ecosystem-based approaches to reduce risks from coastal storms, approaches which draw from the capacity of wetlands, beaches and dunes, biogenic reefs, and other natural features to reduce the impacts of storm surge and waves (Temmerman et al. 2013). While the potential to apply ecosystem-based approaches to flood risk management will depend on the physical, geomorphological, and ecological context, examples of the importance and application of such approaches are increasing worldwide (Temmerman et al. 2013).

Concepts and practices supporting today's notion of NNBF have deep roots in the green infrastructure movement. This movement arose from environmental planning and conservation initiatives that go back over 160 years (yr), originating from the efforts of Frederick Law Olmsted, Warren Manning, and Eugene Odum, which were based on the realization that natural systems can deliver a range of ecosystem goods and services (Benedict and McMahon 2002, 2006; Ely and Pitman 2012). The range of activities captured by the term green infrastructure is based on the context of the problem, opportunity or objectives under consideration. For some, green infrastructure refers to open spaces or parks (Davies et al. 2006; Mell 2010; Mell et al. 2009); for others, it refers to engineered structures (e.g., storm water management features such as rain gardens[1]) that are defined as environmentally friendly; still other practitioners allude to the preservation of natural area networks (e.g., wetlands lined with riparian corridors) emphasizing the benefits of biodiversity and reductions in habitat fragmentation (Lafortezza et al. 2013; Wickham et al. 2010; Williamson 2003). In the context of the NACCS, green infrastructure is taking on a more coastal aspect (Edwards et al. 2013) focusing on coastal

[1] http://water.epa.gov/infrastructure/greeninfrastructure/index.cfm#tabs-1

and nearshore landscape elements (e.g., dunes, barrier islands) that provide the physical matrix that reduces flood damages and promotes resilience in the face of coastal hazards and threats of sea level rise. As such, the focus has turned toward the following definitions:

**Natural Features** are created and evolve over time through the actions of physical, biological, geologic, and chemical processes operating in nature. Natural coastal features take a variety of forms, including reefs (e.g., coral and oyster), barrier islands, dunes, beaches, wetlands, and maritime forests. The relationships and interactions among the natural and built features comprising the coastal system are important variables determining coastal vulnerability, reliability, risk, and resilience.

**Nature-Based Features** are those that may mimic characteristics of natural features but are created by human design, engineering, and construction to provide specific services such as coastal risk reduction. The combination of both natural and nature-based features is referred to collectively as NNBF.

The **built components** of the system include nature-based and other structures that support a range of objectives, including erosion control and storm risk reduction (e.g., seawalls, levees), as well as infrastructure providing economic and social functions (e.g., navigation channels, ports, harbors, residential housing).

The spectrum of relevant NNBF ranges from existing natural features (e.g., barrier islands, sand dunes, wetlands) to features that are the product of planning, engineering design and construction (e.g., a constructed wetland or a beach-and-dune system engineered for coastal storm damage reduction). In the context of the NACCS, the contribution of NNBF to engineering functions in the form of contributions to coastal resilience and storm risk reduction are a particular focus (USACE 2015).

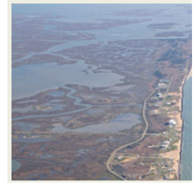
Natural, nature-based, nonstructural, and structural are thus terms used to describe the full array of measures that can be employed to support coastal resilience and risk reduction (USACE 2013). Coastal systems include naturally occurring and built features in a socioeconomic context (McNamara et al. 2011). Natural coastal features take a variety of forms, including reefs (e.g., coral and oyster), barrier islands, dunes, beaches, wetlands, and maritime forests. NNBF can exist due exclusively to the work of natural processes or can be the result of human engineering and construction. The built components of coastal systems can include both nature-based and engineered structures that support a range of objectives, including erosion control and storm risk reduction (e.g., seawalls, levees), as well as infrastructure providing economic and social functions (e.g., navigation channels, ports, harbors, residential housing). The relationships and interactions among the natural and built features comprising the coastal system are important variables determining coastal vulnerability, risk, and resilience. Table 1 and Table 2 provide examples of natural and nature-based versus nonstructural and structural features relevant to coastal systems respectively, along with a listing of factors affecting the performance of these features. An integrated approach to coastal resilience and risk reduction will employ the full array of measures, in combination, to support coastal systems and communities.

The NNBF study was undertaken to fill knowledge gaps and produce relevant information to support the identification, evaluation and integration of NNBF with structural and non-nonstructural measures in order to support coastal risk reduction and resilience. Developing a comprehensive framework was viewed as an important next step in coordinating the advancement of NNBF among the many organizations and stakeholders engaged in the management of coastal systems.

Table 1. Examples of NNBF relevant to coastal systems (USACE 2013).

| NATURAL AND NATURE-BASED FEATURES AT A GLANCE | | | | |
|---|---|---|---|---|
|  |  |  |  |  |
| Dunes and Beaches | Vegetated Features (e.g., Marshes) | Oyster and Coral Reefs | Barrier Islands | Maritime Forests/Shrub Communities |
| **Benefits/Processes**<br>Breaking of offshore waves<br>Attenuation of wave energy<br>Slow inland water transfer | **Benefits/Processes**<br>Breaking of offshore waves<br>Attenuation of wave energy<br>Slow inland water transfer<br>Increased infiltration | **Benefits/Processes**<br>Breaking of offshore waves<br>Attenuation of wave energy<br>Slow inland water transfer | **Benefits/Processes**<br>Wave attenuation and/or dissipation<br>Sediment stabilization | **Benefits/Processes**<br>Wave attenuation and/or dissipation<br>Shoreline erosion stabilization<br>Soil retention |
| **Performance Factors**<br>Berm height and width<br>Beach slope<br>Sediment grain size and supply<br>Dune height, crest, and width<br>Presence of vegetation | **Performance Factors**<br>Marsh, wetland, or SAV elevation and continuity<br>Vegetation type and density<br>Spatial extent | **Performance Factors**<br>Reef width, elevation, and roughness | **Performance Factors**<br>Island elevation, length, and width<br>Land cover<br>Breach susceptibility<br>Proximity to mainland shore | **Performance Factors**<br>Vegetation height and density<br>Forest dimension<br>Sediment composition<br>Platform elevation |
| **General coastal risk reduction performance factors include:** Storm surge and wave height/period, and water levels | | | | |

Table 2. Examples of nonstructural and structural features relevant to coastal systems (USACE 2013).

| NONSTRUCTURAL | | | | STRUCTURAL | | | | |
|---|---|---|---|---|---|---|---|---|
|  |  |  |  |  |  |  |  |  |
| Floodplain Policy and Management | Flood-proofing and Impact Reduction | Flood Warning and Preparedness | Relocation | Levees | Storm Surge Barriers | Seawalls and Revetments | Groins | Detached Breakwaters |
| **Benefits and Processes**<br>Improved and controlled floodplain development<br>Reduced opportunity for damages<br>Improved natural coast environment | **Benefits and Processes**<br>Reduced opportunity for damages<br>Increased community resiliency<br>No increase in flood potential elsewhere | **Benefits and Processes**<br>Reduced opportunity for damages<br>Increased community resiliency<br>Improved public awareness and responsibility | **Benefits and Processes**<br>Reduced opportunity for damages<br>No increase in flood potential elsewhere<br>Improved natural coast environment | **Benefits and Processes**<br>Surge and wave attenuation and/or dissipation<br>Reduced flooding<br>Reduced risk for vulnerable areas | **Benefits and Processes**<br>Surge and wave attenuation<br>Reduced salinity Intrusion | **Benefits and Processes**<br>Reduced flooding<br>Reduced wave overtopping<br>Shoreline stabilization behind structure | **Benefits and Processes**<br>Shoreline stabilization | **Benefits and Processes**<br>Shoreline stabilization behind structure<br>Wave attenuation |
| **Performance Factors**<br>Wave height<br>Water level<br>Storm duration<br>Agency collaboration | **Performance Factors**<br>Wave height<br>Water level<br>Storm duration | **Performance Factors**<br>Wave height<br>Water level<br>Storm duration | **Performance Factors**<br>Wave height<br>Water level<br>Storm duration | **Performance Factors**<br>Levee height, crest width, and slope<br>Wave height and period<br>Water level | **Performance Factors**<br>Barrier height<br>Wave height<br>Wave period<br>Water level | **Performance Factors**<br>Wave height<br>Wave period<br>Water level<br>Scour protection | **Performance Factors**<br>Groin length, height, orientation, permeability, and spacing<br>Depth at seaward end<br>Wave height<br>Water level<br>Longshore transportation rates and distribution | **Performance Factors**<br>Breakwater height and width<br>Breakwater permeability, proximity to shoreline, orientation, and spacing |
| **General coastal risk reduction performance factors include:** Collaboration and shared responsibility framework, wave height, water level, and storm duration | | | | **General coastal risk reduction performance factors include:** Storm surge and wave height/period, and water levels | | | | |

### Natural and nature-based features (NNBF)

*Natural features* are created through the action of physical, geological, biological and chemical processes over time. *Nature-based features*, in contrast, are created by human design, engineering, and construction (in concert with natural processes) to provide specific services such as coastal risk reduction and other ecosystem services (e.g., habitat for fish and wildlife). Nature-based features are acted upon by processes operating in nature, and as a result, generally must be maintained by human intervention in order to sustain the functions and services for which they were built.

**Natural and Nature Based Features (NNBF) Considered in this Report**

- Islands
- Reefs
- Beaches (sand, gravel, cobble)
- Dunes / swale complex
- Mudflats / sandflat
- Submerged aquatic vegetation (seagrass, other - fresh or saline)
- Salt marshes (emergent herbaceous)
- Shrub-scrub wetlands (brackish)
- Flooded swamp forests (brackish)
- Bluffs (any material, if sand assume eroding dune)
- Maritime grasslands
- Maritime shrublands
- Maritime forests
- Riparian buffers
- Emergent herbaceous marshes/wetlands (fresh)
- Shrub-scrub wetlands (fresh)
- Flooded swamp forests (fresh)
- Ponds
- Terrestrial grasslands
- Terrestrial shrublands
- Terrestrial forests

*Natural and nature-based features* (NNBF) can be used to enhance the resilience of coastal areas threatened by sea level rise (Borsje et al. 2011) and coastal storms (e.g., Gedan et al. 2011; Lopez 2009). For example, beaches are natural features that can provide coastal storm risk reduction and resilience where their sloping nearshore bottom causes waves to break—dissipating wave energy over the surf zone. These breaking waves often form offshore bars that help to dissipate waves farther offshore. Dunes that back a beach can act as physical barriers that reduce inundation and wave attack to the coast landward of the dune. Although dunes may erode during a storm, they often provide a sediment source for beach recovery following storms.

Engineered beaches and dunes can provide functions that are similar to natural beaches and dunes and represent nature-based infrastructure specifically designed and maintained to provide coastal risk reduction. These nature-based features often require beach nourishment to mitigate ongoing erosion and other natural processes. Supplying sand to the system through beach nourishment, dune construction, and restoration reinforces risk reduction functions with respect to waves and storm surge.

Coastal wetlands can attenuate waves and stabilize sediments, thereby providing coastal storm protection. Dense vegetation and the shallow water within wetlands can slow storm surge advance somewhat and can reduce the surge landward of the wetland or slow its arrival time (Wamsley et al. 2009a, 2010). Wetlands can also dissipate wave energy, potentially reducing the amount of destructive wave energy propagating on top of the surge. The magnitude of these effects depends on the specific characteristics of the wetlands, including the type of vegetation, its rigidity and structure, and wetland extent and position relative to the storm track. Although wetlands can retard storm surge propagation, water can be redirected, potentially causing a local storm surge increase elsewhere. Engineered and constructed wetlands act in the same manner as natural wetlands, though design features may be included to enhance risk reduction or account for the adaptive capacity of the wetland considering future conditions (e.g., by allowing for migration due to changing sea levels).

In addition to providing engineering functions related to reducing risks from coastal storms, NNBF can provide a range of additional ecosystem services, including those supporting coastal ecosystems and communities. A true systems approach to coastal risk reduction and resilience requires consideration of the full range of functions, services, and benefits produced by coastal projects and NNBF. These include benefits related to commercial and recreational fisheries, tourism, provisioning of clean water, habitat for TES, and support for cultural practices. For example, breakwaters offer shoreline erosion protection by attenuating wave energy, but can provide additional recreational opportunities, valuable aquatic habitat, and carbon or nutrient sequestration. However, it is also important to recognize that there are interactions amongst features (i.e., structural, NNBF, and nonstructural) that could alter (either positively or negatively) the delivery of ecosystem goods and services. A systems approach to integrating these features intends to utilize positive interactions and minimize negative interactions.

Natural features such as coastal wetlands, forests, or oyster reefs provide environmental and social benefits, but can also contribute to coastal risk reduction or resilience, as previously discussed. Nature-based features such as engineered beaches and dunes, or ecosystem restoration projects involving coastal wetlands, forests, or oyster reefs, can provide a range of environmental and social benefits, including those related to coastal risk reduction. Combining NNBF with nonstructural measures may enhance the environmental and social benefits derived from these measures. The combination of these types of measures may reduce social vulnerability to changing sea levels and coastal storms, but some nonstructural actions can also allow for wetland migration over time or support increased benefits associated with recreation.

Developing a more complete understanding of the ecosystem goods and services provided by the full range of coastal features, individually and in combination, will help to inform plan formulation and benefit determination for risk reduction strategies. Some services are complementary, such as wetland restoration that increases habitat and wave attenuation, while others are conflicting, such as dune creation for risk reduction that competes with sightlines, raising viewshed concerns. As sea level rise and climate change influence the coastal environment, taking a comprehensive view of the services and benefits provided by an integrated combination of natural, nature-based, nonstructural, and structural features will provide important information for decision making that supports resilient coastal systems.

### Dynamic character of NNBF

Coastal systems are naturally dynamic and NNBF respond in many ways to storms—with some responses being temporary and others permanent. Storm effects on wetlands often include erosion, stripped vegetation, and salinity burn—all of which can decrease long-term productivity (Michener et al. 1997). However, storms can also introduce mineral sediments that contribute to the long-term sustainability of wetlands with respect to sea level rise. The long-term consequences for wetland systems from hurricanes depends on many factors, including pre-storm landscape structure (including wetland extent and relationship to other natural and built features), proximity of the wetland to a storm track, and the meteorological conditions that persist following a hurricane (e.g., salinity burn effects are reduced if high precipitation occurs during or after the storm). Storms, the greatest source of coastal change on barrier islands, can produce water surge and strong waves. Surging water and stronger waves can erode barrier island beaches, and if the surge is high enough, result in overwash, breaching, or back-bay flooding, thereby reducing the storm damage reduction function of the islands. Over longer time scales, projections of sea level rise show that low-lying areas such as wetlands and barrier islands presently seen as natural may require management and intervention if their ability to provide socially desired ecosystem services is to be retained.

### Performance with respect to objectives

Knowledge about the performance of natural, nature-based, nonstructural and structural features varies, as do the methods to calculate and measure the performance of these features. Factors contributing to this variation include the diversity of objectives at play, the threats under consideration (e.g., a particular range or frequency of coastal storms), and the technical information that is available for describing the relevant processes and functions. Applying a systems approach to coastal risk reduction necessitates a rigorous scientific and engineering analysis of the performance of all system components while planning, designing, constructing, operating, maintaining, and adaptively managing the features comprising the system.

The dynamic behavior and response of NNBF to threats such as coastal storms and development can affect their performance with respect to system-level risk reduction and resilience objectives. Moreover, it is important to design nature-based features in such a way that they will establish and/or re-establish natural processes and become as self-sustaining as possible. As a result, the coastal risk reduction and resilience services provided by these features will vary over space and time. For nature-based features such as engineered beaches and dunes, this variation can be addressed through effective planning and engineering to maintain the desired level of service. While some literature suggests that coastal features (e.g., wetlands and barrier islands) can reduce surge and waves, quantification of this performance has sometimes been based on limited data. This has resulted in widely varying characterizations of risk reduction benefits, from those based on anecdotal, qualitative, and quantitative information (Wamsley et al. 2009a). As a case in point, prior to Hurricane Katrina, the level of protection provided by wetlands had been empirically (but relatively simplistically) estimated with a simple rule-of-thumb. The actual ability of wetlands to provide protection from storms is complex and depends on many factors, including storm intensity, track, speed, and the surrounding local bathymetry and topography; simple rules-of-thumb may not take into account these complexities along a coastline and between storm events (Resio and Westerlink 2008). There are methods, however, for including these complexities and the interactions of storms with NNBF that make use of more quantitative analytical approaches (Suzuki et al. 2012; Yao et al. 2012; Anderson et al. 2011; Cialone et al. 2008).

### Engineering With Nature (EWN) using NNBF

The USACE initiative known as *Engineering With Nature* (EWN)[1] promotes coastal resilience and sustainable development by advancing technical and communication practices that intentionally align natural processes with engineering design to efficiently and sustainably deliver economic, environmental, and social benefits through collaborative processes (Bridges et al. 2014). The tools and projects developed through the EWN program support planning, engineering, and operational practices that beneficially integrate NNBF into traditional engineering design to produce more socially acceptable, economically viable, and environmentally sustainable solutions. EWN is being pursued through innovative research, field demonstrations, communicating lessons learned, and active engagement with field practitioners across a wide range of organizations and business lines. The program's intent is to develop practical methods that use an ecosystem-based approach to transform infrastructure development. By combining sound science and engineering with advanced communication practices, the EWN initiative is providing a robust foundation for collaborative project development using NNBF.

### The role of sound science and engineering

Investment in the use of NNBF intended to provide ecosystem goods and services, including coastal risk reduction and resilience, should be based upon the best available scientific and engineering evidence about the function and performance of these features. Uncertainties regarding the performance of NNBF, frequently related to a lack of empirical data, present challenges to using nature-based infrastructure to reduce coastal risks. These uncertainties should be acknowledged and taken into account when evaluating, planning, and implementing NNBF as a part of actions taken to enhance the resilience of coastal systems. The need to reduce the uncertainties associated with evaluating and quantifying the value and performance of NNBF should be addressed through the coordinated action of relevant public and private organizations. The development of consistent technical approaches for evaluating and integrating NNBF with

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[1] http://el.erdc.usae.army.mil/ewn/

structural and nonstructural approaches would help guide Federal and other investments in coastal systems.

In addition to the practical science and engineering of NNBF (including the economics supporting these efforts), the social sciences are necessary to develop a comprehensive understanding of actions that can be taken to support coastal community resilience (e.g., McNamara et al. 2011). This includes social (technological, institutional, and behavioral) responses (Kates et al. 2012) and potential legal issues that can affect the implementation of NNBF (Craig 2010). Integration across these disciplines would enable the development of comprehensive solutions that include NNBF and address the needs of the natural, social, and built environments. This form of technical integration would help inform investments in coastal systems that produce sustainable societal benefits and coastal risk reduction over the long term.

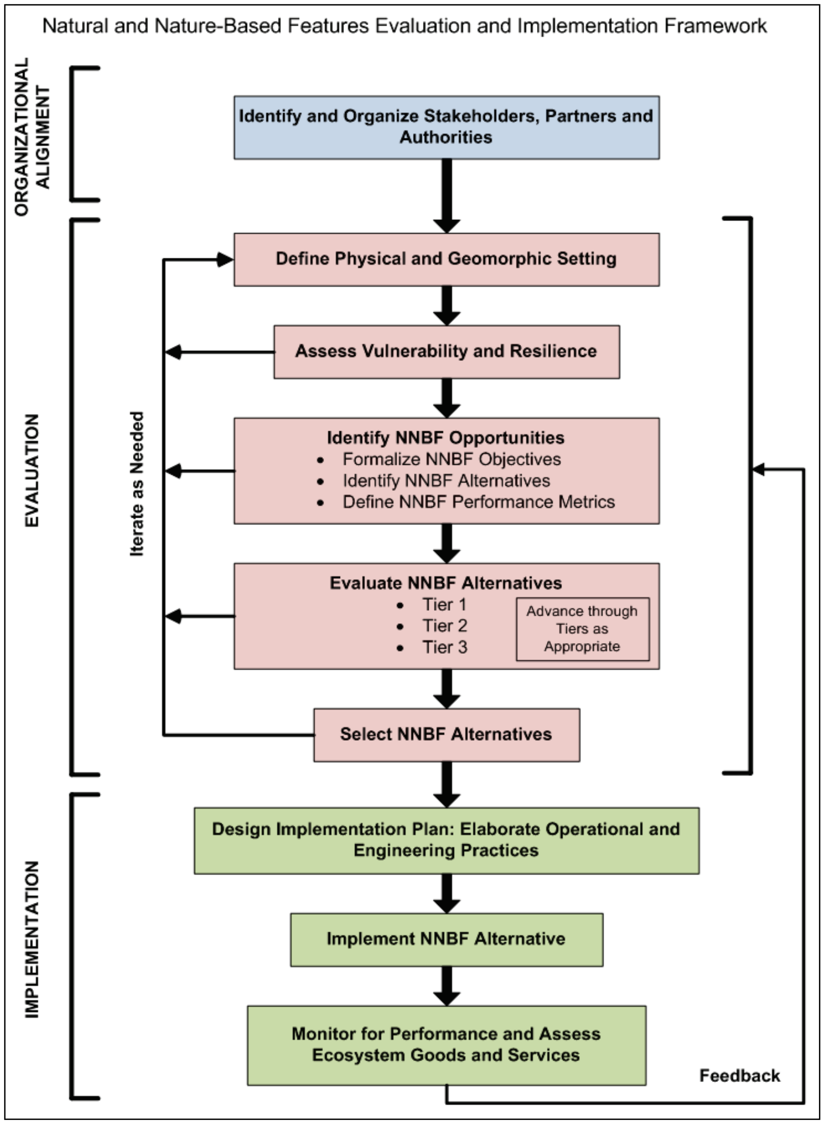
## A framework for NNBF evaluation and implementation

A framework was developed to support the evaluation and implementation of NNBF to achieve coastal risk reduction and resilience. Tools and methods for applying this framework are also being developed to support the application of the framework in the context of planning, designing, constructing, and evaluating NNBF within coastal systems. Chapters 2–7 of this document provide descriptions of the tools and methods under development.

Figure 1 provides a graphical depiction of the overarching framework. The framework includes a range of activities relevant to the use of NNBF and is divided into three categories of activities: Organizational Alignment, Evaluation, and Implementation.

One of the first steps to be undertaken in the process of identifying and analyzing NNBF opportunities is to align the organizations and interests relevant to a given geographic area, opportunity, or project. Projects employing NNBF are relevant to a diverse group of organizations and stakeholders. Public organizations have differing authorities relevant to NNBF. The interests of private organizations, including non-governmental organizations, in regard to NNBF include a broad range of objectives, from protecting private assets to securing specific environmental services. Identifying all the relevant authorities and interests germane to a given area or project and organizing communication about these authorities/interests is needed to appropriately frame the technical evaluation of NNBF.

Figure 1. NNBF evaluation implementation framework.



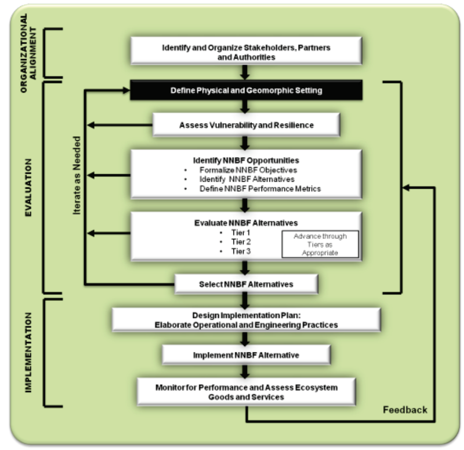

The Evaluation component of the framework defines the NNBF alternatives under consideration, develops the technical information about how those alternatives are expected to perform, and culminates in the selection of specific alternatives (Figure 1). As depicted, the Evaluation process is intended to be flexible and iterative in order to satisfy the information needs of decision making and the selection of alternatives for implementation. The major activities comprising the Evaluation component of the framework are supported by tools and methods described in the following sections of this document: define the physical and geomorphic setting (Chapter 2); assess vulnerability and resilience (Chapter 3); identify NNBF opportunities (Chapters 2 and 3); evaluate NNBF alternatives (Chapters 3–5); and select NNBF alternatives.

The Implementation of NNBF includes design of an implementation plan, implementing the plan/alternatives, and then monitoring the performance of the implemented NNBF. Designing an implementation plan involves a range of engineering activities, including those related to the management and use of sediment resources that are used to construct or support NNBF (Chapter 6). Chapter 7 of this document describes a case study analysis of ecosystem goods and services associated with three NNBF projects within the NACCS project area. The results of performance monitoring are a source of information and feedback for future evaluations of NNBF.

## Looking forward

Coastal systems provide important social, economic, and ecological benefits to the nation. However, our coasts are vulnerable to the influence of a combination of factors, including storms, changing climate, geological processes, and the pressures of ongoing development and urbanization. NNBF can help reduce coastal risks as a part of an integrated approach that draws together the full array of coastal features that contribute to enhancing coastal resilience. By employing sound science and engineering practices, collaborating organizations will be able to identify timely opportunities, formulate and evaluate robust alternatives, and implement feasible approaches for making use of NNBF to enhance the resilience of the social, economic, and ecological systems along our coasts.

# 2 NNBF Classification, Mapping, and Feature Characterization




## Overview

Two existing classification systems in wide use were selected for classifying and mapping NNBF within the study area. The first is a geomorphologic classification of coastlines based on Shepard (1973), and illustrated in the Coastal Engineering manual (USACE 2002). The formation and the long-term sustainability of NNBF are driven by their geomorphology and landscape position—the basis for the Shepard classification system. Profiles were generated to illustrate the generic arrangement of geomorphic features, including NNBF for each of the geomorphologic classes present within the study area. Not all features presented in these profiles may occur at any given location. Geomorphic features commonly found in each coast type and the driving processes that create, sustain, and impact the feature are described in detail.

Vegetation is often chosen as the basis for a single-factor system for classifying terrestrial ecological systems because it generally integrates the ecological processes operating on a site or landscape. Because patterns of vegetation and co-occurring plant species are easily measured, they have received far more attention than those of other components, such as fauna. Vegetation is a critical component of energy flow in ecosystems and provides habitat for many organisms in an ecological community. In addition, vegetation is often used to infer soil and climatic patterns. For these reasons, a classification based on vegetation can serve to describe many (though not all) facets of biological and ecological patterns across the landscape (Grossman 1998). The U.S. National Vegetation Classification (USNVC) (Grossman 1998) delivers a comprehensive, single-factor approach to ecological communities based on a hierarchical classification of vegetation. Geospatial mapping layers are available for the study area and descriptions of the plant communities are available through the State Natural Heritage programs (Table 6).

## How to use these classification systems

Coastlines are classified under Shepard (1973) based on the physical and geological processes responsible for the formation and present configuration of the coast. These processes (e.g., wave attack, erosion, sediment transport, sea level changes, glaciation) also continue to act on and shape both natural and manmade features in the coastal environment. Understanding these processes will be important to engineers and scientists for the design and construction of NNBF.

The Atlantic coast within the study area from Chesapeake Bay to central Maine is classified according to the Shepard (1973) system; generic cross-sectional profiles accompany each class description. The profiles can be used to illustrate the types of NNBF (both natural and anthropogenic) that could be expected to occur and their position in the landscape, as well as how combinations of multiple features could be applied to increase the level of coastal protection afforded. Features and the processes that control their form and function are described separately.

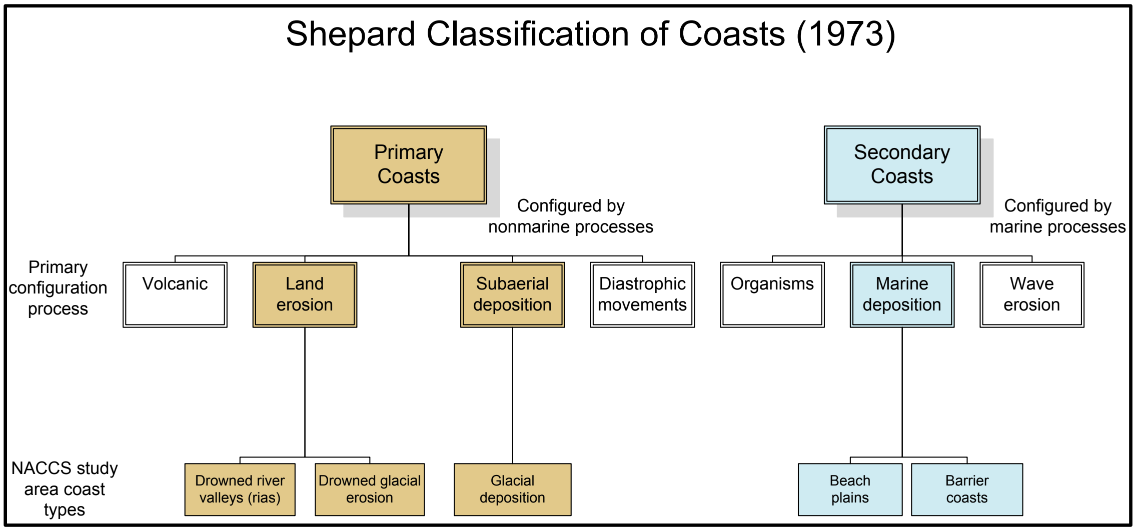
A detailed description of the plant communities in the NACCS study area has been compiled by the authors and is available upon request. The descriptions of the plant community associations can be used in a variety of ways. For example, knowledge of the species composition and structural characteristics of the vegetation could be used to estimate the degree of surface roughness and impedance to the flow of water. The descriptions of the species associations could also be used as a planting guide to select the most appropriate suite of plant species for coastal habitat restoration projects or identify areas vulnerable to salt burn. Mapping layers of the vegetation classes can also be used to identify areas of natural NNBF for conservation and preservation.

## Geomorphologic classification

### Background to coastal classification

The Shepard classification system (1937, 1948, 1973) divides the world's shores into primary coasts (formed mostly by non-marine agents) and secondary coasts (shaped primarily by marine processes). Further subdivisions occur according to which specific agent, terrestrial or marine, had the greatest influence on the coastal development. Although gradational shore types exist, which are difficult to classify, most coasts show only one dominant influence as the cause of their major characteristics (Shepard 1973) (Figure 2).

Figure 2. Shepard (1973) coastal classification hierarchy for the NACCS study area.




Some major beaches in the Northeast are artificial, but because they behave like sand beaches with respect to coastal processes and biological communities, they are classified as barrier or beach plain rather than artificial. For example, Coney Island once consisted of three low islands that were joined and augmented with massive amounts of beach fill (Farley 1923). Jones Beach was created by the Long Island Park commission in the 1930s by dredging 40 million cubic yards (CY) of sand from South Oyster Bay and placing it among and over a group of low islands (Caro 1974; Hanc 2007). Nourished beaches, which include most of the Atlantic shore of Long Island as well and the Jersey shore, are classified as barrier coasts or beach plains, not as artificial.

### Atlantic Coast classification from Chesapeake Bay to central Maine

The Atlantic coast of the northeastern United States is highly variable because of its geological history of Pleistocene glaciations and Holocene sea level changes. The region can be approximately divided at the mouth of New York Harbor. From New Jersey and southward, the Atlantic shore is a wave-dominated coast, where wave action shapes and modifies sand beaches and barrier spits. These extend for 10s or 100s of kilometers (km) and often enclose ponds or marshes. Sediments are almost totally derived from recycled continental shelf deposits or man-made deposition and can move by littoral transport for great distances or be entrained into tidal inlets. Rivers draining the Appalachians carry fine-grain sediment into estuaries (Chesapeake and Delaware Bays) or coastal ponds and marshes.

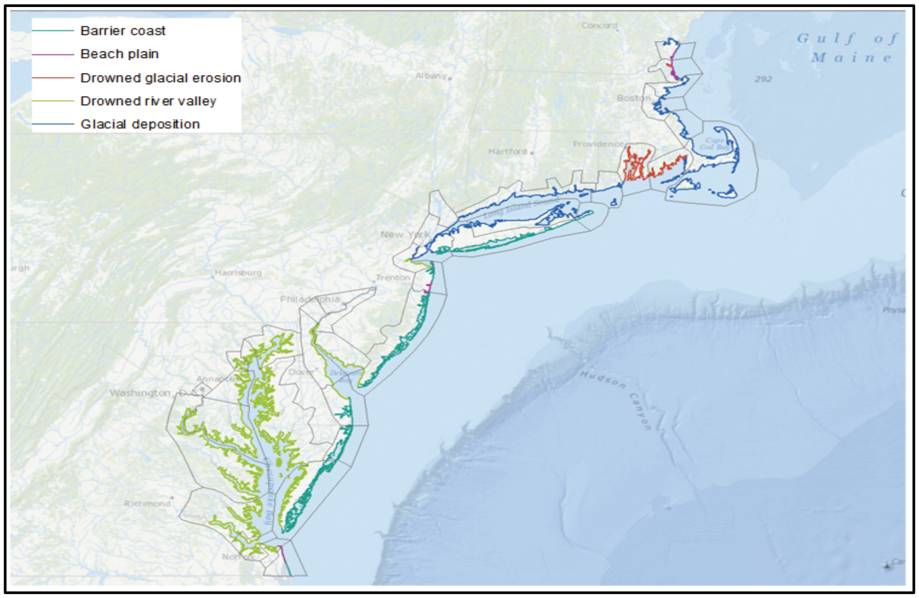
Less than 5% of river sediment reaching the coastal zone is deposited on the continental shelf (Meade 1982). From Long Island northward, the geology changes significantly. Long Island and New England are a complicated paraglacial geological terrain that retains extensive surface cover of easily erodible glaciogenic sediments, with end moraine islands, drowned glacial valleys, sand spits, salt marshes, and bedrock outcrops (Hein et al. 2012). Some of the complex coastal morphologies found in this region include

- barrier spits of southern Rhode Island, Cape Cod, Massachusetts Bay, Plum Island
- glacial till bluffs of Block Island, Nantucket Island, Martha's Vineyard, and islands in Boston Harbor
- Narragansett Bay, a drowned glacial valley with a combination of bedrock outcrops, till bluffs, limited sand and gravel beaches, and limited salt marshes.

Unlike the long barrier beaches of the mid-Atlantic, New England's beaches are much shorter and usually bounded with a topographic feature such as a headland or channel. The south shores of Long Island and Rhode Island west of Narragansett Bay have the closest resemblance to the common Atlantic beach model of sandy beach/spit/pond complex. Many New England spits, such as the ones on the south shore of Martha's Vineyard or southern Cape Cod, are the result of sediment derived from nearby eroding till bluffs. In much of Massachusetts, New Hampshire, and Maine, spits and beaches are more limited and often consist of pocket beaches with bounding bedrock headlands. Barriers typically average only 1 km in length (Duffy et al. 1989; Kelley 1987). The source of sand in these pocket beaches is a combination of locally derived material and minor input from rivers (Fitzgerald and Van Heteren 1999).

For this study, the local topography at the water/land interface has been used as the primary factor in the classification with a scale of approximately 5 km (Figure 3).

Figure 3. Coastal classification for the NACCS study area.




Coastal sediments in Connecticut were derived from glacial and early post-glacial sediments from within the Long Island Sound basin via storage, winnowing, and redistribution (Lewis and DiGiacomo-Cohen 2000). Northern New England is also different than the southern states in that this is the only area on the Atlantic seaboard where rivers bring sand directly to the open coast (FitzGerald et al. 2005). The coastal land forms within the study area can be classified with 5 of Shepard's (1973) categories and the addition of an Artificial category:

1. Drowned River Valley (I A 1): Chesapeake and Delaware Bays
2. Drowned Glacial Erosional Coast (I A 2): Narragansett Bay
3. Glacial Deposition Coast (I B 2): North shore of Long Island, Connecticut, portions of Massachusetts
4. Marine Depositional Barrier Coast (II B 1): Atlantic shores of Long Island, New Jersey, Delaware, Maryland
5. Marine Deposition-Beach Plain (II B 3): Sections in New Jersey, Massachusetts, New Hampshire
6. Artificial (III): Manhattan Island, Boston, Logan and Kennedy Airports.

One of the difficulties in applying a classification scheme to a complicated topography is deciding at what scale to apply different shore types. For example, the coast from Cape Cod to Boston Harbor is overall a drowned glacial deposition shore (I A 2), but within this zone, sand barrier (II B 2) extends from Scituate south to Plymouth and then from Sagmore (near the

Cape Cod Canal) west to Barnstable. The local topography determines how the shore responds to storms, its biological characteristics, and affects how local residents use the shore for recreation or residence.

To begin the characterization process, the team developed idealized cross-shore profiles for each of Shepherd's classes that occur within the region based on idealized topography, geomorphology, and commonly occurring vegetation communities. Given that this entire study area is highly developed, both NNBF and structural features have been included to illustrate how they might be distributed across the landscape on developed coastlines. An attempt was then made to locate example sites emulating these profiles to make a more direct connection between the classification and the on-the-ground features. The USACE Baltimore District (CENAB) then took this information and mapped the study area based on these classifications (refer to Appendix A). The following sections offer details for the profiles.

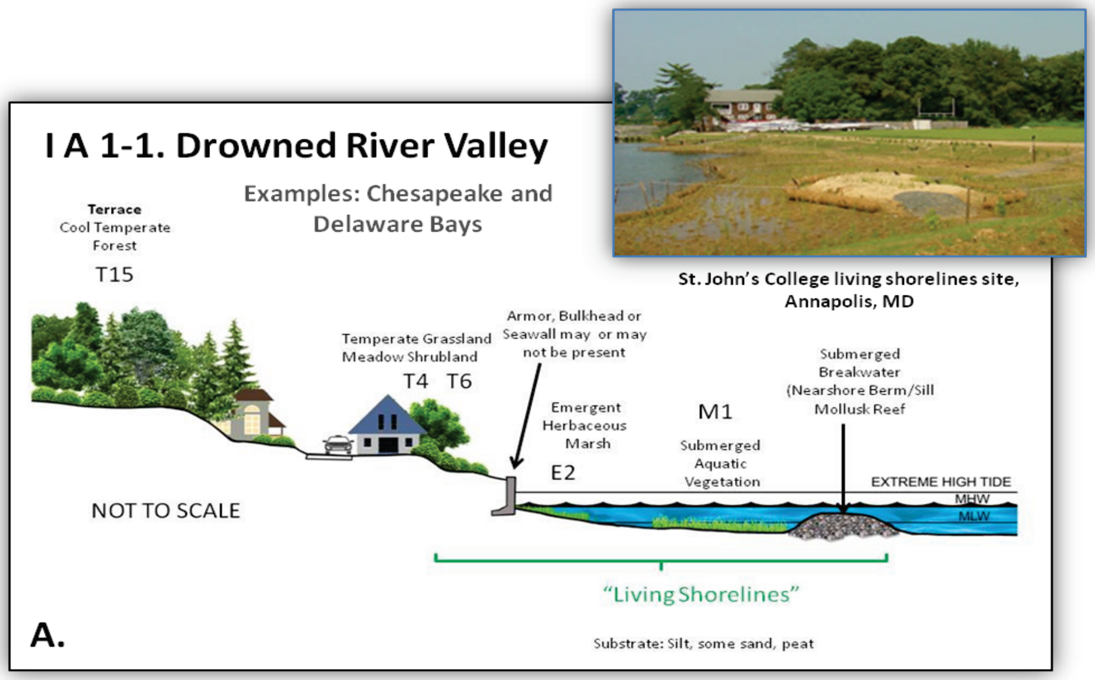
#### *I A 1 Drowned river valley*

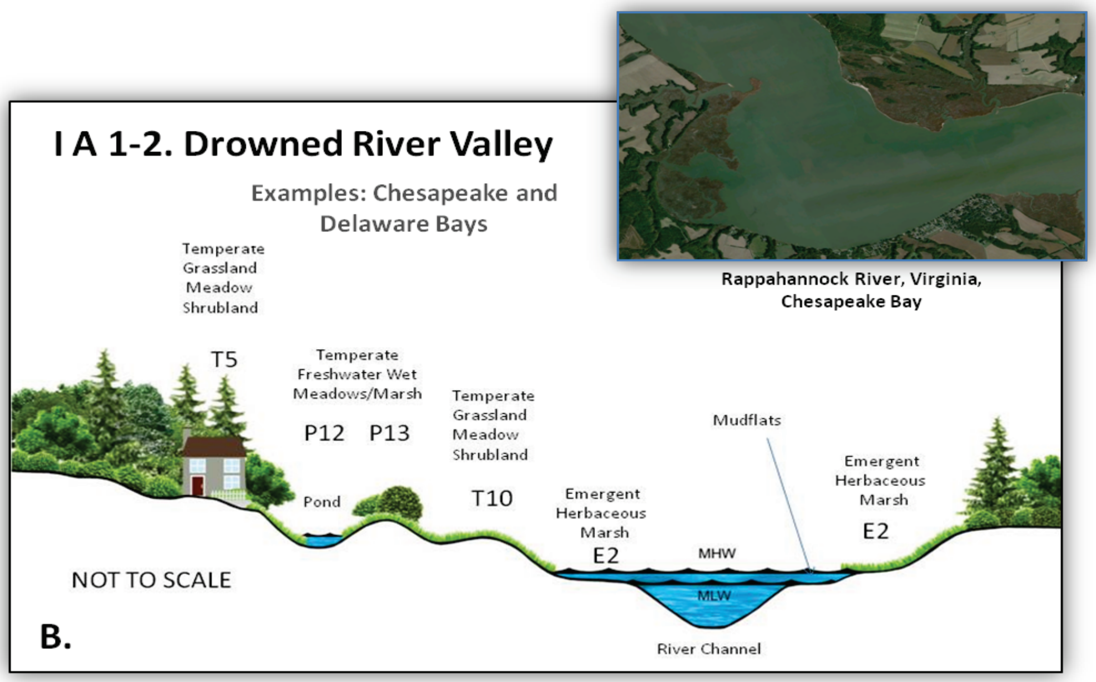
*General*. Conceptual cross-shore profiles of this class are shown in Figure 4. Chesapeake and Delaware Bays are the prominent examples in this study area. Most of the shores consist of low banks and bluffs (typically less than 10 meters (m) high), marshes, short sand spits, beaches fronting the mainland (without ponds or marshes behind). Bluffs sometimes have narrow beaches along the waterline. Extensive portions of the shorelines have been armored (Benoit et al. 2007).

Along the shores, sediment on beaches is derived locally from bluff degradation or from riverine supply. In the lower portions of the large estuaries (Chesapeake and Delaware Bays), sediment on the bay floors has been derived from the continental shelf and ocean beaches (Meade 1982). This, in turn, partially feeds beaches in the lower bays.

*Commonly Occurring NNBF.* Features that regularly contribute to coastal resilience that may occur along drowned river valley coasts are beaches, submersed aquatic vegetation beds, mollusk reefs, tidal flats, marsh platforms, tidal creeks, platforms and terraces, scarps, and possibly islands, both natural and constructed. These features are subsequently described in more detail.

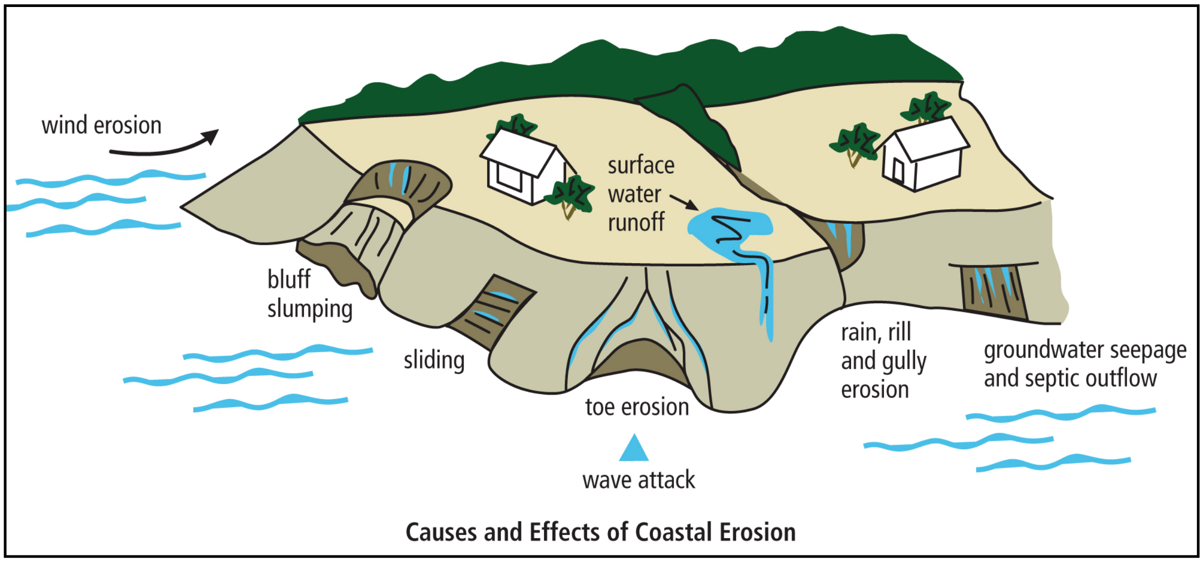
Figure 4. Conceptual cross-shore profiles of the Drowned River Valley class for A. the valley mainstem and B. valley tributaries. Not pictured are natural or artificial islands. (A. inset image taken from NOAA National Marine Fisheries Service Habitat Conservation webpage http://www.habitat.noaa.gov/restoration/techniques /livingshorelines.html; B. inset image taken from Google Earth Pro, February 2014.)



*Hazards*. The main cause of shoreline retreat is wave action. Although Delaware and Chesapeake Bays are protected from open Atlantic waves, local wind-generated waves move sediment alongshore. Irregular hurricanes can cause high waves and surges, which expose normally dry portions of the shoreface to wave attack. In areas with bluffs, erosion is often caused by ground-water seepage and runoff (Figure 5). Tsunamis potentially could cause major surges, but the risk is minimal. Low-lying areas can also be inundated due to subsidence and sea level rise.

Figure 5. Factors contributing to weathering and erosion of bluffs and low banks, exemplary of features found in Chesapeake and Delaware Bays. Some bluffs may be fronted with narrow sand beaches or shore protection.

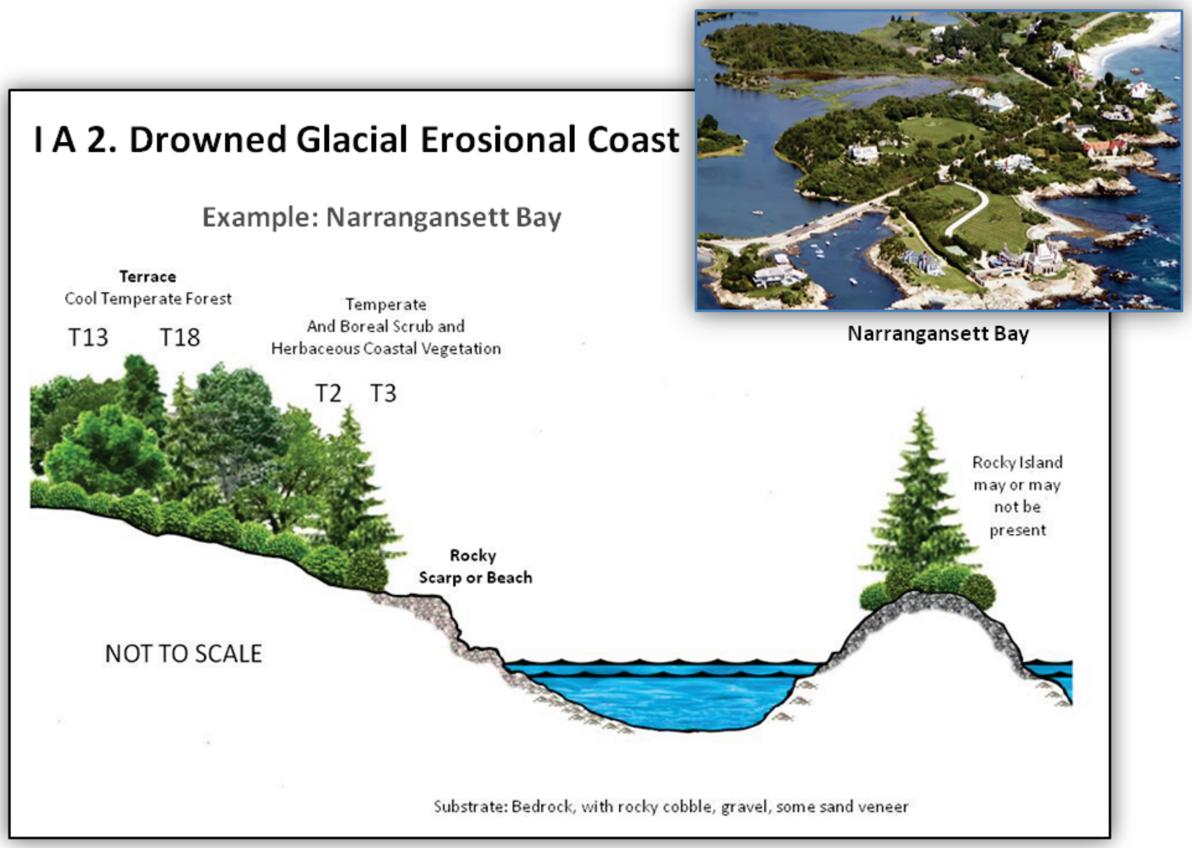



*I A 2 Drowned glacial erosional coast*

*General*. Narragansett Bay, RI, is the main geomorphic area of this classification in the study area. The Bay has a complicated shoreline with bays, salt marshes, bedrock (granitic) bluffs, some gravel and sand beaches, and glacial till outcrops. Figure 6 presents a conceptual cross-shore profile of this classification.

*Commonly Occurring NNBF*. Features of the drowned glacial erosion coast type may include islands (these can be partially submerged glacial features), beaches, marsh platforms, and scarps. Further detail on these features can be found in the following sections.

Figure 6. Conceptual cross-shore profile of the Drowned Glacial Erosion class (inset image from Save The Bay, Inc.).




*Hazards*. The main cause of coastal erosion and nearshore flooding is storm surge. Narragansett Bay suffered three major hurricanes in the twentieth century (1938, 1944, and 1955), which caused major coastal flooding, including inundation of downtown Providence (Morang 2007). In that era, the main emphasis was on property damage and loss of life, and few surveys document geomorphic changes to the coast. Beaches were likely heavily impacted by storm waves. Under normal conditions, local wind waves can move sand along beaches, but most of the bay is sheltered from open Atlantic conditions. Glacial till drumlins could be subject to slumping and erosion, similar to bluffs in Drowned River Valleys (Figure 5). Almost all coastal physical processes affect glacial deposition coasts. The till bluffs and islands are especially susceptible to erosion caused by wave attack and groundwater runoff (Figure 5).

*I B 2 Glacial depositional coast*

*General*. This category covers a broad range of coastal features in Long Island and New England. Most glacial deposition coasts consist of irregular shorelines, indented river valleys, fringing gravel and sand beaches, short barrier spits, and unconsolidated glacial till islands (drumlins), till mainland shores, and, in sheltered bays, salt marshes. In some areas of Connecticut and Massachusetts, bedrock outcrops provide hard shores, which may or may not have narrow fringing beaches. The islands in Boston Harbor are drowned glacial drumlins, many of which have sand spits extending away from the islands in a downdrift direction. Figure 7 is a conceptual cross-shore profile of the Glacial Deposition classification.

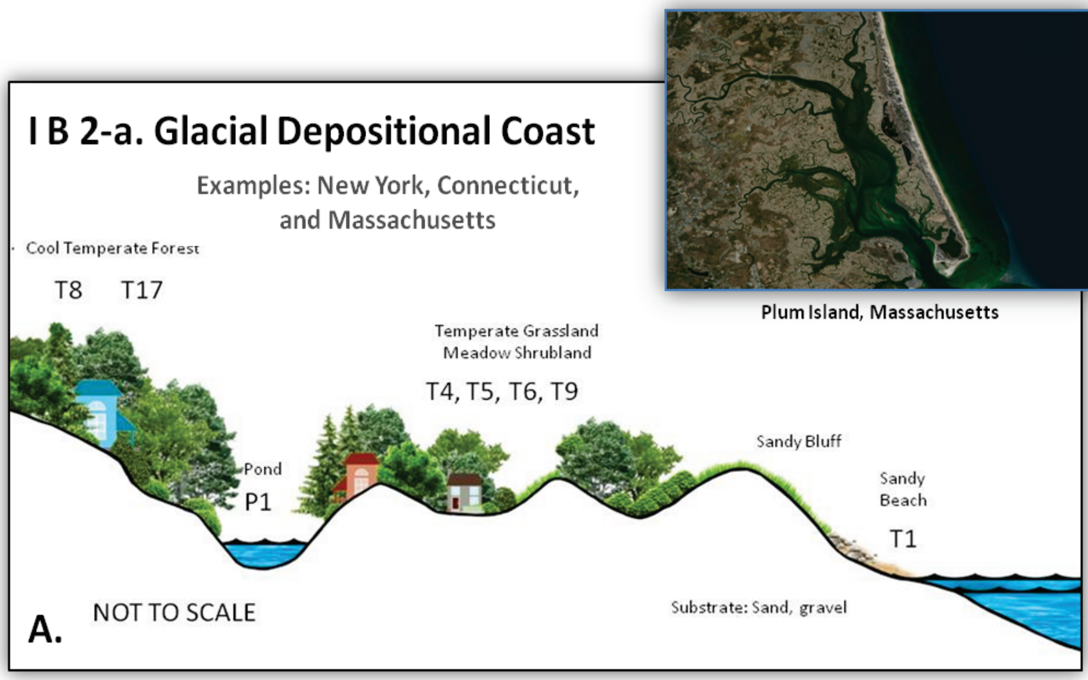
*Commonly Occurring NNBF*. Glacial deposition coasts share similar features with marine deposition coasts though the sediments are glacial in origin rather than marine and may not be as fine or well sorted. Representative features of this coast type include partially submerged glacial features (e.g., drumlins), beaches, barrier features such as spits (which are influenced by the same processes as barrier islands), marsh flats, tidal flats, tidal creeks, and scarps. More information on each of these features is found in the following sections.

*II B 1 Marine depositional barrier coast*

*General*. The barrier coasts in the NACCS study area are characterized by a seaward barrier feature such as a barrier island or spit of marine origin protecting a landward lagoon (may be referred to as a sound or bay geographically) (Figure 8).

Barrier spits and barrier islands are long, narrow, sandy geomorphic features that border much of the Atlantic seaboard south of Montauk Point, Long Island. Shorter spits occur in New England, especially Rhode Island, Cape Cod, and New Hampshire. Barrier form changes as sediment supply and transport vary. If sediment supply increases faster than physical processes can remove the sand, the spits grow wider, and further downdrift occurs. If sediment supply diminishes, barriers diminish and can eventually disappear. Sediment supplies include reworked continental shelf and postglacial deposits and riverine sediments, eroded bluffs and till outcrops, and artificial nourishment (all regions). Physical processes that rework and remove sand from barriers include waves, longshore and tidal

Figure 7. Conceptual cross-shore profiles of the Glacial Depositional Coast class for A. exposed areas and B. sheltered areas (both A. and B. insets are screenshots from ArcMap).



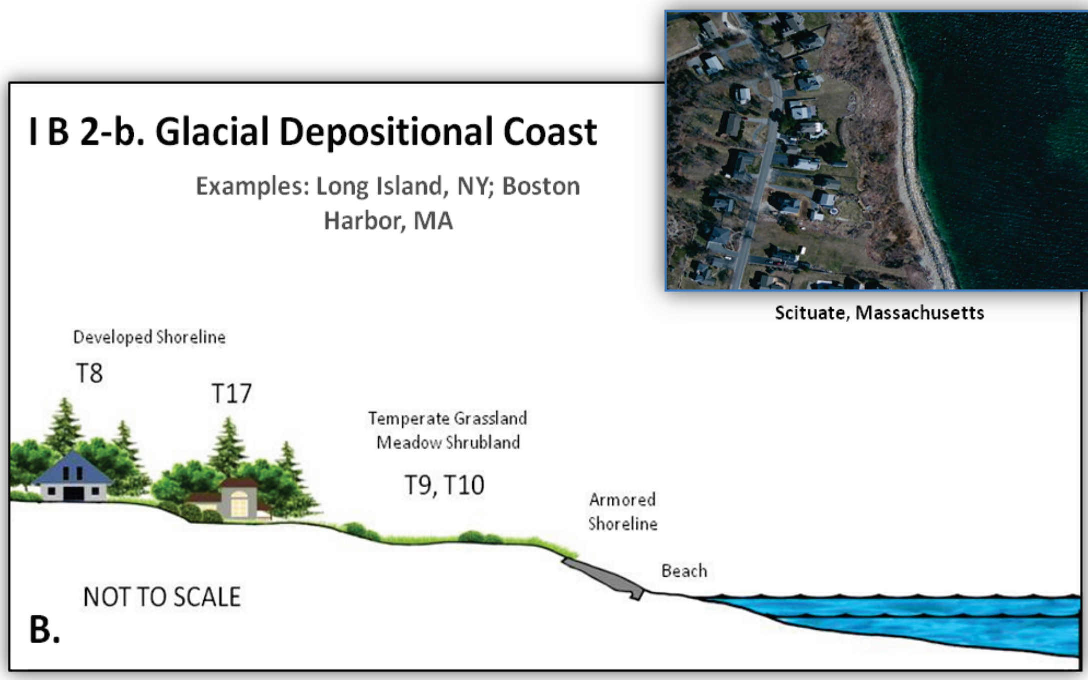
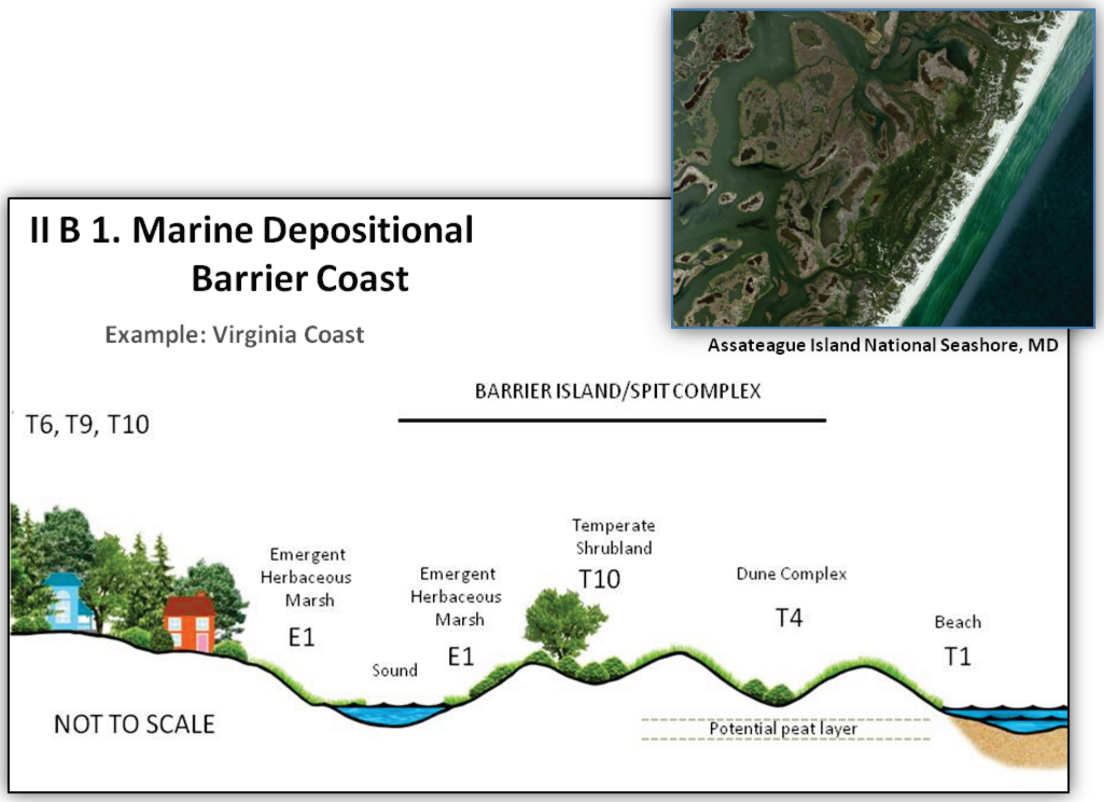



Figure 8. Conceptual cross-shore profile of the Marine Deposition Barrier Coast class. Note the barrier feature can be a barrier island or a spit (inset is a screenshot from ArcMap).

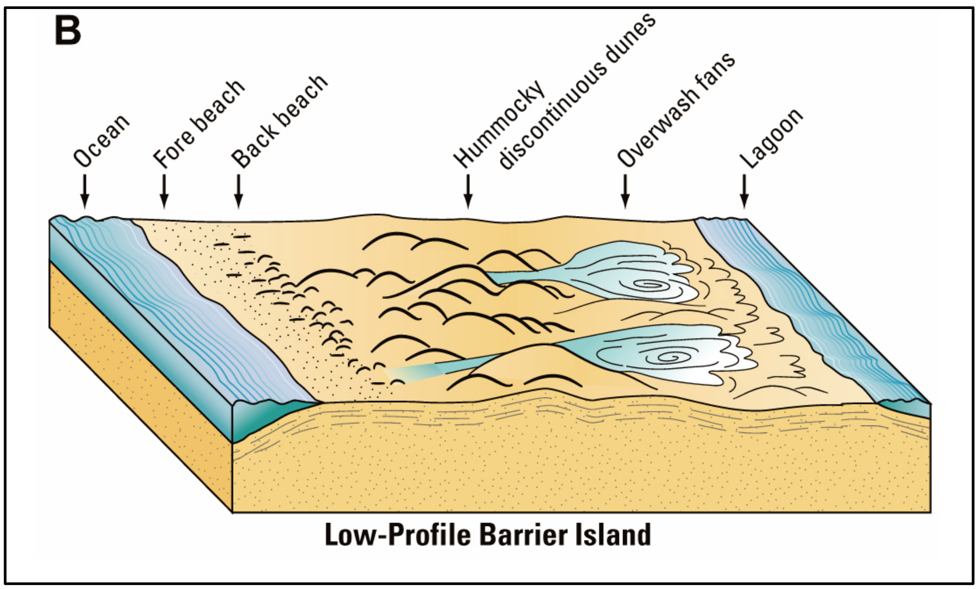



currents, wind, surge (storm, hurricane, and tsunami), flood and ebb shoals, and dredging. Lagoons are characterized by shallow, simple bathymetry with depths on the order of 1–3 m with deeper channels of approximately 5 m (Bird 2008). Lagoon characteristics depend on the configuration of the barrier and the location of inlets and riverine discharges, necessitating site-specific analysis to characterize the features with regards to salinity, waves, or currents.

*Commonly Occurring NNBF.* Barrier coast types can be complex; NNBF may include a beach, dune complex, washover fans, extensive marsh platforms complexes with tidal flats and tidal creeks (along the back of the barrier, on marsh platform islands, and fringing the mainland), mollusk reefs, submersed aquatic vegetation beds, scarps, and terraces. Generally, the coastal slopes along barrier coasts are fairly small, and scarps and terraces are found further inland.

*Hazards*. Any activities that modify natural sediment pathways in and around beaches potentially can affect sediment supply. These include local sediment traps such as terminal groins, harbor jetties, and navigation channels. Distant influences include dams on rivers. During the twentieth century, reservoirs have trapped a significant portion of the sediment load, of which only a portion is remobilized during major floods (Meade 1982). In recent years, there has been an increasing interest in dam removal. If dams are removed upstream, large amounts of sediment may be mobilized and transferred downstream (Stanley and Doyle 2002). During storms, many low barriers are overwashed, and sand is deposited in the back bays (Figure 9). This is the process by which barriers retreat landward. Rollover removes sand from the current littoral system, but it remains part of the barrier complex. More detail on landward retreat of barrier features is found in the barrier islands and washover fans sections.

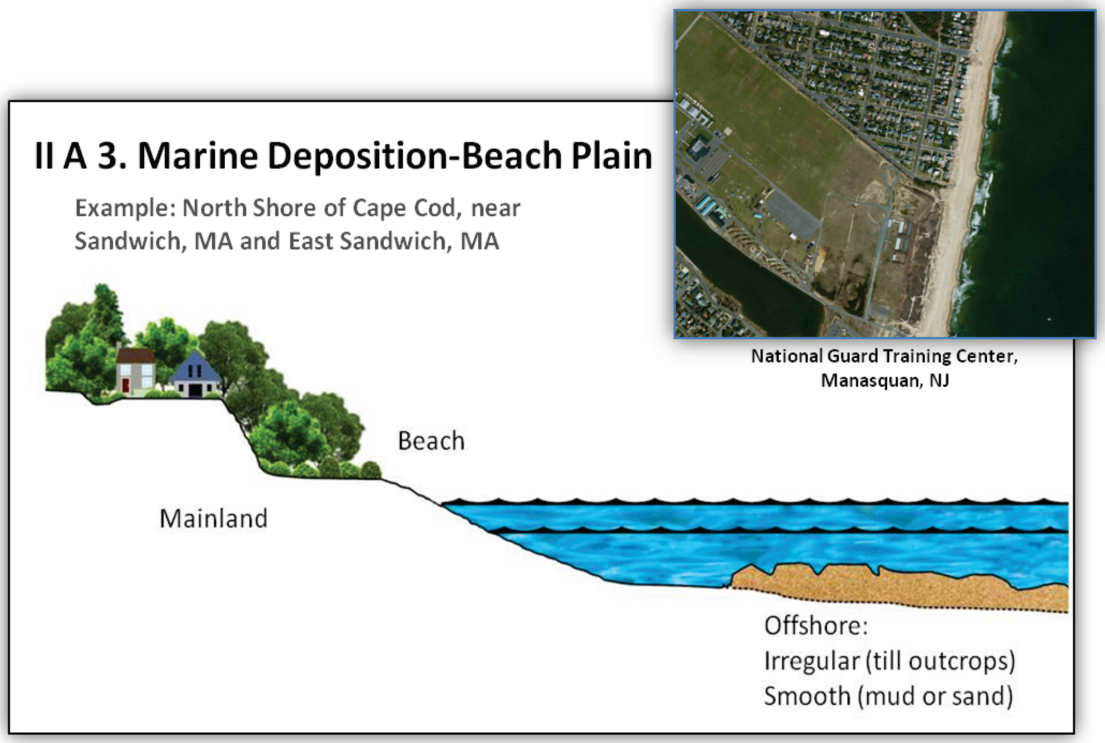
Figure 9. Geomorphic features in barrier spits common in New England. Overwash represents transfer of sand from the open coast into the back bay/pond (figure from USGS).




*II B 3 Marine deposition–beach plain*

*General*. Beach plains are beaches attached to a mainland body or large island without a pond on the back side of the beach (Figure 10). Many coasts have beach plains which merge into barrier spits. Sediment on beach plains can be derived from the same sources as barriers/spits.

Figure 10. Conceptual cross-shore profile of beach plain coast type (inset is a screenshot from ArcMap).




*Commonly Occurring NNBF*. While the processes and sediments that form beach plain coast types are similar to the barrier coast type, the lack of a protected lagoon system limits the number of NNBF that may occur. Features that may occur are the beach, the dune complex, and possibly small marsh platforms directly behind the dune complex.

*Hazards*. Beach plains are subject to the same processes that modify, move, and/or remove sand from spits/barriers. However, beach plains cannot experience rollover. Under severe storm conditions, the beach is inundated, and the mainland behind is flooded. If the beach plain is at the base of a bluff, the bluff may experience degradation and erosion. Also refer to Figure 9 and the discussion of sediment pathways which relate to this class as well.

## Geomorphic features found along coast types

Described earlier were the geomorphic features that may be found along each coast type. Defined and described here is each feature type. Primary process drivers that control the form and function of these features are summarized. Costs of constructing a subset of these features are described in Appendix B.

### Geomorphic feature descriptions (NNBF Categories)

*Beach*

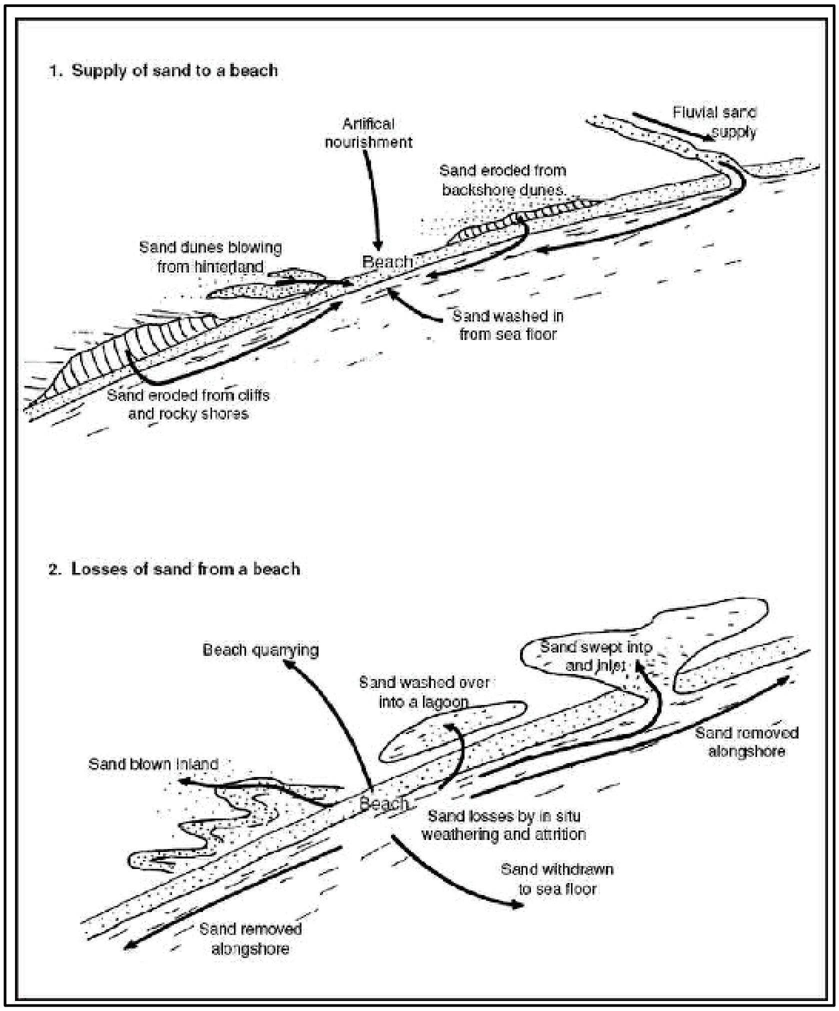
Beaches may occur as a feature in all coast types. The dominant drivers of beach characteristics are physical geometry, hydrodynamic and meteorological characteristics, and sedimentary characteristics. Beaches dominated by larger sediment sizes (coarse sand to gravel) may maintain greater slopes since the natural angle of repose of the materials is greater than for finer sand. Beach grain size is a function of both the energy of the system as well as the geologic origins of the sediment (Bird 2008). Sediment supply is also an important driver of beach form and function. Beaches are dynamic systems; waves, currents, tides, and winds continuously move and rework sediments causing the character of the beach to change rapidly in response to changing environmental forcing. Storms and seasonal meteorological changes can drastically alter the character of a beach. To maintain resilience within this dynamic system, adequate sediment supply of similar size distribution and mineral content must be sufficient to replace the sediment lost from the system (Figure 11).

*Dune complex*

Dune complexes are formed in the supratidal zone along wide, sandy beaches with significant wind action to blow sand landward where it accumulates generally above the spring high tide level. Well-developed dune complexes may include foredunes immediately adjacent to the beach, secondary and even tertiary dunes as well as interdunal areas that may trap water, creating small wetland and/or open water areas. Such well-developed dune complexes are rare in the NACCS area due to anthropogenic alterations; typically, the dune complex is characterized only by natural or artificial foredunes possibly bordered to the landward side by a small marshy area.

Above the spring high tide level, vegetation can colonize the sand accumulations, reducing the wind shear and leading to further accumulation of wind-blown sand. Vegetation stabilizes the sand deposits, creating higher and steeper dunes than if no vegetation were present (Bird 2008). Dune heights vary in height parallel to shore depending on variations in

Figure 11. Common sources and sinks of beach sediments (Bird 2008).




wind, sediment supply, and frictional elements such as vegetation or structures such as fencing. Dunes in the study area tend to migrate landward under the constant influence of coastal winds and occasional storms that can produce surge and wave runup that exceeds the high tide level (e.g., Cape Cod near Provincetown, MA, and near Sandy Neck (East Sandwich); Plum Island near Newburyport, MA; Fire Island National Seashore, NY; and Assateague Island, MD). Several examples exist of engineered dune complexes in the study area (Nordstrom et al. 2000; Nordstrom and Mauriello 2001; Nordstrom et al. 2002). If runup is significant, the foredunes and/or dune complex may be overwashed or breached leading to a washover fan, which is described later in this section, or movement of sediment to the lagoonal littoral system. The primary drivers of dune complex form and function are physical geometry, hydrodynamic and meteorological characteristics, and sedimentary characteristics.

*Drowned river valley islands*

Islands can occur in all coast types excluding the beach plain. However, the origins of islands differ for each coast type, and the different settings lead to differing drivers of form and function. Both natural and artificial islands occur along the drowned river valley coast type. Natural islands are typically remnants of high ground cut off from the mainland by sea level rise following retreat of the ice sheets at the end of the Pleistocene epoch. Many of these islands are rapidly eroding due to reduced sediment load and alterations to hydrodynamic patterns caused by navigation channels (Shepard 1973). These islands are often found near tributary mouths, and their topography is determined by the character of the fluvial sediments from which they were formed. The islands of drowned river valleys are sensitive to changes in hydrodynamic and meteorological forcing (such as sea level rise and increases in wave energy and storm frequency) and sedimentary environment caused by tributary damming. Due to the rapid rate of relative sea level rise in the Chesapeake Bay, many existing islands have disappeared or are losing land area at an increasing rate. Since sediment supply within the Chesapeake Bay is inadequate to replace eroding and submerging islands, these features will be lost permanently without engineering interventions.

In response to the rapid loss of natural islands, dredged material has been used to restore their retreating shorelines to historical footprints (e.g., Barren Island and Poplar Island in the Chesapeake Bay). To combat the erosive forces that degraded these natural islands, engineering structures have been utilized, altering the natural processes that originally shaped the islands (Blama 2012). The lifespan of islands constructed from dredged material without engineering structures is unknown and can vary significantly depending on the location.

The benefits derived from islands in these systems are highly dependent on location. Strategically placed islands can protect mainland and/or populated areas from the full energy of storm systems; poorly placed islands may be sediment sources for navigation channel shoaling.

*Barrier coast islands*

The barrier island is one of the defining features of barrier coast types. Barrier islands in this region are characterized by seaward-to-landward progression of beaches, dune complexes consisting of foredunes and perhaps secondary and tertiary dunes with interdunal areas that may contain small wetland and/or open water areas, and finally transitioning to a barrier flat area that is typically vegetated, and estuarine fringe wetlands dissected by tidal creek networks at lower elevations. To create land suitable for construction, sediments from dunes have been used to fill the low-lying areas of barrier islands, creating a relatively flat island that is typically only a few feet above mean sea level (MSL). Since barrier islands/spits are dynamic systems, the destruction of the natural features of the island as well as the introduction of hard infrastructure has removed much of the adaptive capacity of these systems and made them far more vulnerable to damage from coastal storms and sea level rise (Smith et al. 2008). As barrier islands are assemblages of several smaller scale geomorphic features, the primary process drivers are the same as those for beaches, dune complexes, and wetland features.

*Drowned glacial erosion and drowned glacial deposition islands*

Islands along the drowned glacial deposition coast and drowned glacial deposition coast types are typically glacial in origin (partially submerged moraines and drumlins as well as bedrock) although some have been reworked by marine processes. Examples include the islands of Boston Harbor, some of which are partially submerged drumlins and some of which are composed of bedrock, and Long Island and the islands of Cape Cod, which are partially submerged moraines. Moraines and drumlins are formed from unconsolidated glacial till sediments; drumlins are small, oval-shaped, mounded features while moraines are usually elongated without the characteristic shape of drumlins. Since partially submerged moraines and drumlins are formed from unconsolidated sediments, waves and currents have reconfigured the sediments since the recession of the ice sheets. Because till is not well sorted, marine forces are generally only able to rework smaller particle sizes, leading to the sandy tails and small areas of sandy and pebbles beaches. The glacial origins of these features require them to be considered separately from other islands as their location was not due to hydrodynamic forces.

Rocky outcrop features, sometimes referred to as bedrock islands, are strongly resistant to marine processes; they are not as dynamic and do not have the same adaptive capacity as marine-derived features. Like the islands of the drowned river valley coast type, these are remnant features.

*Wetlands: marsh platform, tidal flats, and tidal channel/creeks*

Marsh platform, tidal flats, and tidal channel/creeks are three different geomorphic features, but they are often intricately linked in form and function and are presented together. Tidal flats can exist without the presence of marsh platform, but they are generally dissected by tidal channels to some extent; likewise, marsh platforms can exist without tidal flats, but nearly always have associated tidal channels and creeks.

**Marsh platforms** are characterized by elevations ranging from mean tide level to spring high tide and occupation by low and high marsh vegetation communities. The vegetation communities that occupy these features are well adapted to frequent inundation and high salinity levels. They also can survive hydrodynamically energetic environments and are resistant to current and wave energy. Marsh platforms can occur in many settings and often fringe lagoons and estuaries or form islands within these features. Fringing marsh platforms can be transitional zones to upland areas with gradients in elevation and salinity. Vegetation communities that occupy marsh platforms change with elevation and salinity and are good indicators of inundation and salinity regimes of the marsh platform (Mitsch and Gosselink 2000). Marsh platforms co-evolve with other features, namely tidal channels and tidal flats (Fagherazzi et al. 2012; Kirwan and Murray 2007). To understand how marsh platforms are resilient and contribute to the overall resilience of the coast, it is important to understand how marsh platforms develop.

In protected areas, flood tides push sediment-rich water onto the aggrading tidal flat where it settles in the upper part of the intertidal zone during slack tide (Bird 2008). Ebb tide may not remove all of the deposited sediments, leading to rapid rates of accretion (on the order of 10–15 millimeters per year (mm/yr) in Newport River, NC) (Gunnell et al. 2013). Once the aggrading tidal flat reaches an elevation of approximately mean tide level, vegetation colonization can occur, further altering flow and sedimentation patterns and increasing belowground biomass leading to an increase in elevation (Mitsch and Gosselink 2003). Factors affecting marsh vertical accumulation rates include sediment inputs, flooding regime, microtopography of the site, plant community structure and compaction of the underlying peat (Orson et al. 1998). Over decadal time scales, episodic sediment deposition events associated with coastal storm activity may allow marsh surface elevation to compensate for accretion deficits and maintain marsh surface elevations with respect to relative sea level rise (Orson and Howes 1992). As the marsh platform elevation increases into the upper intertidal zone and beyond the mean high water elevation, inundation frequency is reduced as well as sediment loading, leading to a natural decrease in accretion rates (Fagherrazi et al. 2012). Recent studies have also shown that nutrient loading of coastal marshes can decrease the resilience of salt marshes and lead to marsh loss (Deegan et al. 2012).

Marsh platforms are inherently unstable horizontally. Eroding marsh platforms and tidal flats are separated by a scarp (Roland and Douglas 2005; Fagherazzi et al. 2006). The scarp is sensitive to wave attack, causing undercutting of the platform leading to geotechnical instability and slumping. The slump block is then vulnerable to erosion from tidal currents and waves. Most marsh platform-tidal/creek-tidal flat complexes occur in shallow, sheltered areas such as lagoons along barrier coasts and in tributaries along drowned river valley coasts. Wind waves are the primary driver of lateral marsh retreat. Along the Gulf coast, Roland and Douglass (2005) found that stable and eroding marsh shorelines and non-vegetated shorelines were associated with low, moderate, and high wave exposures, respectively. Their approach for developing critical wave height thresholds for *Spartina alterniflora* could be used to develop guidance for construction of protective structures for coastal wetland creation and restoration projects. There is no stable balance between marsh platform and shallow open water; when fetch is small, marsh platform advances and replaces shallow water and tidal flat (Mariotti and Fagherazzi 2013). However, when fetch permits significant wind/wave formation, marsh platform retreats, further increasing fetch, leading to more wave erosion and further retreat. Critical fetch distance over tidal flat and shallow open water is on the order of 1 km although the threshold varies with sediment supply and rate of sea level rise (Mariotti and Fagherazzi 2013).

**Tidal channels/creeks** are critical to marsh platform function. Tidal channels are typically formed during flood and ebb tides on tidal flats before vegetation colonizes, creating a network of channels not altogether different from fluvial flow upland drainages. Once the tidal flat is vegetated, flow becomes more concentrated in these nascent channels, incising the channel such that it becomes generally narrower and deeper than a fluvial channel that conveys a similar flow volume (Rinaldo et al. 2004). Tidal channels are important conduits of water, sediment and organisms into the interior of the marsh platform. Flow resistance from marsh platform vegetation would otherwise reduce flow velocities and sediment transport capacity of the flood tide where only the fringes of the marsh platform would receive regular tidal exchange of water, sediments, and nutrients (Fagherrazi et al. 2012). Tidal channels also provide conduits for drainage of the marsh platform providing the necessary hydroperiod for high marsh vegetation communities to thrive.

Tidal channels can end in relatively shallow pools or ponds (sometimes called marsh basins) with varying levels of hydrologic connectivity (Mariotti and Fagherazzi 2013). These pools and ponds may or may not be vegetated depending on the elevation, and the salinity may vary depending on the hydrologic connectivity. If these features become too large (on the order of 1 km), the open water can allow wind-induced waves to form and increase wave erosion on the marsh platform scarp creating a feedback that can erode the marsh platform from the interior (Mariotti and Fagherazzi 2013).

**Tidal flats** are the only feature within this complex that can exist independently; indeed, if marsh platform horizontal degradation continues even absent of sea level rise, the wetland complex will convert to tidal flat (Mariotti and Fagherazzi 2013). Tidal flats can be formed from sand in higher energy environments or finer cohesive sediments where they are frequently referred to as mudflats. As previously discussed, tidal flats can accrete sediments rapidly provided they are hydrodynamically protected. In hydrodynamically energetic environments, tidal flats experience a peak in shear stresses that prevent the accretion of sediments or the establishment of vegetation (Defina et al. 2007). In macrotidal regions of the study area, tidal flats may naturally exist independent of marsh platforms and tidal creeks, but over much of the study area, these features naturally are complex. While tidal flats are valuable benthic habitats, without the presence of marsh platforms and tidal creeks, the lack of topographic diversity can, at times, lead to low ecological diversity and lower relative ecological benefits.

Tidal flats are characterized by mild slopes and contain sediments ranging from clay to sand size. Under tidal action, coarser particles tend to settle lower in the tidal prism with finer particles settling out higher in the intertidal zone (Gao 2009). Wave action and storms can also contribute large deposits of sediments higher in the intertidal zone as well, leading to coarse particles deposited higher in the intertidal zone than tidal action alone would predict. Net bedload and suspended sediment transport rates are landward due to settling and scour lag and asymmetry between flood and ebb tide currents (Gao 2009).

*Fan*

Washover fans are created by the overwashing of dune complexes or barrier features along barrier and beach plain coasts or drowned river valley coasts (although significantly less common due to limited sediment supply and hydrodynamic energy). Overwash can be caused by runup or by surge when flows have sufficient energy to transport beach and/or dune sands to the landward side of the feature (Bird 2008). Washover fans are naturally ephemeral features. At supra- and intertidal elevations, washover fans can be quickly colonized by vegetation and become incorporated into adjacent vegetation communities, becoming morphologically part of the dune complex or marsh platform. Overwash processes and washover fans are essential to the resilience of barrier features to disturbances such as storm events; prevention of overwashing disrupts the natural landward movement of sediments that allows barrier features to adapt to rising sea levels (Smith et al. 2008). If overwash becomes more frequent under the influences of climate change and sea level rise, washover fans will become more common. Conversely, if nature-based infrastructure features (e.g., artificial dunes) are overengineered, the frequency of overwash event will be reduced, eliminating a primary sediment pathway from the open coast to the lagoonal system. If the frequency of such events exceeds the ecological and physical recovery time, the barrier feature and vegetation communities impacted by the overwash event may become degraded to the point that they cannot recover. If overwash events are eliminated, species unsuited to frequent disturbances can become established, ultimately reducing the resilience of the system. Unvegetated barrier features and dune complexes are subject to breaching.

*Scarps*

Scarps are relatively straight, cliff-like faces or slopes of considerable linear extent, which breaks up the general continuity of the land by separating surfaces lying at different levels (as along the margin of a plateau or mesa). Scarps may be found along any of the coast types. They may be composed of highly erodible sediments such as scarps that separate marsh platforms and tidal flats or of highly resistant materials such as cliff faces along drowned glacial erosion coasts. The elevation, hydrodynamic environment (especially waves), and substrate of the scarp determine its vulnerability to erosion.

These features are generally flat and supratidal in elevation. Technically, platform is a more general term than terrace, but for the purposes of this document, platform will refer to any slightly elevated flat area of land that cannot be classified as a marsh platform that may be subject to infrequent inundation from surge or runup. The term terrace will refer to a flat surface slightly higher in elevation. These features are transitional, delineating coastal features from mainland features. While geologically these features may have been formed by marine processes, continental processes currently dominate. Typically, these features are separated from features lower in elevation by a slope or scarp feature (which may or may not be resistant to erosion). They are included in the coastal classification because under future climate change and sea level rise, these features may be more strongly affected by marine processes. They are important buffers zones; under rapid sea level rise, vegetation communities will need higher elevation areas to colonize as the lower elevation ranges of the previous habitat areas become more frequently inundated. If human habitation or other forms of development blocks this natural migration, floral and faunal communities may shrink or even disappear.

*Mollusk reef*

While mollusk reefs are biogenically not geologically formed, they are important features of the coast. Typically, mollusk reefs are found in relatively shallow water where hydrodynamics, salinity, and substrate conditions and larval supplies are conducive to maintaining a viable mollusk population. Large populations of mollusks can create substantial mounds of shells called reefs that will alter flow and water column properties in the immediate vicinity of the reef. Oysters and mussels are good examples of reef-building species capable of altering their environment. Large oyster reefs can also effectively filter suspended sediments and plankton from the water column, improving water clarity. Oyster reefs that occupy a significant portion of the water column may serve as a wave break, creating sheltered areas that are conducive to wetlands or submersed aquatic vegetation beds.

*Aquatic vegetation bed*

Aquatic vegetation beds are important components of NNBF; they are biogenically formed like mollusk reefs though the vegetation must be alive for the feature to exist (remnant mollusk reefs will still alter flow locally although they will degrade rapidly). Aquatic vegetation beds alter local hydrodynamic and sedimentary conditions. They are also important components of the lagoon and estuarine habitats, providing nursery areas for a number of fish and benthic species and improving water quality.

#### Costs associated with the feature construction for NNBF

Examples of costs for previously implemented projects are provided in Appendix B. These projects include oyster reef and island construction, beach renourishment, riverbank stabilization, salt marsh and seagrass habitat restoration, beach fills, revetments, wetland restorations, bulkheads, and living shorelines.[1] Additionally, some basic information on the costs of materials and construction for creation is also provided in the appendix.

Costs for future projects should not be derived directly from these examples. The cost for any project will depend upon site-specific factors, project design, location, construction methods, and the material costs. The information presented here is intended to support early screening and alternative comparisons and is not a replacement for accepted cost-estimating practices.

## Processes that drive feature form and function

Like all engineering solutions, NNBF have a range of forcing conditions for which they are effective, and this range is dependent on the type of NNBF implemented. For example, wetlands generally require environments with much lower mean wave heights than do beaches and dunes. Thus, wetlands are generally found in (or should be located in) estuaries or areas protected by barrier islands, while beach and dune restoration is effective on open coastal sites. This section and Appendix C provide sources of data and analytic methods for describing and estimating the processes and

[1] Living shorelines are defined as NNBF resulting from the application of erosion control measures that include a suite of techniques which can be used to minimize coastal erosion and maintain coastal process. Techniques may include the use of fiber coir logs, sills, groins, breakwaters or other natural components used in combination with sand, other natural materials and/or marsh plantings. These techniques are used to protect, restore, enhance or create natural shoreline habitat (http://www.dnr.state.md.us/ccs/livingshorelines.asp).

drivers of NNBF form and function as well as for selection of NNBF alternatives (Table 3). Processes and drivers are categorized by type: geometric, hydrodynamic and meteorological, sedimentary, and biophysical. Biophysical characteristics also include special considerations such as the likely presence of threatened, endangered, and sensitive species and invasive or non-native species.

Table 3. Primary drivers of geomorphic features.

| Characteristic | | Beach | Dune complex | Fan | Island | Wetland | Scarps | Upland features | Mollusk reefs | Aquatic vegetation beds |
|---|---|---|---|---|---|---|---|---|---|---|
| Geometric characteristics | Elevation | X | X | X | X | X | X | X | X | X |
| | Width | X | X | | X | X | | | X | X |
| | Length | X | X | | X | X | | | X | X |
| | Slope | X | X | | X | X | X | X | | |
| Hydrodynamic and meteorological characteristics | Waves (height, period, angle) | X | X | | X | X | X | | | |
| | Currents | X | X | | | | | | | |
| | Tides | X | | X | X | X | X | | X | |
| | Wind | X | X | X | | | | X | | |
| Sedimentary characteristics | Mineral composition | X | X | | X | X | X | | | |
| | Substrate/sediment characteristics | X | X | X | X | X | X | X | X | X |
| | Sediment supply | X | X | X | X | X | | | | |
| | Erosion/accretion rates | X | X | X | X | X | X | X | | |
| Biophysical characteristics | Salinity | | | | | X | | | X | X |
| | Vegetation | | X | X | X | X | X | X | | X |
| | Fauna | | | | | X | | | X | |
| | TES | | | | | X | | | X | X |
| | Invasive-non-native | | | | | X | | | | X |

Geometric characteristics of features are important because they influence how the features appear in the landscape and determine how physical processes may impact the features. The primary coastal hydrodynamic forcing factors are wave height and period, water level, and current. For features that are not inundated, wind may be a significant forcing factor. Duration of hydrodynamic and meteorological events is important when evaluating NNBF. Long-duration storms with high waves and water levels over many hours or days are generally more damaging than a hurricane with similar wave heights and water levels that last just a few hours. Sedimentary characteristics such as sediment size and material as well as supply and erosion or accretion rates determine how sensitive a feature may be to hydrodynamic and meteorological forcing and how quickly the feature may recover from impacts. Biophysical characteristics such as vegetation may contribute to a feature's resilience or sensitivity to impacts.

Because many of these features are found across different coast types, also included is a summary of physical processes that drive each coast type. For instance, tides are listed as a driver of every feature with an elevation less than or equal to spring high tide. However, tides are of relatively greater importance in drowned river valley, drowned glacial erosion, and glacial deposition coasts. Table 4 summarizes the dominant drivers for each coast type. The following section describes the processes while Appendix D provides detailed guidance for their quantification and assessment. The list of drivers is more extensive than those discussed in this document; the focus is on those most predominant.

Table 4. Primary drivers of features within each coast type.

| Class | Waves | Tide | Wind | Ice | Rain-induced flood | Land slump/ collapse | Storm surge | Earth-quake | Avulsion |
|---|---|---|---|---|---|---|---|---|---|
| Drowned river valley | X | X | | Not likely | X | X | X | Rare | |
| Drowned glacial erosion | X | X | | X | Not likely | X | X | Rare | |
| Glacial deposition | X | X | | X | X | X | X | Rare | |
| Barrier coast | X | | X | X | | | X | | X |
| Beach plain | X | | X | X | | | X | | |
| Artificial | X | | | | X | | X | Rare | |

## Geometric characteristics

### *Elevation range*

The elevation range occupied by a feature determines the frequency of inundation from tides, floods, and/or storm events and is one of the primary drivers of vegetation distribution. Elevation in the subtidal, intertidal, and lower supratidal zones is critical in determining a feature's susceptibility to waves, storm surge, and/or runup during storm events. Frequent inundation provides a supply of sediment that can lead to rapid accretion, which is important for maintaining beaches, tidal flats, marsh platforms, and tidal creeks. Inundation that occurs too frequently can stress wetland vegetation and ultimately lead to habitat switching. Features of marine origin typically occupy a fairly narrow and predictable range of elevations that are a result of the meteorological, hydrodynamic, and sedimentary environment. Features that were glacially formed are more variable in elevation. Features within the drowned river valley coast are generally low in elevation, being formed from the same processes that formed the lower coastal plain of the eastern U.S. Terraces, plains, and bluffs along middle and upper portions of the Chesapeake Bay and some of the upper portions of Delaware Bay are the highest features in the area. Remnant continental features include terraces and dissected uplands as well as dissected outcrops and upland sands and gravels (Ator et al. 2005).

*Width normal to shore*

The width of features normal to the shore is a result of the combination of several processes including hydrodynamic and meteorological processes and sediment transport as well as the slope of the local region. For instance, low slope coasts such as those along the New Jersey shore have larger regions within the defined elevation ranges for marsh platforms, so these features can be of greater width than in a steeper region of the coast. The width influences vulnerability to storm events; narrow features will have a greater proportion of land area acted upon by marine forces with concurrent increases in impacts from storm events. The features presented in this document range over approximately three orders of magnitude. Well-developed barrier features are on the order of 1000 m wide; simple dune complexes (consisting of primarily foredunes) are on the order of 100 m wide; and some low-elevation platforms formed from waves are only on the order of 10 m (Bird 2008).

*Length parallel to shore*

The length of a feature is important for describing the extent of influence along the coast and can affect several processes. Generally the marine-derived features are approximately an order of magnitude greater in length than width. For barrier island and spit features, the length gives an indication of the extent of connection the lagoon system has with the open ocean. The length of marine-derived features also indicates the degree to which sediments are free to move from feature to feature along the coast via longshore transport. For features that are essential habitats, the length gives an estimate of habitat size and connectivity with other features. Generally, features of marine origin will be longer than features of riverine and glacial origin. In the glaciated regions of the study area, features tend to be smaller and isolated as a result of the irregular shoreline from the recent history of glaciation.

#### *Slope*

The slope of the coast in the southern portion of the study area is generally milder than the slope in the northern portion of the study area due to the relative proximity to the Appalachian Mountain chain to the coast and the presence of glacial till near the coast. The slope of individual features is a result of other physical processes and characteristics. For instance, beaches formed from coarse-grained sediments such as gravel and cobbles generally have a greater slope than beaches formed from fine-grained sands. Certain features such as tidal flats and marsh platforms are characterized by very mild slopes (on the order of 1/1000; Bird (2008)). Dunes, by contrast, have greater slopes due to the presence of vegetation that stabilizes sediment. Features such as scarps (bluffs, cliffs, and banks) can be nearly vertical. Feature slope is a function of hydrodynamic and meteorological characteristics, sediment characteristics, and the biophysical environment since vegetation can alter the stable slope of sediments. Both scale (local and regional) can be formative factors in recovery efforts and can be addressed independently or together when given specified study goals and objectives.

### Hydrodynamic and meteorological characteristics

The primary hydrodynamic driver in the coastal environment is wind-generated gravity waves. Waves and wave-driven flows move sediment across and along the shore. Waves force longshore currents, cross-shore currents (undertow), runup and swash, and wave setup. Tides and tidal currents can also be significant drivers of nearshore processes, particularly at tidal inlets and in estuaries. Winds generate waves but also directly force currents and drive aeoliean sediment transport on the beach and dune.

*Waves*

Wave generation is dependent on three parameters: wind speed (at 10 m elevation), fetch (overwater distance that the wind blows), and wind duration. Simple analytical expressions to estimate significant wave height (Hmo) and peak wave period (Tp) are available in the Coastal Engineering Manual (Resio et al. 2008) or other sources. But, as waves propagate into intermediate and shallow water depths (depth < 0.5 wave length), they interact with the sea floor, which can cause focusing of wave energy, wave shoaling, and wave breaking. In detailed studies, these spatially varying processes are typically estimated with spectral wave models. More detail on data sources and calculations is provided in Appendix D.

*Water level and currents*

Water levels and currents are driven by tides, waves, and winds. Tides are primarily caused by the gravitational forces of the moon and sun acting on ocean and local basin geometry and bathymetry. Tide ranges on the U.S. coast vary from less than 0.3 m to more than 10 m. Currents in the near-coast environment are driven by tides, winds, and waves (Smith 2003) and can be modeled with the same circulation models used to represent water levels. Currents that run parallel to the coast are driven by waves breaking at an angle to the shoreline. Current measurements in some coastal locations are available from the NOAA's Center for Operational and Oceanographic Products and Services (CO-OPS) web site (http://www.co-ops.nos.noaa.gov/). The CO-OPS website also provides access to measured water level data and predicted tide levels around the US coast referenced to both fixed and tidal datums.

*Wind*

Winds are an important driving force for waves, currents, and transport of sediment on the subaerial beach. For driving wave or circulation calculations, winds are adjusted to a 10 m elevation with an averaging period of approximately 10–30 minutes (min). Sources of wind information include measurements from NOAA weather stations, National Data Bouy Center (NDBC) buoys, airports, and Coast Guard stations. Hindcast wind information is available on the Wave Information Studies (WIS) website. Aeolian sand transport on beaches is responsible of the accretion and erosion of beaches and dunes (Hsu and Weggel 2002).

## Sedimentary characteristics

*Substrate type and grain size quantification*

Substrate and sediment characteristics are an indication of the physical processes that act upon the features. Higher-energy environments tend to have coarser sediments than low-energy environments. Poorly sorted sediments are indicative of more recent deposits than well-sorted sediments. The particle size distribution of sediments is perhaps the most useful measure of sediment and substrate characteristics. Grain size classes can be used to describe the sediments and substrate more generally; the Wentworth grain size classification (Table 5) is typically used by the coastal engineering community, though other classification systems exist.

Table 5. Wentworth grain size classification for sediments.

| Class | Descriptor | Grain Size (millimeters) | Class Sizes (phi) |
|---|---|---|---|
| Mud | Clay | < 0.004 | > 8 |
| | Silt | 0.004 to < 0.0625 | > 4 to 8 |
| Sands | Very fine sand | 0.0625 to < 0.125 | 4 to < 3 |
| | Fine sand | 0.125 to < 0.25 | 3 to < 2 |
| | Medium sand | 0.25 to < 0.5 | 2 to < 1 |
| | Coarse sand | 0.5 to < 1 | 1 to < 0 |
| | Very coarse sand | 1 to < 2 | 0 to < -1 |
| Gravels | Granule | 2 to < 4 | -1 to < -2 |
| | Pebble | 4 to < 64 | -1 to < -6 |
| | Cobble | 64 to < 256 | -6 to < -8 |
| | Boulder | 256 to < 4,096 | -8 to < -12 |

*Sediment supply*

Sediment supply is critical to the persistence of many coastal features. Typically, any features composed of unconsolidated sediments subject to erosional forces will require some sediment supply to persist in the landscape (although physical processes may alter the shape and/or location of the features at varying rates). Therefore, sediment supply is important in analyzing all features except those composed of highly resistant materials such as bedrock. For many features, both suspended sediments and bedload are important to varying degrees depending on the nature of inundation. To analyze many of the features described in this document, a sediment budget is a valuable tool. The primary incoming and outgoing sediment pathways should be identified for features. For features in a degraded state, the restoration of sediment supply may be critical to restoration or preservation. For features affected by continental or riverine processes, sources of sediment could be terrestrial and should also be considered. Generally, systems that have low sediment supplies will not recover from disturbances as quickly as systems with higher loads.

*Erosion/accretion rates*

Erosion and accretion rates are the result of imbalances in sediment supplies. Features accrete and grow if sediment volume entering the feature system is greater than sediment volume leaving. Erosion is caused by a sediment deficit; hydrodynamic and meteorological forces remove sediment from features, and it is not replaced. This can be caused by a reduction of the sediment supply into a system (e.g., where reservoirs upstream impound riverine sediments that would eventually be transported into the mainstem bay where they could potentially be deposited on islands or wetlands). Erosion could also be caused by changes in the hydrodynamics of the local environment. Anthropogenic influences along barrier coasts such as opening and maintaining inlets and introducing structures such as jetties and groins alter natural sediment transport pathways and can affect the hydrodynamic conditions in what were formerly sheltered areas. USGS calculated and mapped short and long-term erosion and accretion rates for the outer coast (USGS 2013d). Coverages of erosion and accretion rates for estuaries and lagoons are available within the USGS Coastal Vulnerability Index (Hammar-Klose and Thieler 2001), but the scale is coarse. Erosion and accretion rates should ideally be calculated locally from aerial photos and/or historical shoreline information on a local scale.

*Organic composition*

The organic composition of sediments is an important characteristic. High organic content is indicative of a biologically active environment. Sediments in wetland environments typically have high organic content and can contain buried peat deposits. Beaches typically have very low organic content as the marine processes that form them sort the smaller organic sediments from the finer organic sediments, creating deposits of mostly sandy material.

## Biophysical characteristics

### *Salinity*

Concentrations of salts (sodium chloride, bromine, and iodine) in seawater increase conductivity, which is used to measure salinity. Most marine waters have salinities between 34 and 35. Salinity in estuaries and coastal waters vary from zero to more than 40 depending upon precipitation, freshwater inflows, and tidal exchange. Salinity is a defining feature of the structure of coastal waters. Most aquatic organisms function optimally within a narrow range of salinities, which has impact on the ecological balance and trophic structure of communities. Salinity can also affect the density of the water column, which in turn impacts sediment processes that then influence morphological structure.

### *Vegetation*

Vegetation is a critically important feature of natural coastal systems, intricately tied to a number of physical processes such as wave energy and sediment transport. Vegetation is crucial to the form and function of several, such as marsh platforms and dune complexes and a necessary component of aquatic vegetation beds. In coastal environments, vegetation communities are determined primarily by inundation, salinity, and disturbance patterns. More information about vegetation classification and communities within the study area can be found using the links shown in Table 6.

Table 6. Web links to all State plant databases within the study area.

| State | Program |
|---|---|
| Connecticut | http://www.ct.gov/deep/cwp/view.asp?a=2706andq=323840 |
| Delaware | http://www.dnrec.delaware.gov/fw/nhesp/pages/default.aspx |
| Maine | http://www.maine.gov/doc/nrimc/mnap/ |
| Maryland | http://www.dnr.maryland.gov/wildlife/plants_wildlife/nhpintro.asp |
| Massachusetts | http://www.mass.gov/eea/agencies/dfg/dfw/natural-heritage/ |
| New Hampshire | http://www.nhdfl.org/about-forests-and-lands/bureaus/natural-heritage-bureau/ |
| New Jersey | http://www.nj.gov/dep/parksandforests/natural/heritage/datareq.html |
| New York | www.nynhp.org/ |
| Rhode Island | http://www.dem.ri.gov/programs/bpoladm/plandev/heritage |
| Virginia | http://www.dcr.virginia.gov/natural_heritage/ |

*Faunal community*

The faunal community is a critical component of the structure and function of mollusk beds and is necessary for the feature's persistence. Many of the NNBF provide essential habitat to a number of species and given the degree of urbanization within the mid-Atlantic and northeastern U.S., relatively undisturbed coastal features are often necessary to the maintenance of those species and any consequent services they provide.

*Special considerations*

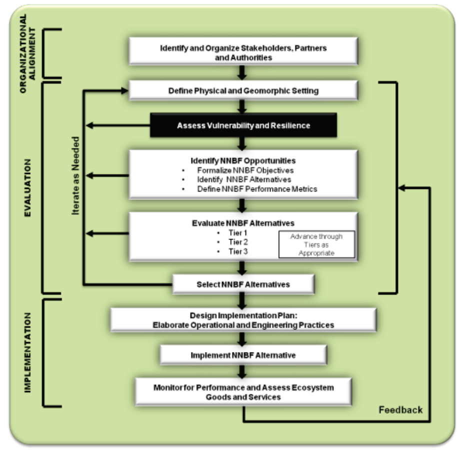
**Threatened, Endangered, and Sensitive species:** The importance of coastal features as critical habitat is magnified when considering TES. Features that serve as important areas for TES should be considered especially valuable, and care should be taken to preserve those features and the conditions that support their continued function and persistence. If measures are taken to alter features important to TES species, care should be taken to not alter the habitat in such a way that it becomes undesirable to the species of interest. Likewise, if critical habitats are disappearing, interventions to restore or protect features that provide habitat may be warranted.

**Invasive species:** Invasive species such as Phragmites australis can be opportunistic, taking advantage of disturbed or altered landscapes. The presence and risk of colonization of an area by invasive species should be considered when characterizing the condition of a geomorphic feature as the presence of invasive species can alter the function and benefits of geomorphic features.

## Conclusions

The generic geomorphological-vegetative classification presented here (and conveyed in the form of system profiles) is considered a good first step in the characterization of the NACCS setting. The system profiles are designed as a guide for identifying specific NNBF (both existing conditions and/or potential implementation opportunities). The deployment of NNBF in this environment to both reduce flooding risks and promote coastal resilience will require more detailed characterizations of potential hot spots (i.e., areas identified by the NACCS for future study). Additional work will then need to be undertaken to refine and further advance the classification system using both readily available data and new imagery, as it becomes available. Application of the classification system to these hot spots will require manual analysis of data and imagery and/or additional work to develop GIS-based detection algorithms based on the characterization of NNBF options presented here.

# 3 Coastal Vulnerability and Resilience Metrics for NNBF




## Introduction

Coastal areas of the U.S. are threatened by erosion and damage due to storm waves, wind, and surge. The potential for environmental and economic damage and loss of life is exacerbated by many factors, including coastal development, relative sea level rise, coastal subsidence, and loss of environmental habitat such as wetlands that may provide natural protection from storm damage and erosion. Appropriate coastal zone management and storm damage risk reduction require the assessment of vulnerability and resilience in natural and human environments. Vulnerability and resilience assessments are therefore key components in the evaluation of NNBF and blended solutions (NNBF and traditional structural) as identified in the framework presented in Figure 1. The purpose of this chapter is to carefully define nomenclature and present definitions of vulnerability and resilience and document approaches for identifying and defining vulnerability and resilience metrics relevant to particular policy or decision-making objectives. Once metrics are established, they can be utilized in the Community Resilience Assessment herein and the evaluation framework presented in Chapter 5 as a means of quantifying vulnerability and resilience and comparing alternatives. Developing an understanding of vulnerability, its spatial distribution, and contributing causes is an important step in identifying NNBF alone or in combinations with structural features (i.e., blended solutions) that can be used to reduce vulnerabilities and enhance resilience.

A number of previous studies have demonstrated various approaches to assessing coastal vulnerability (Gornitz 1990; Klein and Nicholls 1999; Boruff et al. 2005; Nicholls et al. 2008; Jimenez et al. 2009; McLaughlin and Cooper 2010) and resilience (Sempier et al. 2010; The Resilience Alliance 2010; New Jersey Office of Coastal Management 2010, 2011a; Vermont Natural Resources Council 2013; The U.S. Indian Ocean Tsunami Warning System Program 2007; The University of Queensland and

University of Southern Queensland 2008; Schultz et al. 2012). The assessments have been conducted for various hazards (e.g., sea level rise, coastal erosion, tsunamis, climate change, present and future storms) at multiple spatial (global to local) and temporal scales. Typically, an index is developed that is guided by the data available and consideration of what data may be the most appropriate for quantification. The metric development has therefore been data driven, and documentation of systematic approaches for metric development are limited. This chapter lays out a proposed conceptual approach for identifying and defining meaningful metrics to ensure a complete assessment of vulnerability and resilience for a wide range of systems and hazards at multiple scales. The approach is intended to be generally applicable and valid for coastal hazards and systems.

The approach is demonstrated through application to simple, coupled human-environment systems. Special consideration is given to coastal landscapes and how the approach can be applied to develop vulnerability and resilience metrics for NNBF and blended solutions. The approach is applied to develop metrics beneficial for assessing relative vulnerability and resilience of coastal landscapes along the northern Atlantic coast; understanding how NNBF influence vulnerability and resilience of a coastal landscape; and understanding vulnerability and resilience of specific NNBF.

## Vulnerability

Vulnerability is conceptualized in many different ways and depends on the scientific background of those assessing vulnerability. Confusion arises as vulnerability is closely related to and often confused with other concepts such as risk and resilience. Therefore, a complete description of the vulnerability is required. Fussel (2007) documents a methodology and terminology that enables a succinct characterization of any vulnerability concept. The methodology was developed for application in climate change research, but is sufficiently generic to be generally applicable. Fussel (2007) points out that several researchers (Brooks 2003; Luers et al. 2003; Fussel 2004; Downing and Patawardhan 2004; Metzger et al. 2004) have emphasized that vulnerability can only be meaningful with reference to a vulnerable situation. To be inclusive, rather than exclusive, the following definition was developed for this effort:

> **Vulnerability** is defined as the degree to which a system's attributes of concern are susceptible to, and unable to cope with, the adverse effects of hazards over a period of time or temporal reference.

In this case, the system is defined as the area of concern. In the most general sense, this can be any system that is potentially threatened by a hazard. It may be a natural system (e.g., barrier island system), a social system (e.g., a population group), or a coupled human-environment system (e.g., geographic region). The system itself may be a component of a larger system (e.g., a barrier island is part of a larger coastline system), necessitating a system-of-systems view. Attributes of concern are considered system features or components threatened by hazards. The concept of vulnerability is based upon human value judgments with respect to elements such as infrastructure, quality of life, natural resources, cultural resources, and environmental habitat (Green and McFadden 2007). The system must have attributes or perform functions deemed valuable to constitute a situation as vulnerable. An emphasis is placed on valued functions in this definition. For example, storm wave energy dissipation is considered a valued function of salt marshes. As is often the case, hazards are defined as the events or occurrences that have the potential to cause harm to people or property. These are considered influences that may adversely affect a valued function of a system. The hazard may be natural or anthropogenic and can be continuous (e.g., sea level rise) or discrete, such as a storm. In addition, a hazard may be internal or external to the system. Similar terms to describe hazards may include threat, stressors, or damage drivers. Temporal references refer to a point in time or the time period of interest. It is particularly important to define the time horizon over which a vulnerable situation is being assessed when the hazards that may damage the system are changing with time.

While these terms above shed light on the elements that define a vulnerable situation, factors (or variables) that help interpret what constitutes vulnerable must also be identified. Fussel (2007) classifies vulnerability factors as being either internal or external to the system of interest and related to either socioeconomic or biophysical system characteristics. Socioeconomic factors relate to economic resources, political power, culture, and other social science related elements. Biophysical factors are system properties investigated by the physical sciences and engineering. This classification of vulnerability factors is consistent with that identified by United Nations (2004) as relevant in the context of disaster reduction.

### Components of vulnerability

The terminology presented in the previous section provides a general conceptual description of vulnerability. Much of the literature related to coastal vulnerability discussed previously is focused on climate change, but the concepts and definitions are applicable for assessing vulnerability to the coastal storm hazards. Therefore, concepts developed by the 2007 Intergovernmental Panel on Climate Change (IPCC) (2007) are adopted here in defining a conceptual methodology for assessing vulnerability. These concepts are generally applicable and valid for coastal and non-coastal hazards, both continuous and discrete. The IPCC (2001, 2007) states that coastal vulnerability is a function of the character, magnitude, and rate of climate change to which a system is exposed, the sensitivity of the system, and the system's adaptive capacity. As Ramieri et al. (2011) indicate, the definition implies three important elements:

**Exposure** is the nature and magnitude of the hazards by which a system is threatened.

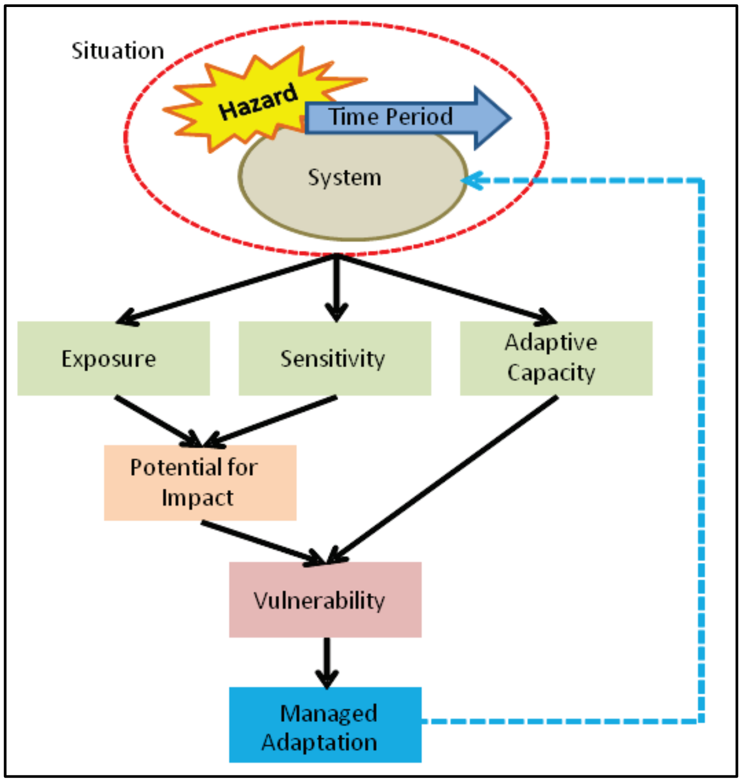
**Sensitivity** relates to the potential of the system's valued attributes or functions to be affected (either positively or negatively) by the changes caused by a hazard.

**Adaptive Capacity** describes a system's ability to evolve, either naturally or through engineered maintenance activities, in such a way as to preserve or enhance the system's valued functions.

In order to be comprehensive, a vulnerability assessment must address all three components.

Figure 12 provides a graphical representation defining vulnerability and related concepts. Considering a given system, a specific hazard, and the appropriate time period, internal and external biophysical and socioeconomic factors are identified to describe the exposure, sensitivity, and adaptive capacity of a system's valued functions. The exposure and sensitivity of a system ultimately determines the potential impacts to the system from the hazard.

Figure 12. Vulnerability and related concepts.




The main purpose of vulnerability assessment is typically to provide information to guide the coastal zone management planning and design process, ensuring that system valued functions are maintained through adaptation to and/or mitigation of hazardous effects. This managed adaptation is a function of policy and decision-making objectives of society and can inform efforts to increase adaptive capacity and/or reduce exposure and sensitivity of the system as illustrated in Figure 12.

It is important to note that a complete picture of vulnerability is not obtained until the adaptive capacity of the system to bounce back from the impacts and regain functional performance or ecological benefit is included. This is particularly important in the case of NNBF as the autonomous adaptation of natural systems may be a key component in reducing vulnerability.

Vulnerability metrics must capture (whether quantitatively, semi-quantitatively, or qualitatively) the exposure, sensitivity, and adaptive capacity of a system (or valued system functions) in order to provide a complete measure of vulnerability. Exposure and sensitivity metrics provide a measure of the potential for impacts of a hazard on the system of interest, whereas adaptive capacity metrics measure the ability of the system to recover from the hazard. Vulnerability metric development should be guided by this methodology to ensure essential elements of vulnerability are not omitted from the analysis.

#### Risk versus vulnerability

Terms such as risk, hazard, and vulnerability tend to be used interchangeably in colloquial language, but represent separate and distinct concepts. In a seminal work in the field of risk analysis, Kaplan and Garrick (1981) define risk as a triplet comprised of the answers to three questions:

- What can happen? (i.e., What can go wrong?)
- How likely is it that that will happen?
- If it does happen, what are the consequences?

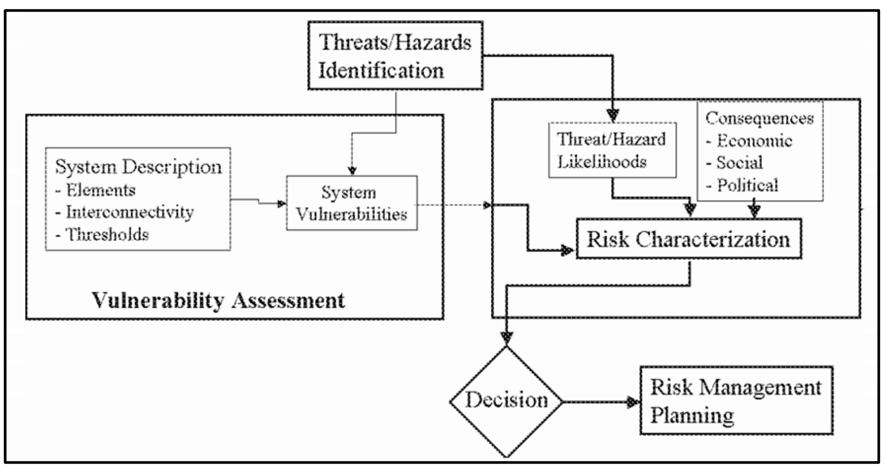
Within this methodology, what can happen/go wrong is identified as a hazard. Skipping to the last question, the consequences of the hazard can be thought of as the effects resulting from the impacts on the valued function. Vulnerability thus relates to the first question–will the hazard have an adverse effect on the system? In probabilistic risk assessment, vulnerability can be thought of as a conditional probability of an adverse effect given a specific hazard. Therefore, even in the presence of hazards, a low vulnerability mitigates the overall risk. From this perspective, the components of vulnerability (exposure, sensitivity, adaptive capacity) can be thought of as the primary means in which to enhance protection of a system from the harmful end effects caused by the hazard.

When vulnerability is viewed in conjunction with a well defined hazard and the resultant negative effects on system performance, risk is fully expressed. While risk can be considerably mitigated through effective vulnerability reduction efforts, it is impossible to fully eliminate all risk. This remaining risk that is not eliminated through control measures is known as residual risk.

> Engineers and planners can reduce their residual risk by reducing their vulnerability to hazards in three ways: decreasing the system's exposure, decreasing the system's sensitivity, or increasing the system's adaptive capacity—or some combination of these. However, projects aimed at reducing vulnerability also come with associated costs—hence the notion of buying down the risk. Given budgetary constraints, it is imperative to understand the benefits (in terms of risk reduction) versus associated costs with proposed NNBF improvement projects.

There is often confusion regarding vulnerability assessment versus risk analysis, and it is important to clarify the difference to define the minimum requirements for metrics to be developed. A vulnerability assessment is a component of a risk analysis as illustrated in Figure 13 from Baker (2005). A vulnerability assessment essentially answers the question of what can go wrong within a specific system subjected to a specific hazard, but does not necessarily address the likelihood that damage will occur or the resulting consequences (Baker 2005). A vulnerability assessment, however, may incorporate a probabilistic approach to understanding the likelihood that a particular system may be vulnerable to a given hazard such as a storm. For example, a system may not be vulnerable to a 100 yr return period storm (or less), but could catastrophically fail when faced with a 500 yr event. A vulnerability assessment is not required to explicitly address the consequences of a system failure unless such a failure or effect further increases the vulnerability of the system of interest.

Figure 13. Risk analysis process (Baker 2005).




### Resilience versus vulnerability

The vulnerability of a valued function of the coastal system, a coastal project, or an integrated coastal system can be assessed as it relates to one hazard at a snapshot in time, or it can be integrated over the lifetime of the attribute, project, or system. An example of a vulnerability snapshot would be whether infrastructure along a beach is vulnerable to surge from an approaching storm, whereas an integrated vulnerability assessment would consider the lifespan of that infrastructure and the likelihood of surge over that duration in time. Ultimately, the vulnerability of coastal projects must inherently integrate vulnerability over the lifetime of the project against a number of known and sometimes unknown hazards, and the adaptability of the system over time must be taken into consideration.

This introduces the concept of resilience:

**Resilience** is the ability of a system to prepare for, resist, recover, and adapt to achieve functional performance under the stress of both natural hazards and human-related disturbances through time.

Although it is important to understand how resilience and vulnerability are related, there is still disagreement among researchers. One of the complicating factors in the discussion of definitions of resilience is that scholars identify different types of resilience. Gallopin (2006) and Walker et al. (2004) distinguish between engineering resilience and ecological resilience, and Schultz et al. (2012) identify a third category of community resilience. In the case of communities, resilience is an informed process that addresses social, economic, cultural, technical, and natural dimension of society and prepares a community to consciously mitigate rather than ignore vulnerabilities and risk (U.S. Department of Homeland Security (DHS) 2013). Given the multiple conceptions of resilience and multiple possible conceptions of vulnerability (Cutter 1996), it is not surprising that there are multiple ways in which to think about how resilience relates to vulnerability. Some view the concepts of vulnerability and resilience as roughly antonyms (Hashimoto et al. 1982; Fujita et al. 2013; Aven 2011), while others (Gallopin 2006) view resilience as a component of adaptive capacity, and therefore a component of vulnerability. In fact, it has even been put forward that resilience is not always a desirable trait (Gallopin 2006; Walker et al. 2004). Table 7 summarizes definitions from several recent studies with these key words identified.

As the table presents, resilience has different meanings when applied to engineering, ecological, or community systems. Engineering resilience implies achieving predictable, constant functional performance under a range of stresses. Engineering systems have not traditionally been considered capable of naturally adjusting or adapting to change while still providing the desired functional service, although there are exceptions (e.g., a storm surge barrier that raises or lowers depending on flood elevation; an engineered beach nourishment that reduces storm surge and naturally rebuilds following the storm). Ecological resilience incorporates

Table 7. Definitions of resilience used by various organizations in recent studies; the key words (or synonyms) are prepare, resist, recover, and adapt.

| Study | Definition |
|---|---|
| American Society of Civil Engineers (ASCE) (2006) http://www.asce.org/Content.aspx?id=8478 | “Resilience refers to the capability to mitigate against significant all-hazards risks and incidents and to expeditiously recover and reconstitute critical services with minimum damage to public safety and health, the economy, and national security.” |
| National Disaster Recovery Framework, Strengthening Disaster Recovery for the Nation (Federal Emergency Management Agency (FEMA) 2011) http://www.fema.gov/media-library/assets/documents/24647?fromSearch=fromsearch&id=5124 | A resilient community has “an improved ability to withstand, respond to and recover from disasters.” |
| The Infrastructure Security Partnership and Society of Military Engineers (SAME). “Understanding Resilience – Disaster Resilience Begins with You” (2012) http://tisp.org/tisp/file/PROOF_121820_SAME_Booklet.pdf | Disaster Resilience is “the capacity, and the capability, to recover rapidly with limited damage.” |
| Disaster Resilience – A National Imperative (National Academies of Science 2012) http://www.nap.edu/catalog.php?record_id=13457 | “Resilience is the ability to prepare and plan for, absorb, recover from, and more successfully adapt to adverse events.” |
| Hurricane Sandy Rebuilding Strategy: Stronger Communities, A Resilient Region (Hurricane Sandy Rebuilding Task Force 2013) http://portal.hud.gov/hudportal/documents/huddoc?id=HSRebuildingStrategy.pdf | “The ability to prepare for and adapt to changing conditions and withstand and recover rapidly from disruptions.” |
| NOAA’s 2013 Infrastructure Rebuilding Principles http://coastalmanagement.noaa.gov/resources/docs/infsysrebuildingprinciples.pdf | “Ability to adapt to changing conditions and withstand and rapidly recover from disruption due to emergencies.” |
| Coastal Risk Reduction and Resilience: Using the Full Array of Measures. USACE (2013) http://www.corpsclimate.us/docs/USACE_Coastal_Risk_Reduction_final_CWTS_2013-3.pdf | “The ability to anticipate, prepare for, respond to, and adapt to changing conditions and to withstand and recover rapidly from disruptions with minimal damage.” |
| Urban Land Institute, “After Sandy: Advancing Strategies for Long-term Resilience and Adaptability” (2013) http://www.uli.org/wp-content/uploads/ULI-Documents/AfterSandy.pdf | “The capacity of a community to recover after a disaster and to return to its state before the event.” |
| Presidential Executive Order on Climate Change, http://www.whitehouse.gov/the-press-office/2013/11/01/executive-order-preparing-united-states-impacts-climate-change (Whitehouse 2013) | "Resilience means the ability to anticipate, prepare for, and adapt to changing conditions and withstand, respond to, and recover rapidly from disruptions.”. |
| Rockefeller Foundation (2013) http://www.rockefellerfoundation.org/blog/city-resilient | “The capacity of individuals, communities and systems to survive, adapt, and grow in the face of changes, even catastrophic incidents.” |
| Community and Regional Resilience Institute (CARRI) (2013) http://www.resilientus.org/wp-content/uploads/2013/08/definitions-of-community-resilience.pdf | “Community resilience is the capability to anticipate risk, limit impact, and bounce back rapidly through survival, adaptability, evolution, and growth in the face of turbulent change” |
| USACE Safety of Dams, Policy and Procedures, ER 1110-2-1156 (2014) http://www.publications.usace.army.mil/Portals/76/Publications/EngineerRegulations/ER_1110-2-1156.pdf | “The ability to avoid, minimize, withstand, and recover from the effects of adversity, whether natural or manmade, under all circumstances of use.” |
| Intergovernmental Panel on Climate Change Fifth Assessment Report, “Climate Change 2014: Impacts, Adaptation, and Vulnerability” (2014) http://ipcc-wg2.gov/AR5/images/uploads/WGIIAR5-Glossary_FGD.pdf | “The capacity of a social-ecological system to cope with a hazardous event or disturbance, responding or reorganizing in ways that maintain its essential function, identity, and structure, while also maintaining the capacity for adaptation, learning, and transformation” |

the concept that natural systems can adapt such that similar functional services are provided as conditions change with time. An example is a wetland that can accrete vertically through organic and mineral sedimentation such that it maintains desired elevation (and continues functional performance as habitat) with increasing relative sea level rise. Resilient communities, like resilient ecological systems, can adapt to continue desired functions. Unlike ecological systems, resilient communities (individuals and political entities) have the capacity to learn and make conscious decisions to avoid future loss in functioning, conditioned on the type of disturbance.

It is beyond the scope of this chapter to resolve all of these differences; however, it is clear that the concepts of vulnerability and resilience are related, but distinct. It is also clear that designing for resilience will require a shift in the prevailing design thinking. Park et al. (2012) identify design processes involving inclusion of continuous system monitoring, recognition and acceptance of uncertainty, and a departure from traditional fail-safe designs towards more adaptable safe-fail designs all as ways in which resilience can be designed into systems. Park et al. (2012) also note that designing for resilience is an iterative process, involving the sequence of sensing, anticipation, learning, and adaptation.

In the context of vulnerability and resilience assessments, and in particular the development of vulnerability metrics, the interest is in measuring resilience as a characteristic of a system for the given time period of interest. For NNBF, the processes of natural adaptation are a characteristic of the system itself, whereas managed adaptation is a human process that can increase the adaptive capacity of a system or reduce its exposure and sensitivity. Managed adaptation, when instituted, may then become a characteristic of system. An example of a resilient NNBF with natural adaptation would be a freshwater wetland that becomes more saline with sea level rise and is able to convert to salt water marsh vegetation. For this same wetland, managed adaptation would be diverting a nearby river to provide more freshwater to the marsh, thereby reducing the salinity and attempting to maintain the system’s freshwater wetland functionality.

## Review of selected previously developed coastal vulnerability metrics

A number of previous studies have demonstrated various approaches to coastal vulnerability assessment. The assessments have been conducted for various hazards (e.g., sea level rise, coastal erosion) at multiple spatial scales (global to local). The review contained in this section is not intended to be comprehensive, but to provide examples of metrics and approaches used by others to assess vulnerability, which includes metrics upon which vulnerability value judgments are made. Comparison of previous approaches demonstrates the subjective nature of developing vulnerability metrics.

One of the earliest attempts to assess coastal vulnerability was developed by Gornitz and Kanciruk (1989). While the focus of the study was to assess vulnerability primarily to sea level rise, the approach considered multiple hazards and system characteristics and combined the identified vulnerability factors to obtain an index of coastal vulnerability. The approach of Gornitz (Gornitz and Kanciruk 1989; Gornitz et al. 1991; Gornitz and White 1992) identified seven metrics (elevation, geology, geomorphology, sea level trends, shoreline displacement, tide range, and wave height), and then assigned a relative vulnerability value on a linear scale of 1 to 5 based on classifications and value judgments as to how the metrics relate to the inundation and erosion damage drivers.

A summary of the assignment of relative vulnerability made in these studies is provided in Table 8. Note that for sea level trends, Gornitz assumed a single value of eustatic sea level rise for the U. S. coast, and therefore only subsidence was assigned relative vulnerability values. Also note that the assignment of the values is highly subjective and is dependent upon the spatial scale of the assessment. For example, the classification of the geology in Table 8 for an assessment of the Gulf coast would have very little meaning as the entire region would be classified as having a very high relative vulnerability.

Thieler and Hammer-Klose (1999, 2000a, 2000b) adopted the general approach of Gornitz for assessing vulnerability along the U.S. shorelines. The approach is aimed at identifying the relative vulnerability of different coastal environments to sea level rise by assessing the coastal system's susceptibility to change with its natural ability to adapt to changing environmental conditions. Thieler and Hammer-Klose (1999, 2000a, 2000b) identified six metrics for their assessment and assigned relative vulnerability values based on the potential magnitude of each factor's contribution to physical changes on the coast as sea level rises. Different values were assigned for each coast (Atlantic, Pacific, and Gulf) and are summarized in Appendix D (Table 63, Table 65). The data that define the various metrics are both quantitative and qualitative. The vulnerability for the quantitative metrics are based on data value ranges (i.e., coastal slope, relative sea level change, shoreline displacement, tidal range, and wave height) while the non-numerical geomorphology metric is ranked according to the relative resistance of a given landform to erosion.

Table 8. Relative risk metrics assigned by Gornitz (Gornitz and Kanciruk 1989; Gornitz et al. 1991; Gornitz and White 1992) for a Coastal Vulnerability Index (CVI).

| Factor | Very Low<br>1 | Low<br>2 | Moderate<br>3 | High<br>4 | Very High<br>5 |
|---|---|---|---|---|---|
| Mean elevation (m) | >30.0 | 20.1 to 30.0 | 10.1 to 20.0 | 5.1 to 10.0 | 0.0 to 5.0 |
| Geology | Igneous rock<br>Lava | Metamorphic rock | Sedimentary rock (e.g., shale, sandstone, limestone) | Gravel<br>Glacial till | Unconsolidated sediments (e.g., sand, silt, clay) |
| Geomorphology | Rocky-cliffed coasts<br>Fiords | Medium cliffs<br>Indented coasts | Low cliffs<br>Salt marsh<br>Coral reefs | Beaches<br>Lagoons<br>Alluvial plains | Barrier beaches<br>Mudflats<br>Deltas |
| Subsidence trend (mm/yr) | <-1.0<br>Land rising | -1.0 to 1.0 | 1.1 to 2.0 | 2.1 to 4.0 | >4.0<br>Land sinking |
| Mean shoreline displacement (m/yr) | >2.0<br>Accretion | 1.1 to 2.0 | -1.0 to 1.0 | -2.0 to -1.1 | <-2.0<br>Erosion |
| Mean tidal range (m) | <1.0<br>Microtidal | 1.0 to 1.9 | 2.0 to 4.0 | 4.1 to 6.0 | >6.0<br>Macrotidal |
| Maximum significant wave height (m) | 0.0 to 2.9 | 3.0 to 4.9 | 5.0 to 5.9 | 6.0 to 6.9 | >6.9 |

Several modifications in assigning values are evident when comparing Theiler (Table 63 and Table 65) with Gornitz (Table 8). Only the shoreline displacement metric vulnerability values are identical. The relative sea level change metric from Thieler includes both the eustatic and subsidence component, but still assumes a constant eustatic rate for the entire U.S. coast as was the case in the Gornitz index. The geomorphology metric value assignments are similar, but some landforms have been given different values. For example, Gornitz assigned salt marsh a vulnerability value of 3 while Thieler assigns it with a very high vulnerability ranking of 5. This highlights the subjective nature of assigning values that will depend on the purpose and decision-making objectives of the vulnerability assessment. Thieler has removed elevation and geology as metrics and coastal slope have been added. In Thieler, the geomorphology metric expresses the relative erodibility of different landforms and the regional coastal slope permits and evaluation of not only the relative risk of inundation, but also the potential rapidity of shoreline retreat (Thieler and Hammer-Klose 2000b). The coastal slope is generally calculated from land elevations extending landward and seaward of the shoreline from the coastal plain to the continental shelf. For wave height, Gornitz used the maximum significant wave height while Thieler chooses to use a mean wave height. An interesting difference in the two indices is the mean tide range. Gornitz assigned coastlines with a large tidal range as highly vulnerable because a large tidal range is associated with strong tidal currents. Thieler reversed the value assignment based primarily on the potential influence of storms on coastal evolution and their impact relative to tidal range (Thieler and Hammer-Klose 2000b).

Comparing Table 63 and Table 65 to one another, it can be seen that geomorphology, shoreline erosion/accretion, and mean tide range are all assigned identical vulnerability values. However, coastal slope, relative sea level change, and mean wave height are assigned different values for all three coastal regions. The varying values reflect the different coastal characteristics and forcing found for the Atlantic, Pacific, and Gulf coasts and allows for identification of relative vulnerability within the region. Note that the relative vulnerability among the coastal regions cannot be determined using these three distinct scales.

Boruff et al. (2005) examined the vulnerability of the U.S. coast to erosion by combining Thieler's physically based coastal vulnerability index with a socioeconomic vulnerability index. The social vulnerability index was developed by first identifying 39 socioeconomic variables (Table 66). These variables were placed in a principal component analysis to identify 10 factors (Table 67) that explained the majority of vulnerability variance for U.S. coastal counties. Note that Boruff et al. (2005) found that biophysical factors were the primary determinant of overall vulnerability for the Atlantic and Pacific coasts, but socioeconomic factors were found to be the primary driver for the Gulf coast vulnerability.

McLaughlin and Cooper (2010) developed a coastal erosion vulnerability index for Northern Ireland that followed the general approach of Gornitz (1989). The conceptual basis for the McLaughlin and Cooper erosion vulnerability index is consistent with other approaches in that overall vulnerability is determined by physical coastal characteristics (e.g., geology, elevation), coastal forcing (i.e., tide range, wave height, storm frequency), and socioeconomic characteristics (i.e., population, cultural heritage, land use). A summary of the assignment of the vulnerability values made in this study are provided in Table 68 and Table 69. Table 68 lists metrics applicable at a regional scale while Table 69 summarizes value assignments for local scale vulnerability assessments. McLaughlin and Cooper (2010) found that although a common index architecture can be applied, the selection of factors and metric used to measure them must consider the scale at which the hazard is being assessed.

The values summarized in Table 68 and Table 69 are specific to the northern Irish coast and may not be applicable for other coastlines. However, many of the metrics are transferable to other regions and several deserve additional discussion. McLaughlin and Cooper (2010) followed Thieler and Hammer-Klose (1999, 2000a, 2000b) in assigning macrotidal areas as less vulnerable as a high tidal range is typically associated with a wide intertidal area which dissipates wave energy. The presence of rivers within a given distance was chosen to have a high vulnerability value assigned as river mouths are potential zones of higher erosion vulnerability due to their generally lower elevation and the potential for them to migrate. McLaughlin and Cooper (2010) also identified the temporal variability in modal morphodynamic state of a beach as an important variable in determining potential vulnerability. The modal state is closely related to the mobility of the beach (Wright and Short 1984; Wright et al. 1985) and reflects the modal breaker height and dominant sediment characteristics. Dean's parameter (Dean 1973) can be used to predict the morphodynamic state of the beach as it is a function of significant breaking wave height, incident wave period, and sediment settling velocity. The temporal variability of Dean's parameter expresses the temporal variability of the beach state and therefore the difference in Dean's parameter for modal and storm waves was considered an indicator of greater potential vulnerability. Rocky shores and other-than-sand beaches were assigned a very low vulnerability to erosion value. Reflective and dissipative beaches (Dean's parameter <1.5 or >5.5 for the northern Irish coast) were assigned a low vulnerability value as they are at the extremes of beach state and are normally slow to shift from these states. Beaches that move between the reflective and intermediate states were assigned a moderate vulnerability value, and those that move between intermediate and dissipative were considered to have high vulnerability. The reason reflective-to-intermediate beaches are considered to have lower vulnerability is that the range of Dean's parameter is narrower for these beaches and therefore considered less mobile. The highest vulnerability is assigned to beaches that move through all beach states as they are the most mobile.

Abuodha and Woodroffe (2006) developed an index to assess the vulnerability of the Australian coast to climate change. They slightly modified Gornitz (Gornitz and Kanciruk 1989; Gornitz et al. 1991; Gornitz and White 1992) and Thieler and Hammer-Klose (1999, 2000a, 2000b) to develop an index applicable on a local scale for the Australian shoreline. Because the Australian coast is primarily barrier beaches, the mean elevation, geology and geomorphology metrics of Gornitz (Table 8) were replaced with dune height, barrier type, and beach type (Table 70).

Barrier types were classified according to Thom et al. (1978) based on depositional environments and histories. Transgressive barriers are attributed to locally high rates of sand supply at the downdrift terminus of a littoral system. Because of the abundant sand supply, these barriers are classified as having very low vulnerability. Prograded barriers are typically characterized by multiple beach ridges and imply an ongoing supply of sand so it was deemed to have low vulnerability. Stationary barriers are generally narrower and characterized by vertical as opposed to lateral growth and are typically recognized based on the absence of progradation, implying less sand supply. The high and very-high vulnerability classifications are assigned to receded barriers and mainland beach barriers, respectively. Receded barriers are thin marine sand deposits over estuarine or back bays sediments, and mainland beaches are thin veneers of sand over pre-Holocene erosional substrate.

Beach type was assigned relative vulnerability values based on the ability of the beach to dissipate wave energy. Therefore, areas with dissipative beaches are assigned values indicating low vulnerability, and reflective beaches are considered to have high vulnerability. Note that this approach differs substantially from that of McLaughlin and Cooper (2010) who deemed beaches that were mobile to be indicative of beaches that were more vulnerable to coastal erosion, again illustrating the subjectivity of assigning vulnerability values.

Jimenez et al. (2009) developed a framework to determine the relative vulnerability of sites on the Mediterranean and Adriatic Seas to coastal storm wave runup inundation and erosion. Their analysis quantifies the vulnerability to inundation and erosion through process parameterization or numerical modeling. Additional details are provided in Appendix D.

Comparison of previous approaches demonstrates the subjective nature of developing vulnerability metrics. The various approaches differ in how vulnerability is measured as they depend on the purpose of the vulnerability assessment, the spatial and temporal scale for which the assessment is being conducted, the specific coastal characteristics for the area of interest, and data availability. Metrics can be both quantitative and qualitative. While qualitative metrics are non-numerical, they may still reflect measurable characteristics such as the relative resistance of a given landform to erosion. Comprehensive approaches recognize that overall vulnerability is determined by physical coastal characteristics (e.g., geology, elevation), coastal forcing (i.e., tide range, wave height, storm frequency), and socioeconomic characteristics (e.g., population, cultural heritage, land use). Finally, it is recognized that assessment of vulnerability can be improved through process parameterization and/or numerical modeling.

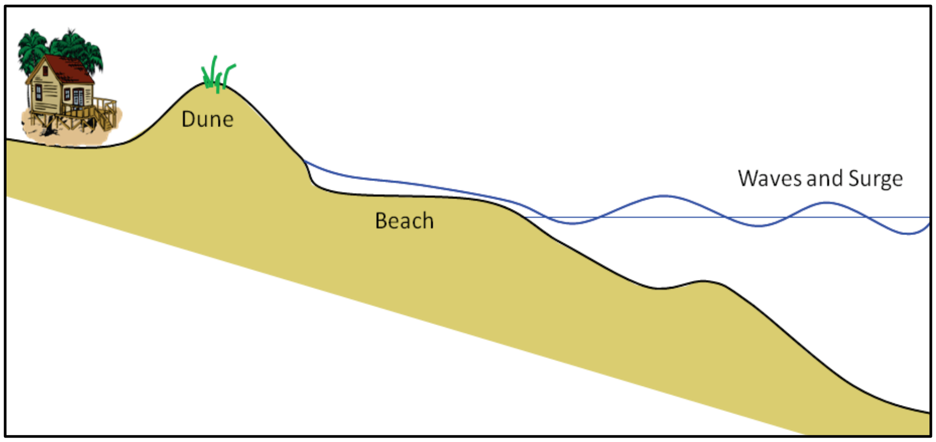
## Vulnerability metrics development process

A satisfactory conceptual approach for identifying and defining meaningful metrics must consider all dimensions of vulnerability. The approach documented in this section is designed to ensure a set of metrics is developed for a complete assessment of vulnerability for a wide range of systems and hazards at multiple scales. The focus of this chapter is on assessing vulnerability of natural and nature-based systems within a coastal landscape, and the approach is initially demonstrated through application to the simple, coupled, human-environment system shown in Figure 14. The system is a characteristic profile representing a coastline that includes a beach and dune system with a locally funded beach nourishment project that reduces risk of a community from the coastal storm hazard.

### Step 1: Identify purpose

The first step in the metric development process it to clearly identify and understand the policy and decision-making objectives that are hoped to be achieved through the vulnerability assessment. In October of 2010, the European Environment Agency (EAA) organized an expert workshop on methods for assessing coastal vulnerability to climate change. One of the main conclusions from the workshop was the need for coastal vulnerability assessments to have a clear definition of policy and decision-making objectives (Ramieri et al. 2011). The hazards, valued system functions, and temporal reference are all defined by the purpose of the vulnerability assessment. For the example represented by the simple system in Figure 14, a given purpose is to assess the vulnerability of the beach and dune system (an NNBF) to a 25 yr return period storm. Application of the metric development process in this section is informed by this stated purpose.

Figure 14. Simple, coupled, human-environment system.




**Step 2: Describe vulnerability profile**

The second step in the metric development process is to create a matrix of internal and external socioeconomic and biophysical factors to describe the vulnerability profile of a given system to a specific hazard at a given point in time or over a specified time period. A complete set of vulnerability metrics must necessarily address all dimensions (internal, external, biophysical, and socioeconomic) of vulnerability factors as it relates to each element (hazard, system, temporal reference) of a vulnerable situation. In completing the vulnerability profile, the analyst must be cognizant of how exposure, sensitivity, and adaptive capacity contribute to vulnerability as the metric development should explicitly consider each one of these elements. The vulnerability factors for the example situation are presented in Table 9.

These factors define the vulnerability profile for the given situation. This step should be considered a brain storming activity with the purpose of identifying as many vulnerability factors as possible to completely describe the situation. Some of the factors may not be utilized for metric development depending on the scope and purpose of the assessment, but it is prudent not to ignore or dismiss any factors at this stage in the process.

Table 9. Example situation vulnerability profile.

| Knowledge Domain | | |
|---|---|---|
| **Sphere (Scale)** | **Biophysical** | **Socioeconomic** |
| Internal<br>(Properties of the vulnerable system or community itself) | Beach berm | Building codes |
| | Beach slope | Community wealth |
| | Dune | Insurance |
| | Longshore transport processes | Emergency beach action plans |
| | Sediment supply | Pop mobility |
| | Coastal geology | Tourist beach recreation use |
| | Subsidence | |
| | Sensitive habitat on beach and dune | |
| | Beach nourishment project renourishment interval | |
| | Upland elevation | |
| | Sediment type | |
| | Vegetation type | |
| | First-floor structure elevation<br>Open water fetch | |
| External<br>(Something out-side the vulnerable system) | Surge | FEMA flood maps |
| | Waves | National emergency response policies |
| | Storm duration | |
| | Wave runup | |
| | Tide range | |
| | Eustatic sea level rise<br>Wind<br>Storminess | |

**Step 3: Define system components and valued functions**

Table 9 provides vulnerability factors for the entire situation described herein, but even this simple example is comprised of multiple systems or components. When developing metrics in this step of the process, it is instructive to break down the system of interest into its various components and valued functions. The components of the entire system in Figure 14 include the population or community (as represented by the house), as well as the beach and dune system. The resolution with which components of a system are broken down is based on experience and professional judgment of the individuals conducting the assessment and will depend on decision-making objectives, valued functions of the system or system components, and spatial scale of the analysis. In the simple example, the dune and beach may be considered a single integrated system, or separate systems for metric development. Likewise, the wildlife communities that live within the beach and dune system may be considered an integrated part of the system or treated separately. The metrics for each component can later be aggregated to describe the vulnerability of the larger system or system of systems, but metric development should begin at the component level as a vulnerability factor may be common to multiple components, but require different metrics to measure that factor.

Because vulnerability is based on human value judgments, the system components should be further resolved to the valued functions that the system component provides. A given system or system component may have multiple functions, but depending on the decision-making objectives of the vulnerability assessment, only certain valued functions may be of interest. Specifying the valued function of the system enables the identification of critical vulnerability metrics and prevents the inclusion of unnecessary metrics that could inappropriately skew results of an assessment.

Also note that a particular function may only be applicable at the entire system level, and a metric may only be meaningful at the entire system level. Metric development is therefore a cascading process that necessitates consideration of the entire system (or system of systems), as well as the individual components, in order to arrive at a final comprehensive set of metrics.

To illustrate, the system for the example application is divided into three sub-systems: (1) the community, (2) the beach, and (3) the dune system. Based on the stated purpose for the vulnerability assessment, there is interest in developing metrics to measure the vulnerability of the beach and dune systems, so the only need is to identify the valued functions of the beach and dune systems. The valued functions of the dune and beach systems identified for the example application are coastal (flood, wave damage, erosion), risk reduction, and beach recreation, respectively. Note, however, that community vulnerability is directly linked to the vulnerability of the coastal landscape and NNBF.

### Step 4: Link factors to functions

The fourth step in the process is to link the vulnerability factors and their characteristics to valued functions of the system. At this point in the process, exposure, sensitivity, and adaptive capacity of the system to the hazard must be explicitly considered. The factors identified in the matrix from Table 9 are classified as related to exposure, sensitivity, or adaptive capacity for each system valued function. A factor may be a consideration for multiple components of vulnerability and for multiple functions. Note that the actual classification of factors is not as important as ensuring that all components of vulnerability are considered.

Specific characteristics of the factors should be determined at this stage, if applicable. Many of these characteristics may be identified as individual metrics in the next step, or they may be combined to create metrics. For example, specific characteristics of waves (a vulnerability factor) might include wave height and wave period, because they contribute to the exposure of the system, and affect the vulnerability of the dune to provide coastal storm damage reduction (a valued system function). The result of this process is given in Table 10 for the example application. The factor identified in Table 9 is provided in parentheses to the identified characteristic (if it is different) to illustrate the progression toward a metric that is made in this step. In practice, this may be done to a certain extent in Step 2, but it must be done here and all three components of vulnerability must be explicitly considered.

Note that the exposure component of vulnerability is primarily populated by the external biophysical factors identified in Step 2. One exception is the beach slope, which is an internal biophysical factor. Beach slope is related to exposure as the slope exercises control on the wave energy that ultimately impacts the dry beach area that is of concern. The sensitivity factors largely stem from the internal biophysical factors, though they may also include some internal socioeconomic factors (e.g., building codes), depending upon the identified system of interest. Adaptive capacity factors are developed from both the biophysical and socioeconomic knowledge domains. Natural characteristics such as sediment type and long-term shoreline change rate that indicate whether the beach is accretive or erosive are determinants of the adaptive capacity. Perhaps more important on a developed coast is the community and its capacity (wealth) and motivation (e.g., economic stability) to restore the beach and dune to a healthy state.

Table 10. Vulnerability factor and system function matrix.

| Valued System Functions | Vulnerability Factors | | |
|---|---|---|---|
| | Exposure | Sensitivity | Adaptive Capacity |
| Coastal storm damage reduction | Water level (Surge)<br>Tide range<br>Wave height (Waves)<br>Wave period (Waves)<br>Wave runup (Waves)<br>Beach and nearshore slope<br>Storm duration<br>Storminess | Median sediment grain size (Sediment type)<br>Berm width (Beach berm)<br>Dune height (Dune)<br>Dune or dune field width (Dune)<br>Dune or dune field volume (Dune)<br>Presence of vegetation (Vegetation type)<br>Dune sediment compaction | Long-term shoreline change (Longshore transport processes and Sediment supply)<br>Emergency beach action plan<br>Beach renourishment interval<br>Community wealth<br>Tourist beach recreation use<br>Sediment type<br>Dune or dune field volume (Dune) |
| Beach recreation | Water level (Surge)<br>Wave height (Waves)<br>Wave period (Waves)<br>Tide range<br>Beach slope<br>Storm duration<br>Storminess | Median sediment grain size (Sediment type)<br>Berm width (Beach berm)<br>Dune or dune field volume (Dune) | Long-term shoreline change (Longshore transport processes and Sediment supply)<br>Beach renourishment interval<br>Community wealth<br>Tourist beach recreation use<br>Sediment type<br>Dune or dune field volume (Dune) |

Note that the specified valued function of the system of interest affects which vulnerability factors are used. For example, wave height and wave period are used to characterize the Waves factor for both the coastal risk reduction and beach recreation functions. This is because both are determinants of erosion potential, which affects the beach's ability to be used for recreation and the dune's ability to provide coastal storm damage reduction. The coastal storm damage reduction function also includes wave runup, as this is of primary concern for wave-induced flooding and overtopping of the dune system. Wave runup is, of course, a function of water level, wave height, wave period, and beach slope, but it is helpful to explicitly list processes that are primary vulnerability factors.

There are other differences evident between the risk reduction and recreation functions in Table 10 that illustrate the importance of identifying factors by function. For example, dune height is of less importance for the beach recreation function as the concern for this function is only the area of the beach that is used for recreation, namely the sub-aerial beach berm. Loss of the dune does not eliminate the recreation area. The presence of a dune may be beneficial as it can limit overwash which deprives the beach of sediment, and can also serve as a sediment source for the beach berm; thus, the dune volume factor is retained. For adaptive capacity, the emergency beach action plan drops out for recreation. The reason for this is that beach action plans are typically related to construction of an emergency dune through beach scraping or pushing overwash back into the dune field, neither of which benefits the beach recreation area.

A final note from Table 10 is to recognize that a factor may be relevant to more than one component of vulnerability. For example, sediment type characteristics are relevant for both sensitivity and adaptive capacity. For sensitivity, the sediment grain size is important as the finer the sediment, the more sensitive the beach and dune are to storm stresses. For adaptive capacity, the actual grain size is less of concern, but whether a beach is comprised of cohesive or sandy material is a factor. Sandy beaches recover rapidly after a storm as the sediment moved offshore during the storm and into a bar is returned to the beach. A beach comprised of primarily cohesive material does not have this characteristic.

### Step 5: Establish metrics

At the completion of Step 4, all factors that should be measured have been identified, and the metrics to quantify these factors can then be established. The development of metrics, however, will depend not only on what has been identified as important to measure, but also on the spatial scale of the vulnerability assessment and data availability. Vulnerability from hazards can be considered at various spatial scales (McLaughlin and Cooper 2010). As the spatial resolution of an analysis increases to the local scale, a greater level of detail is required to distinguish between areas of vulnerability. Consider, for example, dune height. For a regional assessment, an approximate range of dune heights across a reach may be sufficient, but at the local scale, detailed measurements are likely to be required. If sufficient resolution of data is not available, a particular metric may not be viable. In addition, the gradient of a particular metric may differ depending on the scale of the analysis, potentially rendering a metric useless at one scale even though it may be quite valuable at another. For example, tidal range may be an appropriate metric to help identify vulnerable areas at a global or regional scale, but at the local scale it may change so little spatially that it becomes obsolete. In addition, when defining metrics, consideration must be given to issues of metric quality. While several lists of desirable qualities for metrics exist, generally speaking, metrics should be operational, direct, relevant, unambiguous, measurable, understandable, analytically sound, responsive, anticipatory, and comprehensive (McKay et al. 2012; Convertino et al. 2013).

Table 11 lists the metrics developed for the beach and dune system for the coastal storm damage reduction and recreation valued functions. Also included in the table are the factors each metric is intended to measure. For most metrics, the factor they measure is self evident, and in some cases, the metric and the factor are identical. However, for some metrics, it is not as clear, and an analyst may need to exercise some creativity in metric development depending on the data available as well as other considerations. For example, note that storm duration and storminess is being measured by a shoreline change variance metric. It can be difficult to obtain measurable data on both the number of storms that impact a given coastline, and storm durations. Therefore, shoreline change variance is used as a proxy for these factors as the erosional impact of the storms on the shoreline will be reflected in this metric. Emergency beach action is another factor that may be difficult to measure. For this example, the value of the property in the area of interest and the amount of traffic traveling on the roads through that area are used as a proxy as to the likelihood that emergency actions will be taken.

Table 11. Vulnerability metrics developed for the beach and dune system.

| System Function | Metric | Related Factor(s) |
|---|---|---|
| Coastal storm damage reduction | Surf zone slope (%) | Beach and nearshore slope |
| | Beach slope (%) | Beach and nearshore slope |
| | Sediment grain size (mm) | Sediment type |
| | Beach berm width (m) | Berm width |
| | Shoreline change variance (m) | Storm duration; Storminess |
| | Long-term shoreline change rate (m) | Long-term shoreline change |
| | Average dune elevation (m) | Dune height |
| | Alongshore dune elevation variance (m) | Dune height |
| | Dune field volume (m3) | Dune field volume; Dune field width |
| | Dune vegetation coverage (%) | Presence of vegetation |
| | Vegetation type (Manning's n) | Presence of vegetation |
| | Dune age (yr) | Dune sediment compaction |
| | Max still-water elevation level (m) [Water level] | Water level |
| | Max wave runup elevation (m) | Wave height, period; Wave runup; Beach slope |
| | Max wave height (m) | Wave height |
| | Tidal range (m) | Tidal range |

| System Function | Metric | Related Factor(s) |
| --- | --- | --- |
| Coastal storm damage reduction | Traffic volume | Emergency beach action plan |
| | Median Income ($) | Community wealth |
| | Property values ($) | Emergency beach action plan; Tourist beach recreation use |
| | Scheduled renourishment interval (yr) | Beach renourishment interval |
| Recreation | Surf zone slope (%) | Beach and nearshore slope |
| | Beach slope (%) | Beach and nearshore slope |
| | Sediment grain size (mm) | Sediment type |
| | Beach berm width (m) | Berm width |
| | Shoreline change variance (m) | Storm duration; Storminess |
| | Long-term shoreline change rate (m) | Long-term shoreline change |
| | Dune field volume (m3) | Dune field volume; Dune field width |
| | Max still-water elevation level (m) [Water level] | Water level |
| | Max wave runup elevation (m) | Wave height, period; Wave runup; Beach slope |
| | Max wave height (m) | Wave height |
| | Median Income ($) | Community wealth |
| | Property values ($) | Tourist beach recreation use |
| | Scheduled renourishment interval (yr) | Beach renourishment interval |

*Any metric listed here may not be viable if data are unavailable or lacking to characterize conditions.

Note that the metrics identified do not all contribute to vulnerability equally. Certain metrics are much more important than others, depending on the function being considered. For example, in terms of storm damage reduction, dune elevation is much more important than vegetation cover or dune age. The relative importance of various metrics is considered in the vulnerability assessment when vulnerability values are assigned and the various metrics integrated.

## Vulnerability metrics for coastal landscapes

Metrics for the multiple coastal classifications identified in Chapter 2 were developed following the approach documented herein. The metrics identified are not necessarily all inclusive, nor may they all be necessary, depending on the purpose of a given vulnerability assessment. The purpose of the metrics presented in this section is to provide suggestions on metrics that may be beneficial for the following:

- assessing relative vulnerability of coastal landscapes along the northern Atlantic coast
- understanding how NNBF influence vulnerability of a coastal landscape

- understanding vulnerability of specific NNBF.

The actual number of metrics applied for a vulnerability assessment should typically be as few as possible with the most informative and important metrics taking precedence as discussed herein. Metrics for marine depositional coastal landscapes (Figure 8) are provided in the next section as example of the process.

Note that metrics for drowned river valley coasts (Figure 4), drowned glacial erosional coasts (Figure 6), and glacial depositional coasts with and without bluffs (Figure 7) are offered in Appendix E. Appendix F offers an example of metric quantification using GIS-based methodologies to characterize a portion of the New Jersey coastline.

### Marine Depositional Barrier Coast (II B 1) vulnerability metrics

Figure 8 illustrates a marine depositional coast and is representative of a landscape found, for example, along the Virginia coast. Following the process described earlier, the set of metrics developed for this coastal landscape in determining vulnerability to coastal storms is given in Table 12. Table 12 also presents the reason each metric is included. The metrics in Table 12 are for consideration at the landscape scale. The following section presents metrics at the individual feature scale, and those should be considered, depending on the spatial scale and purpose of the vulnerability assessment.

Table 12. Vulnerability metrics for marine depositional barrier coast landscape.

| Metric | Reason |
|---|---|
| **Coastal Characteristics** | |
| Average elevation at point of interest (m) | Primary driver of coastal vulnerability to storms and should always be included as a metric. |
| Max elevation between point of interest and nearest shoreline (m) | Considers the presence of protective features (e.g., dunes and levees). |
| Shoreline sediment median grain size (mm) | Used as a measure of the erodibility of the coastline and the ability of the shoreline to recover (e.g., gravel vs. sand vs. clay) |
| Distance from point of interest to nearest shoreline (m) | Accounts for presence of the landmass, which dissipates wave energy, slows surge propagation, and provides a buffer for erosion. Shoreline could be considered at multiple datums such that sub-tidal features could be accounted for, if desired. |
| Land cover type along distance from point of interest to nearest shoreline (Manning's n) | The coverage on a landmass also influences wave energy dissipation, surge propagation, and erodibility. |
| Open-water fetch from nearest shoreline (km) | In the absence of wave and water level data, can be used, along with wind data, as an indicator of the wave energy and storm surges to which shoreline may be subject. |

| Metric | Reason |
|---|---|
| Nearest shoreline change variance (m) | A proxy for measuring the storminess along a sandy coastline, particularly as an indicator of how storminess effects the erosion hazard. |
| Long-term nearest shoreline change rate (m) | An eroding shoreline is more vulnerable than an accreting shoreline, and recovery of a beach along a chronically eroding shoreline is less likely. |
| Average max elevation between nearest shoreline and open coast (m) | Accounts for the presence of a landmass, such as a barrier island, offshore the nearest shoreline. |
| Landmass area between nearest shoreline and open coast (km2) | Accounts for the presence of a landmass, such as a barrier island, offshore the nearest shoreline. |
| Coastal slope (%) | In the absence of water level data, may be used as an indicator of storm surges that an area may experience during a storm. |
| Open coast shoreline sediment median grain size (mm) | Used as a measure of the erodibility of the coastline and the ability of the shoreline to recover (e.g., gravel vs. sand vs. clay) |
| **Forcing** | |
| Max still-water elevation (m) | Primary driver of coastal vulnerability to storms. Application of statistically derived values allows for the consideration of storminess over the temporal reference of interest. |
| Max wave height (m) | Important driver of coastal vulnerability to storms. Application of statistically derived values allows for the consideration of storminess over the temporal reference of interest. |
| Max wave runup elevation (m) | Not typically available directly from data, but may be calculated based on other available date (e.g., offshore wave height, period, and beach slope). May be the primary source of flooding on some coasts. |
| Max wind speed (m/sec) | Should be considered as a damage driver and can also be used to estimate other metrics (such as wave heights) in the absence of that data. |
| Relative sea level rise (mm/yr) | Important consideration for vulnerability assessments with a long temporal reference. |
| Tidal range (m) | Shorelines with large tidal ranges typically dissipate more wave energy. |
| **Socioeconomic** | |
| Pop | Because vulnerability is based on human value judgments, the presence of humans on a coast must be a consideration and also increases the likelihood of planned adaptation. |
| Land cover | Indicator of coastal land use and the likelihood of planned adaptation and emergency response activities. |
| Median income ($) | Indicator of a community's ability to engage in planned adaptation and emergency response activities. |
| Property values ($) | Indicator of coastal land use and the likelihood of planned adaptation and emergency response activities. |
| Traffic volume | Indicator of the likelihood of planned adaptation and emergency response activities. |

### Specific NNBF vulnerability metrics

Table 13 lists the set of metrics developed for individual coastal landscape NNBF for determining vulnerability to coastal storms. Table 13 also documents the reason each metric is included. Only the metrics related to the coastal characteristic itself are shown in Table 13 as the coastal forcing and socioeconomic metrics are consistent with those presented in Table 12. The metrics for the individual features reflect a smaller spatial scale of consideration, but are generally consistent with the landscape scale metrics. Other metrics such as geologic setting, sediment supply, and relative sea level change affect the long-term viability of these features and are implicitly included in Table 13 as reflected in other metrics.

Table 13. Vulnerability metrics for selected nature-based features.

| Metric | Reason |
|---|---|
| **Barrier Island** | |
| Average maximum elevation (m) | Primary driver for vulnerability of barrier islands to storms is elevation and width. Barrier island breaching typically occurs at the lowest and narrowest location along the island. |
| Alongshore maximum elevation variance (m) | |
| Average barrier width (m) | |
| Minimum barrier width (m) | |
| Fetch of back barrier open water (km) | Barrier islands can breach from the return flow to the ocean after a storm passes. The larger the storage area behind the barrier the greater the vulnerability to return-flow breaching. |
| Sound-side nearshore depth (m) | The deeper the sound-side bathymetry, the more likely a breach will occur. |
| Shoreline change variance (m) | A proxy for measuring the storminess along a sandy coastline, particularly as an indicator of how storminess effects the erosion hazard. |
| Long-term shoreline change rate (m) | An eroding shoreline narrows the barrier island and can lead to dune lowering, making it more susceptible to breaching and other storm-induced damage. |
| Barrier vegetation coverage (%) | Vegetation can reduce losses from erosion and also facilitates natural barrier recovery. |
| Coastal slope (%) | In the absence of water level data, may be used as an indicator of storm surges that an area may experience during a storm. |
| Shoreline sediment median grain size (mm) | Used as a measure of the erodibility of the coastline and the ability of the shoreline to recover (e.g., gravel vs. sand vs. clay). |
| **Beach** | |
| Sediment median grain size (mm) | Used as a measure of the erodibility of the coastline and the ability of the shoreline to recover (e.g., gravel vs. sand vs. clay). |
| Surf zone slope (%) | Indicator of nearshore wave energy dissipation. |

| Metric | Reason |
| --- | --- |
| Beach slope (%) | Influences wave runup and therefore the likelihood of sediment loss from overwash. |
| Beach berm width (m) | The wider the beach the less vulnerable it is to catastrophic erosion. |
| Shoreline change variance (m) | A proxy for measuring the storminess along a sandy coastline, particularly as an indicator of how storminess effects the erosion hazard. |
| Long-term shoreline change rate (m) | An eroding shoreline narrows the beach and the long-term rate is an indicator of the prevailing driving processes. |
| Distance to nearest inlet (m) | Higher erosion vulnerability near inlets due to typically low elevations and potential for inlet migration. |
| Dunes | |
| Average dune elevation (m) | Primary driver for vulnerability of dunes to storms is elevation and width. The width of the dune field is controlling as opposed to width of individual dunes. |
| Alongshore dune elevation variance (m) | |
| Dune crest width and/or dune field volume (m3) | |
| Beach berm width (m) | Beach protects the dune from wave impact and erosion. The wider the beach the less vulnerable the dune to coastal storms. |
| Beach slope (%) | Influences wave runup and therefore the likelihood that the dune will be subjected to wave runup impact. |
| Dune vegetation coverage (%) | Vegetation can reduce losses from erosion and also facilitates natural dune recovery. |
| Sediment grain size (mm) | Used as a measure of the erodibility of the dune and ability of the shoreline to recover. |
| Dune age (yr) | Indicator of compaction within the dune which influences erodibility. |
| Distance from dune to back barrier shoreline (m) | Dunes can be compromised from bayside, and this metric is intended to measure that vulnerability. |
| Marsh | |
| Elevation (m) | Primary driver of coastal vulnerability to storms and should always be included as a metric. |
| Aerial extent (km2) | Aerial extent influences surge propagation and wave energy dissipation. |
| Bulk density of wetland soil (g/cm3) | Indicator of erodibility. |
| Vegetation type (Manning n) | The type of vegetation influences wave energy dissipation, surge propagation, and erodibility. |
| Land/water continuity (%) | Marsh continuity can influence surge propagation and wave energy dissipation. |
| Watershed drainage area (km2) | Fresh marshes have difficulty rebounding after storm surge inundation if the saline water is not flushed by precipitation runoff. Drainage area used as an indicator of potential for marsh to be flushed after an saline inundation event. |
| Ratio of vertical sedimentation (through organic production, or sources from rivers and estuary) to relative sea level rise | Ratios less than 1 are more vulnerable to erosion and disintegration of the marsh (Donnelly and Bertness 2001; FitzGerald et al. 2008). |

### Vulnerability metrics discussion

The metrics presented in this section are not all of equal importance nor are they mutually exclusive. The actual selection of metrics to apply for a given vulnerability assessment will depend on many factors, most notably the purpose and scale of the vulnerability assessment and data availability. The selection of metrics, and the use of those metrics, involves value judgments therefore, careful thought and attention must be given to the process of engaging interested and affected parties, stakeholders, and other organizations. These entities may include representatives from the public and private sector, and will likely include Federal, State, and local government agencies, non-governmental organizations, and those that represent multiple disciplines with interests in the region. Typically, vulnerability should be assessed with as few metrics as possible to measure all the relevant vulnerability factors and be as simple as possible, which is often a function of data availability. The following should be considered when selecting metrics to apply in a coastal storm hazard vulnerability assessment:

- Elevation is the most important measure of vulnerability from the coastal storm hazard, and all elevation-related coastal characteristic metrics are of significant importance. In many cases, it is important to not only consider maximum elevations, but also alongshore variability in elevations for a given reach.
- Water level and wave data are also key drivers of coastal vulnerability. The best data available should be used. Storm modeling and statistical analysis of water levels and wave data can provide useful information on the storm climate and should be applied when available.
- Coastal forcing metrics (e.g., measurements of wind speeds, surge depths, wave velocities) can be even more powerful depending on where it is collected. For example, the closer to shore wave heights are measured, the more valuable they are in providing information regarding vulnerability. Waves measured in the nearshore, which must be made before breaking, provide information regarding nearshore bathymetry, rendering slope metrics less important than they would be if only offshore waves were available. In the case of coastal waters with a limited fetch, if wave data is available that reflect the limited fetch conditions, metrics related to the fetch may not be necessary.
- Forcing metrics are often not available in the nearshore or at least not at the spatial resolution necessary. In these cases, other methods are required to measure vulnerability. For example, open-water fetch and

winds are metrics that can be combined to estimate waves in protected water. Numerical modeling can also be conducted to provide data at the locations where it is most needed.

- Vulnerability assessments may be conducted as part of an alternative analysis. In these cases, the vulnerability with and without given features in place must be estimated. Measured forcing or response data will not typically be available for both alternatives, and estimates based on analytical or numerical modeling techniques will be required.

The metrics provided are intended to allow for an evaluation of how NNBF influence vulnerability to the coastal storm hazard. When NNBF are added to or removed from the landscape, the following metrics may be modified due to landscape change:

- average max elevation between nearest shoreline and open coast,
- landmass area between nearest shoreline and open coast,
- maximum elevation between point of interest and nearest shoreline,
- land cover type along distance from point of interest to nearest shoreline,
- open-water fetch from nearest shoreline,
- distance from point of interest to nearest shoreline, and
- shoreline sediment median grain size.

The modification of the landscape will change the relevant metrics which will in turn change the overall assessment of vulnerability.

Note that the metrics are intended to assess the vulnerability of the landscape. The vulnerability of anything on the landscape is directly linked to the vulnerability of the coastal landscape and NNBF. Examples of things on the landscape include communities, structures, species habitat, and cultural resources. The total vulnerability of anything on the landscape is a function of the landscape vulnerability (which is what the metrics in this section are intended to provide measures for assessing) and vulnerability specifically inherent to the thing of interest. For example, community mobility is a factor that will influence the vulnerability of the people in a community, but is not considered in the landscape metrics. The landscape vulnerability can be applied to partially quantify the vulnerability of any system, ecological or human.

## A community self-assessment of resilience

More and more, coastal communities are moving away from post-storm crisis response toward more proactive planning initiatives to prepare for disasters in advance to ensure their community's future existence in the dynamic coastal landscape. Communities can work towards coastal resilience through strong leadership, citizen engagement, collaboration, and interdependence. Unfortunately, limiting hazard exposure, reducing sensitivity, and building adaptive capacity in a multi-stakeholder environment present unique challenges in a rapidly evolving coastal environment. A facilitated group elicitation exercise is offered here to help struggling communities characterize their vulnerabilities and identify opportunities to improve resilience in a collaborative manner. This approach is not new—it has been adopted by NOAA (and others) to facilitate community assessments of preparedness and resilience in the wake of Hurricane Katrina (Sempier et al. 2010), and more recently has been employed by the New Jersey Office of Coastal Management (NJOCM) to assess New Jersey's coastal communities (NJOCM 2011b). The purpose of this self-assessment is to provide community leaders with a simple and inexpensive method of assessing exposure, sensitivity, and adaptive capacity, while identifying planning, mitigation, and adaptation opportunities to reduce vulnerability and promote opportunities to build capacity for coastal resilience. For now, the approach is presented as a simple decision tree that walks the community through the assessment. In the future, this diagram could be converted into a questionnaire that could be distributed at public meetings or hosted on a website to engage the community's stakeholders.

Organizations advocating for resilience emphasize four key words in the definition of resilience: prepare or anticipate, resist, recover, and adapt. The definition for community resilience developed by the Community and Regional Resilience Institute (CARRI) has been adopted herein (CARRI 2013):

> **Community resilience** is the capability to anticipate risk, limit impact, and bounce back rapidly through survival, adaptability, evolution, and growth in the face of turbulent change.

### Examples of community self-assessments

Organizations world-wide have developed approaches to assess coastal community resilience; three are described here to highlight essential elements of these assessments.

The Mississippi-Alabama Sea Grant Consortium (MASGC) developed a community self-assessment to evaluate whether communities can maintain and recover functioning following a disaster (Sempier et al. 2010). The self-assessment provides relative resilience indices (low, medium, high) based on how a benchmark historical storm and a future storm of greater intensity affect community functionality. Functioning elements that are evaluated include critical infrastructure, facilities, and transportation. Existing plans, mitigation measures, and social support systems increase the likelihood of rapidly returning to functioning and therefore increase community resilience. The assessment is meant to identify weaknesses within individual communities such that these weaknesses can be mitigated and reduced, and overall resilience increased. Community resilience can be reassessed at later times and evaluated whether overall resilience has increased or decreased with changes in the system. It is not meant to intercompare communities, because assessments are subjective. The Resilience Alliance (2010) developed a resilience assessment framework for social-ecological systems that considers five stages of assessment:

- **Stage 1** describes the system of interest, both spatially and temporally. The magnitude of both time and space scales are determined by the main issue(s) of concern.
- **Stage 2** is understanding system dynamics, whether cyclic or long-term, and when management interventions might best be achieved. Historical and future evolution of the system should be described, as well as thresholds which might transfer the system to an alternate state.
- **Stage 3** involves understanding system interactions and cascading thresholds of change. System interactions can be explained as sacrificing a small part of the system for overall, long-term benefit at the larger scale. An example is managed fires that prevent uncontrolled burning and also release seeds necessary for new growth. In a watershed, providing controlled flooding of low-lying areas on river systems such that catastrophic flooding of towns is prevented serves as an illustration of understanding and managing system interactions for increased resilience. Cascading thresholds of change are the critical,

slow-changing variables that can trigger abrupt change either alone or through interaction with other variables. An example is a freshwater marsh that becomes more saline with relative sea level rise, triggering decline in plant growth, destabilization of marsh sediments, and breakup of the marsh.

- **Stage 4** concerns governance systems—individuals, organizations, laws, policy, and social networks—that could collaborate and adapt to better manage the system and rebound after disasters.
- **Stage 5** is acting on the assessment. Two diagrams are constructed: a conceptual model of the social-ecological system, and a thresholds and interaction diagram for slow variables of change, which may trigger other variables to cross thresholds. The overarching goal of the assessment is to "sustain the capacity of the social-ecological system to provide benefits to society," and provide ecosystem stewardship.

New Jersey's Office of Coastal Management developed a Getting to Resilience Questionnaire that has been applied to assess resilience of several coastal communities, including Cape May Point, Little Silver, Oceanport (NJOCM 2010), and Greenwich Township, New Jersey (NJOCM 2011). The Questionnaire is directed towards a focus group of coastal managers and decision-makers to increase resilience to coastal hazards and sea level rise. NJOCM recognized that many decisions related to disaster preparedness and responses are dispersed amongst various agencies, and the Questionnaire is intended to inform and prepare these leaders. The Questionnaire has five sections:

1. Risk and Vulnerability Assessment. This assessment highlights areas most likely to experience future storm damages and other areas that are less vulnerable to damage and better suited for future land development.
2. Public Engagement. Engaging the public in the assessment serves to derive anecdotal data from coastal residents about past storms and damages, as well as to educate.
3. Planning Integration. This section recognizes that many long-term planning documents are required in New Jersey with varying frequencies of updates. Planning for hazards and recovery are encouraged to be incorporated into these documents.
4. Disaster Preparedness and Recovery. Emergency managers and community leaders are recipients of this portion of the Questionnaire, which leads the community to prepare for disaster response prior to the

hazard events. The goal is to reduce the loss of life and the time required for recovery following storms.

5. Hazard Mitigation Implementation. This last section of the Questionnaire is intended for all focus group participants to reduce vulnerabilities in the region of interest. Concepts such as user fees to provide a funding source for restoration, and land buy-outs are discussed.

Many other types of community assessments for resilience are available; a few are briefly discussed here. The State of Vermont has developed a community scorecard to assess resilience of communities for land use, transportation, energy, and healthy community design in the face of climate change (Vermont Natural Resources Council 2013). The U.S. Indian Ocean Tsunami Warning System Program (2007) developed a coastal community resilience assessment to identify strengths, weaknesses, and opportunities to increase resilience of coastal communities to tsunamis. The University of Queensland and University of Southern Queensland (2008) developed a toolkit directed towards building resilience in rural communities, with 11 key resilience concepts including social networks, learning, diverse economy, and leadership, among others.

Wealthy coastal communities have the potential to be more resilient than poorer communities, because they have the resources to better prepare (e.g., build protective structures and maintain NNBF, provide backup options for basic needs, utilize generators, buy out/relocate endangered properties, ensure adequate evacuation routes) and provide support for rapid recovery (e.g., temporary housing, food). However, economically disadvantaged communities can increase their resilience through sufficient planning and education. Assessing community resilience is one way of identifying features critical for protection, safety, and recovery. Also identified are developing plans to reduce the vulnerability of these features and services and providing an assessment to inform and provide a baseline for future comparison.

To summarize, there are several excellent assessment tools available for communities to qualitatively evaluate existing resilience and identify ways to increase their resilience to coastal disasters. These tools are useful to increase awareness and understanding rather than intercompare communities.

### Steps in the community's self-assessment

A quantitative community resilience metric (CRM) is presented here that merges the qualitative concepts presented in the community assessment tools described previously with the quantitative method presented by Schultz et al. (2012) for engineering systems. This method builds upon work that is being conducted for the Coastal Engineering Research Board (CERB) to develop a strategy and identify research needed to implement resilience assessments in the USACE (Rosati and Lillycrop 2014). The CERB team recommended coastal system assessment of community, ecosystem, and engineering resilience, proposed that hierarchical levels of analysis be developed, and identified a number of research needs. The CRM discussed herein is one of these assessments focused on the community, with less focus on ecosystem services and engineering features of the system. Suggested functions and features populate the CRM, but individual communities may have other elements to include to adequately represent their resilience. It is recommended that the CRM be tested on several pilot communities, and modified as needed, prior to adoption for the NACCS. The CRM should be populated by community leaders, decision-makers, social groups, and property owners. Each of these community members has a role and contributing perspective in preparations, response, and recovery of the community, and should be involved in the assessment for communication and education. Leaders and decision-makers can coordinate and document recovery plans, identify emergency communication systems, prioritize rehabilitation or relocation needs, and define management actions to maintain critical NNBF for the region. More active social systems such as strong faith-based networks, cultural entities, neighborhood associations, business cooperatives, and strong civil organizations can provide support during and following crises. Individual property owners can be educated as to what they can do to reduce their vulnerability to storm damage (e.g., raising or relocating homes, developing evacuation plans, establishing temporary retreats during storms and recovery periods). The CRM should be documented and revisited on a regular basis. Documenting and communicating the resilience assessment will help inform and educate the public as well as identify regions or procedures needing most action to increase resilience of the community.

**Green text boxes** in the next sections offer insight regarding assumptions and background details for the exercise. Note that all data shown in green is purely conjectural and is displayed simply to illustrate the process.

A hypothetical assessment exercise is offered in the following sections along with a decision tree to guide the community through the process (Figure 15).[1] The assessment focuses on identifying critical system functions that are valuable to stakeholders and society. The community's assessment of its perceived exposure, sensitivity, and adaptive capacity involves customized sociotechnological methods and solutions to ensure these functionalities are sustained under a broad range of hazard forcings.

Relative importance values (i.e., weightings) in Figure 15 can be derived through any manner of formalized elicitation (see Meyer and Booker, 2001; Gregory et al. 2012 for protocols) and aggregated using prescriptive trade-off analysis (see Chee 2004; Riabecke et al. 2012 for examples of weighting). Interactive group sessions, or even online polling can be used to elicit the value preferences of the community's stakeholders. The key is to develop weightings in a transparent and unbiased manner to capture the community's perspective on its relative vulnerabilities and resiliencies. Armed with the results of the assessment, communities can plan and engineer solutions that build resistance, adaptability, and the ability to recovery quickly in the face of adverse events (Linkov et al. 2014; Schultz et al. 2012).

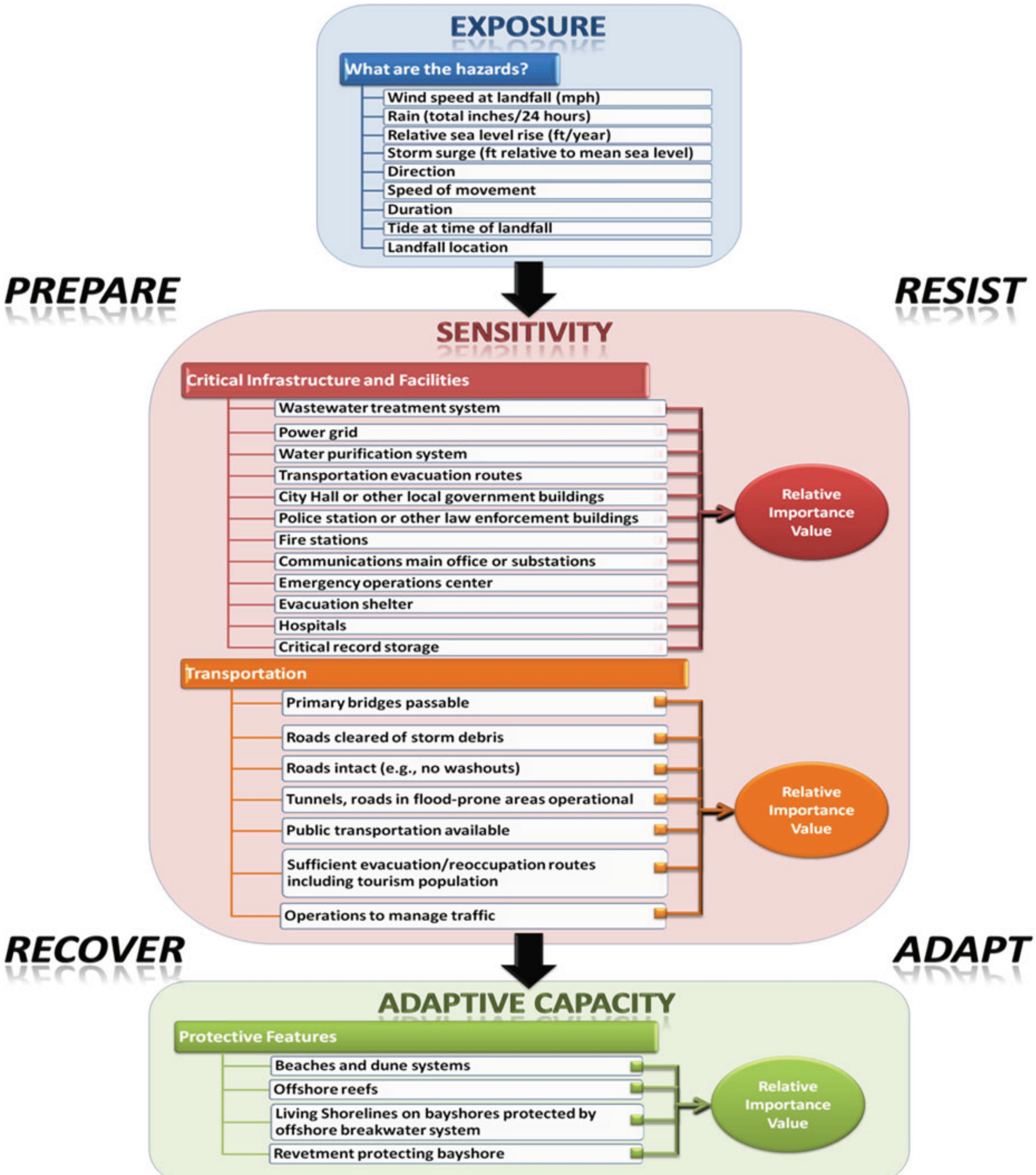
*Step 1: Define spatial and temporal boundaries*

The spatial extent of consideration as well as the duration over which resilience will be assessed sets the bounds for the assessment. For example, a coastal community near an estuary may include the entire coastal watershed as the spatial boundary, which would identify extreme precipitation and river flooding as potential contributors to disasters. The temporal frame of reference is significant when defining benchmark and future storms in Step 2, and considering long-term trends such as relative sea level rise, change in frequency and severity of storms, and urban expansion.

**For the purposes of the hypothetical example herein,** a residential coastal community on a barrier island serves as the focus, and the community's resilience is evaluated over a 50 yr time period.

[1] ERDC has developed a spreadsheet calculator that can be used to facilitate this process, which can be made available upon request.

Figure 15. Decision tree to support the community's self-assessment of vulnerability and resilience. Elements in the tree can be customized to reflect the needs of each community's unique situation.



*Step 2: Identify benchmark and future storms*

As discussed by Semper et al. (2010), the benchmark storm is a historical storm that will give the community the most information about likely vulnerabilities. The purpose of identifying a benchmark storm is to determine what critical facilities and infrastructure will be affected by this storm. For a primarily residential coastal community, it may be that a 30 yr return period storm, representing the typical duration of a home mortgage, is a representative benchmark storm. Other communities with infrastructure with greater longevities may want to consider more a severe storm. The future storm should be one approximately 50% worse than the benchmark storm, to prepare the community for a storm that has not been witnessed in historical records (Table 14).

**For the hypothetical example,** the benchmark storm has a return period of 30 yr, and the future storm is similar to a present-day 50 yr storm.

Table 14. Step 2 – Identify the benchmark and future storm conditions.

| Variables | Benchmark Storm: Storm Return Period = 30 yr | Future Storm: Storm Return Period = 50 yr |
|---|---|---|
| Wind speed at landfall (mph) | 70 | 90 |
| Rain (total inches/24 hr) | 6 | 10 |
| Relative sea level rise (ft/yr) | 0.01 | 0.01 |
| Storm surge (ft relative to mean sea level)* | 6 | 9* |
| Direction | NW | NW |
| Speed of movement | Slow-moving | Slow-moving |
| Duration | 36 hr | 36 hr |
| Tide at time of landfall | High | high |
| Landfall location | East of town | East of town |

* Surge for the Future Storm should factor in the change in mean sea level in the temporal period of consideration.

*Step 3: Identify critical infrastructure and facilities and a recovery goal for each*

**Example values are shown in Table 15 in green** which indicate that the hypothetical community's CI and CF are 75% and 40% resilient for the benchmark storm and future storm, respectively.

Critical infrastructure (CI) includes power, wastewater treatment and purification, and evacuation routes. Critical facilities (CF) include fire, communications, safety, hospital, and emergency operation buildings/features. Flood maps should be overlain with locations of these critical infrastructure and facilities and used to identify which locations are in danger of storm damage or inoperability during disasters. The minimum floodplain of concern for CI/CF is the 0.2% floodplain (Sempier et al. 2010); this slight chance of flooding is considered too great for these critical facilities. The vulnerability of each of these facilities to potential storm damage during the period of consideration will highlight which facilities and functions must be protected, or services provided elsewhere, to ensure emergency response during the disaster and a rapid return to functionality during the recovery period. As a part of Step 3, the time to be back to operability—the recovery goal (RG) for each facility or function—should be identified in the case that these functions/facilities are inoperable or damaged during the storm. A RG should be identified for the benchmark storm (RG-B) and future storm (RG-F). For the benchmark storm, historical information as to whether each facility/function was damaged or inoperable during the storm, and whether it met the RG-B can be determined from the historical record. Values are entered into the table and multiplied according to community-specified weighting factors which total 1.0. These weighting factors represent the relative importance of each CI and CF to the community in reducing loss of life and providing essential services during and after the storm. Functionality is calculated as the sum of whether the CI or CF was functional during the storm (1 = yes; 0 = no) times the weighting factor (W). Recovery is calculated similarly: the sum of whether the CI or CF recovered in the specified time after the storm (1 = yes; 0 = no) times the weighting factor (W). The overall resilience metric is calculated for each storm as the average of the sum of the functionality and recovery calculations.

Table 15. Step 3 – Identify the critical infrastructure, facilities, and recovery goals for the benchmark (RG-B) and future (RG-F) storms.

| Critical Facility or Function | Benchmark Storm (30 yr) | | | Future Storm (50 yr) | | | Weight-ing (W) (totaling 1.0) |
|---|---|---|---|---|---|---|---|
| | What is the RG-B for this facility or function? | Functional (F) during storm? (Yes=1; No=0) | Recovery (R) Is it operational by RG-B? (Yes=1; No=0) | What is the RG-F for this facility or function? | Functional (F) during storm? | Recovery (R) Is it operational by RG-F? (Yes=1; No=0) | |
| **Critical Infrastructure (CI)** | | | | | | | |
| Wastewater treatment system | 0.5 wk | 1 | 1 | 0.6 wk | 0 | 0 | 0.05 |
| Power grid | 0.5 wk | 0 | 1 | 0.6 wk | 0 | 0 | 0.2 |
| Water purification system | 1 wk | 0 | 1 | 1.1 wk | 0 | 0 | 0.05 |
| Transportation evacuation routes | 1 wk | 1 | 1 | 1.1 wk | 0 | 1 | 0.1 |
| **Critical Facilities (CF)** | | | | | | | |
| City Hall or other local government buildings | 1 wk | 0 | 1 | 1.5 wk | 0 | 0 | 0.025 |
| Police station or other law enforcement buildings | 0.5 wk | 0 | 1 | 1 wk | 0 | 0 | 0.025 |
| Fire stations | 0.5 wk | 1 | 1 | 1 wk | 0 | 0 | 0.05 |
| Communications main office or substations | 0.5 wk | 0 | 1 | 0.6 wk | 0 | 1 | 0.1 |
| Emergency operations center | 0.2 wk | 1 | 1 | 0.5 wk | 1 | 1 | 0.1 |
| Evacuation shelter | 0.2 wk | 1 | 1 | 0.5 wk | 0 | 1 | 0.1 |
| Hospitals | 0.2 wk | 1 | 1 | 0.5 wk | 1 | 1 | 0.1 |
| Critical record storage | 1 wk | 0 | 1 | 1.5 wk | 0 | 1 | 0.1 |
| $\frac{\Sigma(F*W+R*W)}{2}$ = | | | | | | | |
| Resilience Metric for CI and CF | | 0.75 | | 0.40 | | | |
| | | 75% | | 40% | | | |

*Step 4: Identify transportation issues*

> **Example values are shown in Table 16 in green** based on functional and recovery goals, and weighting values, the example calculations indicate that the hypothetical community's transportation routes are 85% and 25% resilient to the benchmark and future storms, respectively.

Transportation is critical to evacuate community members prior to the storm and return them to their homes once the storm has passed. If the coastal community being considered is a tourist destination, factoring in seasonal traffic is essential to ensure sufficient evacuation routes are available in the event the storm occurs during tourist season. Similar to Step 3, critical transportation routes and capabilities (e.g., public transportation) should be identified and RGs specified for the benchmark storm and future storm. Calculations are as described previously.

*Step 5: Identify protective features*

> **For the example shown in Table 17,** the beach-and-dune system is given the greatest weighting; with the storm surge projected for the benchmark and future storms, it is likely that the offshore reefs and living shorelines will be inundated and not effective during the storm. Overall example resilience for critical NNBF is 90% and 20% for the benchmark and future storms, respectively.

The next step is to identify protective features such as critical NNBF and blended (traditional structural and NNBF) solutions as well as engineering projects that may reduce the risk of storm damage. NNBF discussed previously such as reefs, wetlands, living shorelines, vegetation, and dunes have the capacity to reduce storm surge, wave, and wind impacts to coastal communities. Blended solutions such as a living shoreline protected by an artificial breakwater and a beach-and-dune system backed by a seawall should be also included. Finally, engineering projects such as a storm surge barrier or revetment that stabilizes the bayshore on a narrow portion of the barrier island that is prone to breaching have the potential to reduce storm damage. Identifying critical NNBF, blended solutions and engineering projects highlight the importance of protecting these features with proper management (e.g., constructing dune walk-overs to protect dune vegetation, sand fencing to encourage vertical growth of dunes via wind-blown sand transport, reduced vessel speeds in vicinities with erodible shorelines). Similarly to the previous steps, RGs will be specified, but these can be natural recovery or managed recovery because NNBF have the capacity to recover naturally if not damaged severely and given sufficient time.

Table 16. Step 4 – Identify critical transportation routes, issues, and recovery goals for the benchmark (RG-B) and future (RG-F) storms.

| Critical Transportation Route or Issue | Benchmark Storm (30 yr) | | | Future Storm (50 yr) | | | Weighting (W) (totaling 1.0) |
|---|---|---|---|---|---|---|---|
| | What is the RG-B for this facility or function? | Functional (F) during storm? (Yes=1; No=0) | Recovery (R) Is it operational by RG-B? (Yes=1; No=0) | What is the RG-F for this facility or function? | Functional (F) during storm? | Recovery (R) Is it operational by RG-F? (Yes=1; No=0) | |
| Primary bridges passable | 1 wk | 1 | 1 | 1.5 wk | 0 | 0 | 0.2 |
| Roads cleared of storm debris | 1 wk | 0 | 1 | 1.5 wk | 0 | 1 | 0.2 |
| Roads intact (e.g., no washouts) | 1 wk | 1 | 1 | 1.5 wk | 0 | 0 | 0.2 |
| Tunnels, roads in flood-prone areas operational | 1 wk | 0 | 1 | 1.5 wk | 0 | 1 | 0.1 |
| Public transportation available | 1 wk | 1 | 1 | 1.5 wk | 0 | 0 | 0.05 |
| Sufficient evacuation/ reoccupation routes including tourism Pop | 0.5 wk | 1 | 1 | 1 wk | 0 | 1 | 0.2 |
| Operations to manage traffic | 1 wk | 1 | 1 | 1 wk | 0 | 0 | 0.05 |
| Σ (F*W+R*W) = 2 | | | | | | | |
| Resilience Metric for Transportation | | 0.85 | | 0.25 | | | |
| | | 85% | | 25% | | | |

Table 17. Step 5 – Identify the critical protective features (NNBF, structural, and blended measures) and the recovery goals for the benchmark (RG-B) and future (RG-F) storms.

| Critical Protective Features | Benchmark Storm (30 yr) | | | Future Storm (50 yr) | | | Weighting (W) (totaling 1.0) |
|---|---|---|---|---|---|---|---|
| | What is the RG-B for this facility or function? | Functional (F) during storm? (Yes=1; No=0) | Recovery (R) Is it operational by RG-B? (Yes=1; No=0) | What is the RG-F for this facility or function? | Functional (F) during storm? | Recovery (R) Is it operational by RG-F? (Yes=1; No=0) | |
| Beach and dune system | 1 mos | 1 | 1 | 3 mos | 0 | 0 | 0.7 |
| Offshore reefs | 1 mos | 0 | 1 | 6 mos | 0 | 1 | 0.1 |
| Living shorelines on bayshores protected by offshore breakwater system | 1 mos | 0 | 1 | 6 mos | 0 | 1 | 0.1 |
| Revetment protecting bayshore | 1 mos | 1 | 1 | 3 mos | 1 | 1 | 0.1 |
| Σ (F*W+R*W) = 2 | | | | | | | |
| Resilience Metric for Protective Features | 0.90 | | | 0.20 | | | |
| | 90% | | | 20% | | | |

*Step 6: Overall community resilience rating*

This last step is provided to rollup the resilience metrics for each of the previous steps—Critical Infrastructure and Facilities, Transportation, and Protective Features—such that an overall resilience rating can be derived for the community. Weighting factors will be specified by the community to indicate the relative importance of each of these features and functions.

**For the example presented in Table 18,** the greatest weighting has been given to transportation to ensure adequate evacuation of community members. The overall example community resilience rating is 84.5% and 26.5% for the benchmark and future storms, respectively. This example community could increase resiliency by better protecting critical infrastructure and facilities, as well as conducting long-term planning to prepare for future storms.

Table 18. Step 6 – Overall community resilience rating.

| Facility, Feature, or Function | Resilience Metric (from Table 15, Table 16, and Table 17) | | Weighting (totaling 1.0) |
|---|---|---|---|
| | Benchmark Storm | Future Storm | |
| Critical infrastructure and facilities | 75% | 40% | 0.2 |
| Transportation | 85% | 25% | 0.5 |
| Protective features | 90% | 20% | 0.3 |
| Overall Community Resilience Rating | 84.5% | 26.5% | 1.0 |

**Measures to increase community resilience**

Based on the resilience rating presented in the previous section, individual communities can understand which elements of their infrastructure, facilities, transportation, and protective features are less able to withstand and recover from storm impacts and work to modify these elements to increase their resilience ratings. Each of the four key words in the definition of resilience—prepare, resist, recover, and adapt—provide insight into how community resilience can be increased. Increasing community resilience provides collateral benefits to existing federal projects in the region. In this section, measures to increase community resilience are discussed with respect to each key word.

*Prepare*

- Provide an early flood warning system.
- Establish communication system to be used before, during, and after a disaster.
- Conduct education programs to communicate evacuation routes and shelters to the public. Ensure sufficient evacuation routes are available for permanent and tourist populations.
- Anticipate weak links in the system that are most likely to be damaged and/or have a cascading effect during a storm (e.g., narrow portions of a barrier island likely for breaching, low dune/seawall/revetment elevations).
- Stockpile sand to rapidly close breaches and repair dunes.
- Establish protection and maintenance practices for sensitive coastal habitats, ecosystems and natural features.
- Provide diverse and redundant protection wherever possible.

- Strive to provide modular networks with components that are independent yet complementary of each other (e.g., multiple evacuation routes).
- Provide readily-accessible information for decision making at the community, city, county, and State levels.

*Resist*

- Identify critical physical features, NNBF and engineering projects in the community. Ensure these features are in good condition.
- Restore critically eroding shorelines.
- Identify critical facilities and infrastructure that are vulnerable to storm damage, and relocate or protect these facilities/infrastructure. Consider bridges, tunnels, low-lying roads, power, wastewater treatment, water purification, safety, emergency operations, hospitals, fire stations, etc.

*Recover*

- Encourage active social systems such as civic and neighborhood organizations. Provide incentives for these groups to develop evacuation and recovery plans.
- Establish memorandums of understanding (MOU)/agreement (MOA) with adjacent communities to assist each other during times of disasters.
- Develop plans for recovery: storm debris removal, temporary power supplies, backup options for basic needs (e.g., water, sewer, food, communication), ice distribution, and restoration of protective features.

*Adapt*

- Consider buying out residences in flood-prone areas and converting these to public park lands.
- Provide incentives for elevating residential, nonresidential, and infrastructure in endangered areas.

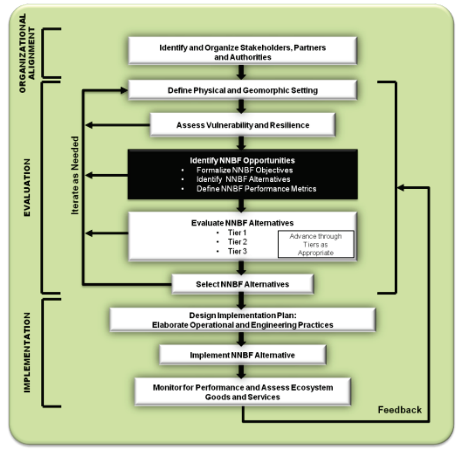
## Conclusions

Appropriate coastal zone management and storm damage risk reduction requires the assessment of vulnerability and resilience in natural and human environments. Factors affecting vulnerability and resilience can be internal and external to the system of interest and reside in either the socioeconomic or biophysical knowledge domains. Socioeconomic factors relate to economic resources, political power, culture, and other social science related elements. Biophysical factors are system properties investigated by the physical sciences and engineering. These two domains can be integrated, or overlap, as in the case of built infrastructure. Vulnerability and resilience are functions of the hazard to which a system is exposed, the sensitivity of the system to the hazard, and the system's adaptive capacity. Exposure is the nature and magnitude of the hazards by which a system is threatened. Sensitivity relates to the potential of a system's valued attributes or functions to be affected (either positively or negatively) by the changes caused by a hazard. Adaptive capacity describes a system's ability to evolve, either naturally or through engineered maintenance activities, in such a way as to preserve or enhance the system's valued functions. A vulnerability and resilience assessment must address all three of these components to be complete.

A satisfactory conceptual approach for identifying and defining meaningful metrics must consider all these dimensions. The approach documented in this chapter is designed to ensure a set of metrics is developed for a complete assessment for a wide range of systems and hazards at the local, regional, and landscape scales. The approach is intended to be generally applicable and valid for coastal hazards and systems.

Metrics for multiple coastal landscapes were developed. The metrics presented are intended to assess relative vulnerability of coastal landscapes along the northern Atlantic coast; provide an understanding of how NNBF influence vulnerability of a coastal landscape; and provide an understanding of the vulnerability of specific NNBF. Infrastructure, facilities, transportation, and protective features that affect community resilience were also presented. The metrics presented are not all of equal importance, nor are they mutually exclusive. The actual selection of metrics to apply for a given vulnerability and resilience assessment will depend on many factors, most notably the purpose and scale of the assessments and data availability. Typically, assessments should be conducted with as few metrics as possible to measure all the relevant factors; and be as simple as possible, which is often a function of data availability. The metrics developed through the process documented in this chapter can be incorporated into numerous assessment approaches, including the tiered framework developed in Chapter 5 of this document.

# 4 Performance Metrics for Ecosystem Goods and Services Generated by NNBF and Structural Features in the Post-Sandy Environment




## Introduction

Ecosystem goods and services characterization is a relatively new tool in the flood risk assessment and management arena, but one that shows significant promise in providing planners and managers with a method to assess competing NNBF and structural design options with the intent of enabling better, more holistic flood risk management solutions. There is strong interest across a range of organizations to use NNBF in combination with structural features to reduce coastal flooding risks and improve the social, economic, and ecosystem resilience of coastal systems nationwide. In the aftermath of Superstorm Sandy, there is now evidence that NNBF can reduce flood risks and provide a wide range of economic, environmental, and social benefits above and beyond increased flood protection (Figure 16).

Moreover, NACCS is pursuing the development of integrated decision-support tools to inform the decision process and distinguish amongst possible actions or design features (USACE 2015). The purpose of this effort is to support the NACCS by identifying ecosystem-based goods and services and developing quantitative performance metrics that can capture a full suite of social, environmental, and economic benefits generated by natural, nature-based, and structural features, implemented individually and/or from a coastal systems perspective to promote flood risk reduction, improve ecosystem integrity, and ensure coastal resilience. The intent is to provide the NACCS decision-makers, stakeholders, and the public with an approach that transparently communicates returns on investment (i.e., benefits) and supports the formulation, implementation, and adaptive management of NNBF strategies at a systems level.

Figure 16. An example of NNBF performance was seen on the Rockaway Peninsula in Queens, NY (USA) after the storm. The pictures on the top compare a site with NNBF structures (i.e., dunes) offering a level of protection to the inland communities, whereas the picture on the bottom compares a site absent NNBF (Source: http://www.nyc.gov/html/sirr/html/report/report.shtml).


To achieve these goals, the following objectives were established:

- **Identify** relevant risk reduction features (natural, nature-based and structural) and determine which ecosystem goods and services are generated by functioning ecosystems.
- **Develop** a matrix of performance metrics relevant to human welfare benefits attributed to ecosystem goods and services arising from the presence of natural, nature-based and structural features acting alone or in concert.
- **Draw** from existing resources related to ecosystem goods and services to generate operational metrics.
- **Document** examples where these or related metrics have been used and how they have been applied.
- **Develop** a multi-level approach that deploys these services in a decision-making methodology using qualitative, semi-quantitative, and quantitative methodologies (refer to Task 3A and 3B).

### Coming to terms with the science and practice

The ability of coastal ecosystems to sustain and maintain resilience to dynamic coastal processes including catastrophic events requires an understanding of key processes and the expression of those processes in the form of function and structure. Paramount to that understanding is the establishment of well-vetted, germane terminology. Terminology appropriate to coastal ecosystems and NNBF which is scientifically-based and broadly accepted, yet intuitive,

- provides a common interdisciplinary language between engineers, scientists, stakeholders, and the public,
- facilitates the linkages between ecosystem goods and services and the USACE decision-making paradigm,
- provides, in part, a frame of reference for coastal ecosystem classification, and
- sets the stage to address concepts and practices regarding NNBF.

As an integral part of this study, 117 pertinent terms have been identified (contact Dr. Kelly Burks-Copes, U.S. Army Engineer Research and Development Center (ERDC)). The concepts of ecosystem goods and services, and performance metrics are provided here to orient the reader towards the study's purpose and intent.

### Ecosystem goods and services

The concept of ecosystem services originated with Westman (1977) who suggested that the social value of benefits provided by ecosystems could potentially be quantified such that society could make more informed decisions regarding policy and management. The concept that nature contributed materially to both the personal well-being of the populace and the health of the market economy offered a unique perspective, suggesting a bridge could be made between economic and ecological assessments. Brinson (1993) referred to products derived from aquatic ecosystems as extractable goods which included intangibles, commodities, and all other goods and services that contribute to the human life support system. The idea rapidly evolved over the next several years (Fisher et al. 2009) culminating in a series of definitive papers with formative definitions including

- conditions and processes through which natural ecosystems, and the species that make them up, sustain and fulfill human life (Daily 1997)
- benefits human populations derive, directly or indirectly, from ecosystem functions (Costanza et al. 1997)
- benefits people obtain from ecosystems (Millennium Ecosystem Assessment (MEA) 2005)

- components of nature, directly enjoyed, consumed, or used to yield human well being (Boyd and Banzhaf 2007)
- aspects of ecosystems utilized (actively or passively) to produce well-being (Fisher et al. 2009).

Over time, the definition for services has evolved into a seminal concept—one that advocates a valued production of goods and services by natural capital (i.e., indispensable resources essential for human survival and economic activity provided by the ecosystem) (Kareiva et al. 2011). Just recently, Murray et al. (2013) defined ecosystem goods and services for USACE planning activities as socially valued outputs tied to self-regulating or managed ecosystems.

With these concepts in mind, and with the intent of holistically capturing the entire suite of economic, engineering, environmental, and social benefits targeted by NACCS recovery efforts, ecosystem goods and services for the study are defined as follows:

**Ecosystem goods and services** are tangible items or intangible commodities generated by self-regulating or managed ecosystems whose composition, structure, and function are comprised of natural, nature-based and/or structural features that produce socially valued benefits that can be utilized either directly or indirectly to promote human well-being.

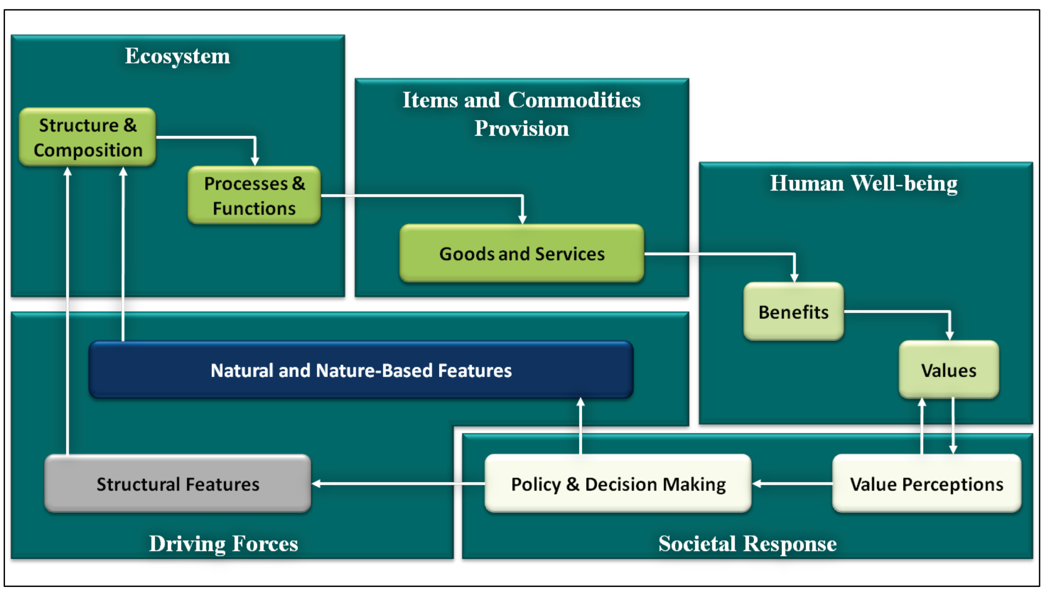
This definition assumes that ecosystem goods and services can be derived from ecosystems that include natural and built capital that work in combination, and that their value is simply a way to depict their importance or desirability to the consumers. The definition further assumes that the ability of the ecosystem to provide goods and services is dependent on critical ecosystem processes tied to both the structure and function of the system, and that these processes and the ultimate functionality of the system can be regulated through the introduction of natural and nature-based and structural features – especially those features advocated by the Engineering With Nature[1] (Bridges et al. 2014) and the Building With Nature[2] initiatives.

[1] http://el.erdc.usae.army.mil/ewn/

[2] http://www.ecoshape.nl/overview-bwn.html.

By definition, purely *natural features* are created through the action of physical, biological, geologic and chemical processes operating in nature, whereas *nature-based features* are created by human design, engineering and construction. Nature-based features engineered and constructed by humans to emulate natural features and function within the natural ecosystem, establish a systemic continuum between ecosystem structure, processes, goods and services and resultant economic, engineering, environmental and social benefits. NNBF embody a holistic perspective centered on the construction and management of constituent parts (e.g., measures) that are organized into a **pattern** (i.e., the landscape matrix); to sustainably perform **ecosystem functions** (i.e., storm attenuation, flood storage, habitat preservation), that in turn provide **goods and services** that are either directly or indirectly utilized by humans (e.g., flood protection or damage reduction, clean water, biodiversity, recreation, tourism). Benefits, defined as the socio-economic welfare gains derived from these ecosystem goods and services, form the end point between ecosystems and humans (van Oudenhoven et al. 2012) (Figure 17).

Figure 17. The link between NNBF features and ecosystem goods, services and benefits production (adapted from van Oudenhoven et al. 2012) characterized by state conditions (structure and function under conditions driven by forces) attributed to natural, nature-based and structural features that generate benefits of perceived value that can be used to make decisions and inform policy.




Society determines the value or worth of these benefits. Shifts in these perceived values can be driven by any number of factors including the state of the economy as well as the dynamics of supply and demand of the goods and services themselves. These shifts can lead to changes in policy and the decision-making paradigm. Ultimately, policy dictates constraints and offers incentives to integrate NNBF and structural solutions into the decision-making paradigm.

Paramount to successful implementation of NNBF is the ability to create, enhance or preserve ecosystem features and associated processes, structure and function, which ultimately culminate in the expression of goods and services. Thoughtful attention to design, location and construction of NNBF which are resilient and self-repairing, while providing a suite of goods and services, is imperative to successful coastal ecosystem recovery in the aftermath of Superstorm Sandy.

### Typologies

When presented with an extensive list of potential ecosystem goods and services to choose from, it is often informative to explore typologies (i.e., classification schemes), and select a strategy that facilitates ecosystem goods and services prioritization and trade-off analysis (Boyd and Banzhaf 2007; Chee 2004; Fisher et al. 2009). There is a rich, and extensive body of scientific research surrounding ecosystem goods and services typologies [e.g., see reviews in National Research Council (NRC) 2005; Murray et al. 2013], and it is generally agreed that there is no one-size-fits-all schematic that works in every planning context (Costanza 2008). An extensive literature review was conducted and a list of NNBF-relevant typologies were compiled that could be used by planners and managers to select and aggregate ecosystem goods and services to address a variety of project goals and objectives (Table 19).

Table 19. Selected ecosystem goods and services typologies (sorted by publication date).

| Typology (Source) | Main Classification Categories |
|---|---|
| Engineering With Nature<br>(Triple Bottom Line)<br>(Bridges et al. 2014) | • Economic<br>• Environmental<br>• Social |
| Ecosystem Response<br>(Burks-Copes et al. 2015) | • Hydrological<br>• Ecological<br>• Biogeochemical<br>• Sociological |
| Sustainable Services of Natural and Semi-Natural Ecosystems<br>(de Groot et al. 2002; van Oudenhover et al. 2012) | • Regulation<br>• Habitat<br>• Production<br>• Information |

| Typology (Source) | Main Classification Categories |
|---|---|
| Disaggregated<br>(Balmford et al. 2011) | • Food<br>• Freshwater<br>• Raw Materials<br>• Energy<br>• Property<br>• Physical Health<br>• Psychological Well-being<br>• Knowledge |
| Use-Based<br>(Aylward and Barbier 1992; Barbier et al. 2011; Hein et al. 2006) | • Direct Use<br>• Indirect Use<br>• Non-Use |
| Final vs. Intermediate<br>(Fisher et al. 2009) | • Intermediate<br>• Final |
| Spatial<br>(EU's Habitats and Water Framework Directives, http://ec.europa.eu/environment/nature/legislation/habitatsdirective/) | • In-situ<br>• Omni directional<br>• Directional |
| Human Value-Based<br>(Wallace 2007) | • Adequate Resources<br>• Protection from Predators/Disease/Parasites<br>• Benign Physical and Chemical Environment<br>• Socio-Cultural Fulfillment |
| Millennium Ecosystem Assessment<br>(MEA 2005) | • Supporting<br>• Regulating<br>• Provisioning<br>• Cultural |
| Goods vs. Services<br>(Chee 2004) | • Production of Goods<br>• Regeneration Services<br>• Stabilizing Services<br>• Life-fulfilling Services<br>• Preservation of Options |
| Services Provided by Rivers, Lakes, Aquifers, and Wetlands<br>(Postel and Carpenter 1997) | • Water Supply<br>• Supply of Goods Other Than Water<br>• Nonextractive or Instream Benefits |
| Wetland Ecosystem Services<br>(Ewel 1997) | • Biodiversity<br>• Water Resources<br>• Global Biogeochemical Cycles |
| Ocean Ecosystem Services<br>(Peterson and Lubchenco 1997) | • Global Materials Cycling<br>• Transformation, Detoxification, and Sequestration of Pollutants and Societal Wastes<br>• Support of the Coastal Ocean-Based Recreation, Tourism, and Retirement Industries<br>• Coastal Land Development and Valuation<br>• Provision of Cultural and Future Scientific Values |

Post-Sandy recovery efforts will dynamically shift the production of goods and services over space and time. In selecting a typology, it will be important for planners to be mindful of competing and complementary services across these continuums and conduct trade-offs between jointly produced goods and services in a transparent manner (i.e., accounting for both final and intermediate goods and services) to avoid (or at least minimize) the potential for double-counting benefits (Boyd and Banzhaff 2007; Tazik et al. 2013). Planners can opt to select a typology and sort the ecosystem goods and services into these classes to investigate redundancies and/or pare down the number of metrics deployed to characterize the alternative performance. Alternatively, they can sort the ecosystem goods and services by category and formulate designs to address full ecosystem goods and services provisioning in each category, bundling ecosystem goods and services that overlap in the categories using a variety of trade-off techniques as described in Chee (2004) to avoid double counting issues and address issues of service bundling (Martín-López et al. 2012; Raudsepp-Hearne et al. 2010). Ultimately, the selection of a typology will be driven by the decision context—the project's specific goals and objectives, the proposed NNBF and structural solutions, and the unique characteristics of the ecosystem generating the goods and services will all play a role in strategically operationalizing ecosystem goods and services production for the recovery efforts.

### Performance metrics

At the simplest level, a performance metric is a specific indicator that can be used to consistently estimate and report the anticipated effects of an alternative or engineering design with respect to a particular objective. Whereas objectives might be quite broad, performance metrics need to be specific because they define how an objective is to be interpreted and evaluated for the purposes of a planning or management decision. They articulate the exact information that will be collected, modeled, elicited from experts, or otherwise developed and presented to decision makers to characterize plan performance and engineering design. Performance metrics must provide the ability to distinguish the relative degree of ecosystem response (conveyed in terms of impacts or benefits) across alternatives and designs, either qualitatively or quantitatively, in ways that make sense and will help decision makers consistently and transparently compare alternatives and engineering designs. As such, performance metrics are defined as follows:

**Performance Metrics** are specific measures of production or indicators of system response that can be used to consistently estimate and report the anticipated consequences of an alternative plan with respect to specific planning and engineering objectives, or observed effects of completed construction projects.

Although it is widely understood that objective setting is a value-based exercise, researchers, planners, managers, and engineers tend to view the selection of performance metrics as a largely technical exercise. In fact, selecting performance metrics is a subjective exercise, with both technical and value-laden judgments coming into play. For NNBF, performance could be based on the generation of habitat units in a constructed wetland, the preservation of property values behind a dune and beach complex, or the production of park fees generated at a wildlife refuge in support of bird watching. The project goals and objectives will also define the production area (i.e., the action footprint) and the benefit accrual area (i.e., the identity and geographic extent of the beneficiaries) (Fisher et al. 2009).

Performance metrics are not the same as vulnerability metrics. Vulnerability metrics are used to assess the degree to which a system is susceptible to, and damaged by, adverse effects from a hazard. Vulnerability is a function of the character and magnitude of a hazard to which a system is exposed, its sensitivity, and its adaptive capacity (Chapter 3). While vulnerability metrics are important in the right context, they are not what is meant by performance metric. There are two main reasons to clarify this concept:

1. In the decision-making context, performance metrics are used to report on the expected performance of alternatives or engineering designs, for the purposes of making a choice among possible actions or constructs. Predictions are made using some combination of data, models, and expert judgment, in advance of an action, whereas vulnerability indicators are typically measures of system state before the action has been taken. The vulnerability assessment is performed in advance of alternative formulation to guide the coastal zone management, planning, and or processing; ensuring that NNBF are maintained through adaptation to and/or mitigation of hazardous effects (Chapter 3).
2. In the decision-making context, less is more. A performance metric is only of use if it serves the direct purpose of communicating key differences in performance of one alternative over another given a specific objective.

Performance metrics serve a host of purposes in decision making. Large, complex studies are undertaken in an iterative fashion, requiring constant reflection and recursion to incorporate new information as it comes available, forcing planners and managers to constantly adjust their goals and objectives to address rapidly evolving opportunities and constraints. Performance metrics can reduce uncertainties associated with vaguely defined or ambiguous objectives by providing specific meaning. They eliminate uncertainties associated with ambiguity in objectives. Because they define what matters when comparing alternatives, they also define information that will be collected and provide a much needed focus for prioritizing and designing technical studies and predictive modeling efforts. They facilitate the accurate and consistent comparison of alternatives. Critically, they provide a way of synthesizing large volumes of technical information into a summary format so that everyone on a multistakeholder team can understand critical aspects of performance. As a result, performance metrics are the key to leveling the playing field across participants with different levels of technical capabilities and knowledge. Ultimately, they provide a means for communicating the rationale for difficult decisions.

While there are no right or wrong performance metrics, there are certainly better or worse ones. According to Gregory et al. (2012), good performance metrics must be as follows:

1. **Complete and concise**—they must cover the range of relevant consequences under all reasonable alternatives concisely and avoid double-counting or redundancies.
2. **Transparent and unambiguous**—they must be clear, accurate, representative of the relationship that exists between the implementation of management measures (features and actions that together comprise an alternative plan) and the ensuing consequences, and their outcomes must be interpreted the same way by different people.
3. **Accurate**—they must report accurately and consistently on relative differences in performance across alternatives, including differences in the degree of uncertainty associated with the performance estimates.
4. **Direct**—they must report directly on the fundamental objective and provide enough information so that the decision makers understand the key implications of performing trade-offs.

5. **Understandable**—the outcomes reported must be easily understood and communicated clearly and consistently to stakeholders with varying backgrounds and expertise.
6. **Operational**—they must be easily and readily put into practice within the constraints of the decision-making process (i.e., a determination must be made whether the necessary information can be obtained to assess them; whether the data, models, and expert judgments, or other sources are obtainable given resource constraints such as time, budgets, or personnel.

### Key take-home messages

Performance metrics transform objectives into specific measures of effectiveness. They are an essential element of any decision that requires quantitative estimation of consequence and are used throughout the decision process to

1. help clarify situations and to generate responsive and creative solutions
2. facilitate discussions about stakeholders' preferences and priorities
3. consistently and accurately compare alternative,
4. prioritize information needs
5. expose trade-offs (particularly among outcomes with varying degrees of uncertainty)
6. communicate the rationale for, and improve the transparency of, decisions.

The goal of this study is to support the NACCS by identifying ecosystem-based goods and services and developing quantitative performance metrics that can capture a full suite of social, environmental, and economic benefits generated by natural, nature-based, and structural features, implemented individually and/or from a coastal systems perspective to promote flood risk reduction and improve ecosystem integrity.

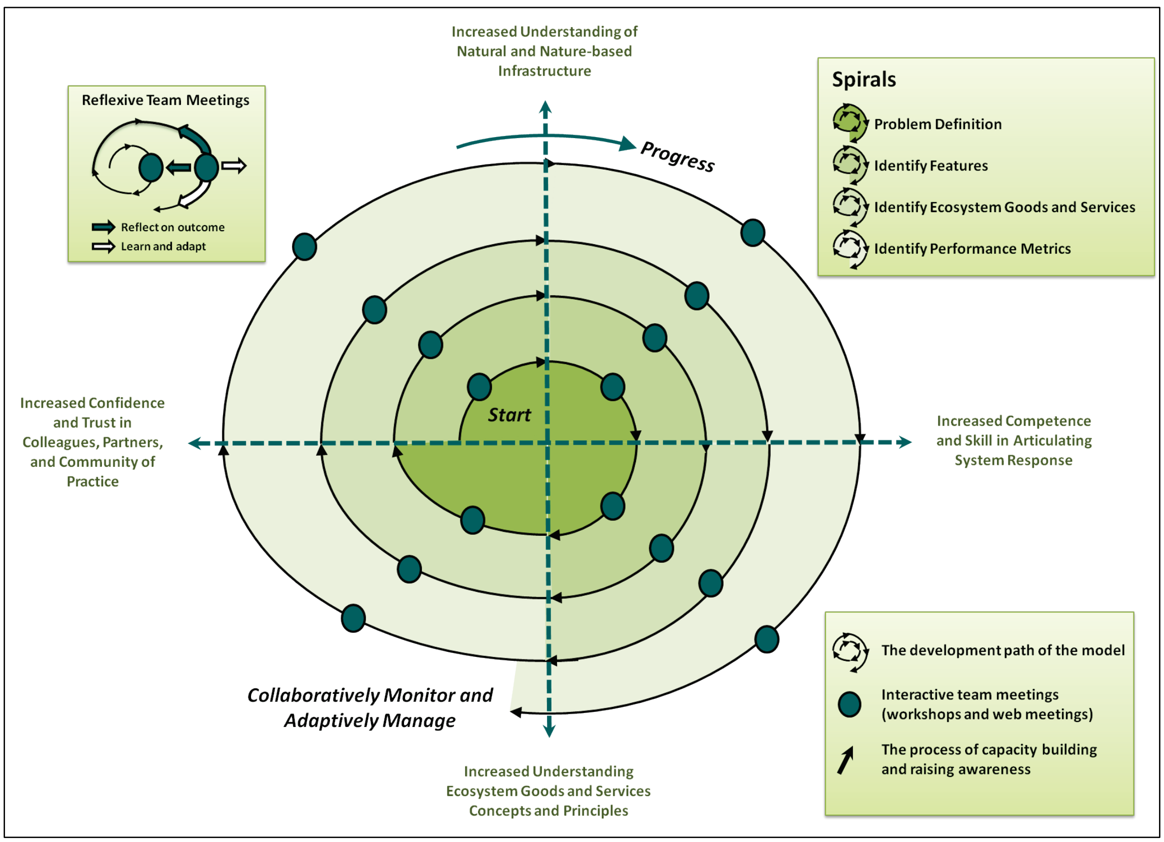
The result is a suite of clear and concise performance metrics that characterize and estimate the ecosystem's response to change (i.e., benefits derived from the construction and operation of NNBF designed to reduce flood risks and promote coastal resilience) at a systems level. In these situations, the best metrics are unambiguous, direct, accurate and understandable, but compromises are often necessary to generate readily applicable (i.e., operational) metrics—sometimes proxies must be utilized. There is no absolute or fixed collection of performance metrics; some are simply more useful than others. The key questions to ask are the following:

1. Do the metrics accurately represent the issues and concerns that matter?
2. What assumptions are embedded within the metrics and are these reasonable?
3. Would a different choice of metric change the decision?

## Methods

With these overarching questions guiding the efforts, a recursive spiral-based approach modeled after the works of Boehm (1988) and Du Toit (2005) was developed to support project teams characterize ecosystem goods and services production for their proposed NNBF solutions in post-Sandy recovery efforts (Figure 18).

Figure 18. The spiraled approach offered a unique opportunity for planners and managers to actively engage with stakeholders in the process through reflexive team meetings that promoted active learning, increasing knowledge and fostering trust and confidence in the products while honing the skills and competence of the team.




In essence, the spiraling methodology involved a series of weekly face-to-face interactive meetings (11 meetings in total, each lasted 2–3 hr) where the team worked through four spirals:

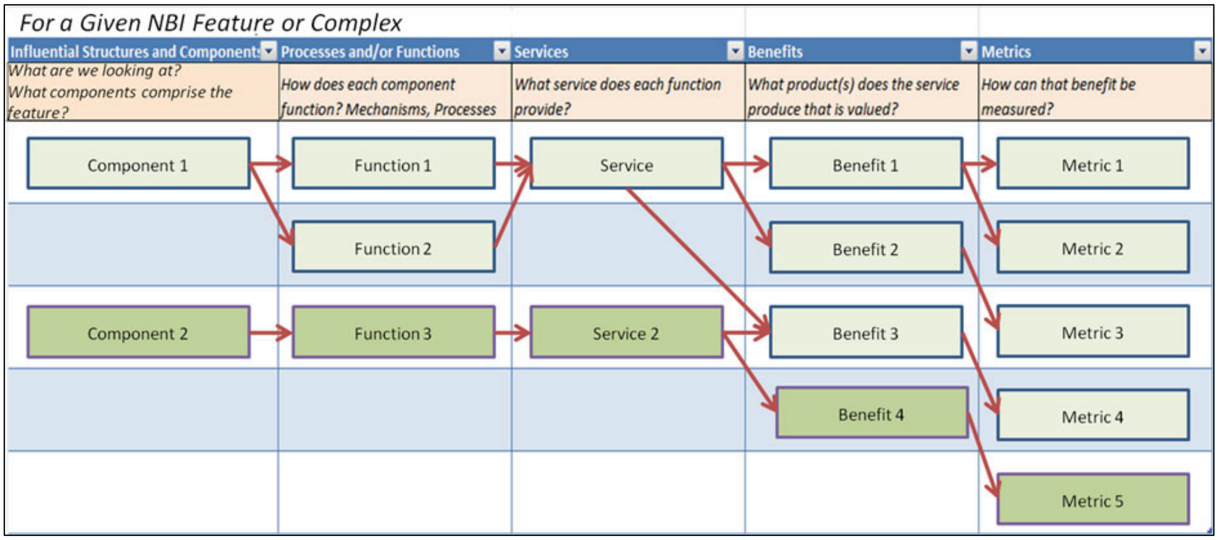
1. **Problem Definition**—establishing the study domain, clarifying the goals and objectives of the NACCS and the study effort itself, agreeing on a purpose statement, and detailing the tasks to achieve success.
2. **Feature Identification**—using parallel studies (NNBF characterizations and profiling) to establish a list of features that should be addressed under this effort.
3. **Ecosystem Goods and Services Identification**—working through the process of component definition and function/process descriptions, and basing decisions on current literature reviews, identifying key ecosystem goods and services and generating a list of benefits that could serve as indicators of desired outcomes.
4. **Performance Metric Identification/Development**—conducting a literature review of readily available metrics to characterize the identified benefits, mining for data, and using benefit transfer methods and GIS-based protocols to generate quantifiable performance metrics.

Between meetings, the team members were assigned specific data gathering or modeling/metric development tasks to fill knowledge gaps and assure forward progression toward the final product. The incremental spirals were completed in fewer than 12 weeks (including one week to compile the documentation). Each spiral took approximately 2 weeks to complete.

Once features and target goods and services were identified (Spirals 1–3), the team meetings revolved around a series of decomposition tables—a tool the team devised to trace the interconnections between the ecosystem goods and services of import and the features that generated those outputs (Figure 19). Working from the middle of these spreadsheets outward, the team traced the causal pathways linking ecosystem goods and services to their origin (feature structures and components) and to their endpoints (i.e., benefits and metrics that could be devised to measure their response to change).

The spiraling approach served as a means to combine what the experts agreed should be included in the performance metrics with the realities of how end-users would actually be using these metrics to make decisions. The development process was designed to be an exercise in "reflexive learning in context" —a term coined by Du Toit (2005) to describe an interactive group exercise that encouraged the team members to identify problems, deliberate, propose solutions, and respond to contextual changes in recursive reflection cycles (centered around information presented at each meeting).

Figure 19. Performance metric development process.




Constant and structured team interactions promoted trust amongst the participants and led to increased confidence in the final metric constructs. Iterative and recursive reflection supported group learning and increased both the team's understanding of the coastal ecosystems as well as the manner in which the metrics would likely be utilized to support the recovery efforts. Constant feedback increased the modeling competence and improved the ability to articulate ecosystem responses. Note that the spirals were intentionally designed to be open-ended. In the future, the team should be actively engaged in the use of these metrics for the NACCS recovery efforts, and the feedback from the NACCS managers and planners can be proactively incorporated into the adaptive management of the metrics themselves. The idea was to create indicators that were defensible, efficient, and operational (i.e., readily implementable). The hope was to develop performance-based metrics that could transparently communicate the rationale for making hard decisions in the NACCS recovery efforts to not only the stakeholders and collaborators involved in the process, but also to the public.

## Results

Twenty-one ecosystem-based goods and services were indentified and 72 quantitative performance metrics were created to capture a full suite of social, environmental, and economic benefits generated by the 30 natural, nature-based, and structural features, implemented individually and/or from a coastal systems perspective to promote flood risk reduction and improve ecosystem integrity. The sheer number of these goods and services, features, and metrics begs the question “Where should we focus?” To begin to answer this question, a workshop was held in November of 2013, and a group of stakeholders were engaged to discuss the potential utility of NNBF in post-Sandy coastal recovery efforts. During the workshop, an expert elicitation exercise was used to determine if there were preferences or important services that should direct the research and planning efforts of the area in the future. A synopsis of the elicitation exercise is offered below with a discussion of how this approach can be used by the region’s decision makers to narrow their focus to key or important ecosystem goods and services based on problems, opportunities, goals, and objectives. Both a qualitative and a semi-quantitative methodology is presented to characterize these services to support decision making in situations where time and resource constraints limit the availability of hard data.

### Features of concern

Building from the products developed by the classification team and the data mining team, working to devise compatible inputs for the assessment framework team (refer to Chapter 5), drawing on the published and internal literature, and reviewing other post-Sandy coastal assessments and reconnaissance efforts, a list of 30 relevant NNBF and structural features was produced that described engineering options to provide or maintain socially valued benefits for the region (Table 20).

Note that this list is a first approximation of the potential features that could be used in future recovery efforts for post-Sandy recovery efforts. The list will need to be updated to include additional features when the future feasibility-level studies engage in plan formulation exercises.

Table 20. Risk reduction features considered in this study.

| Natural and Nature-Based Features (NNBF) | |
|---|---|
| 1. Beach (sand, gravel, cobble) | 11. Submerged aquatic vegetation (SAV) (e.g., seagrass, other —fresh or saline) |
| 2. Mudflat / sandflat | 12. Riparian buffer |
| 3. Bluff (any material; if sand assume eroding dune) | 13. Emergent herbaceous marsh / wetland (fresh) |
| 4. Dune / swale complex | 14. Shrub-scrub wetlands (fresh) |
| 5. Salt marsh (emergent herbaceous) | 15. Flooded swamp forest (fresh) |
| 6. Shrub-scrub wetlands (brackish) | 16. Pond |
| 7. Flooded swamp forest (brackish) | 17. Terrestrial grassland |
| 8. Maritime grassland | 18. Terrestrial shrubland |
| 9. Maritime shrubland | 19. Terrestrial forest |
| 10. Maritime forest | |
| **Feature Complexes** | |
| 20. Reef, intertidal, or submerged (also see breakwater) | |
| 21. Breakwater, subaerial or emergent (nearshore berm, sill, reef, can contain oysters, rock, shells, mussels, submergeged aquatic vegetation (SAV), emergent or herbaceous vegetation) | |
| 22. Breakwater, submerged (nearshore berm, sill, artificial reef - if containing living organisms or plants, see reef) | |
| 23. Island (can include one or more of beach, dune, breakwater, bluff, marsh, maritime forest, other vegetation) | |
| 24. Barrier island (can include one or more of beach, dune, breakwater, bluff, marsh, maritime forest, other veg) | |
| 25. Living shoreline (e.g., vegetation w/ sills, benches, breakwaters) | |
| **Structural Features** | |
| 26. Levee | |
| 27. Storm surge barrier | |
| 28. Seawall / revetment / bulkhead | |
| 29. Groin | |
| 30. Breakwater | |

### Ecosystem goods and services considered

With deliberate consideration of NNBF functional concepts derived above, the study team moved through the process outlined in Figure 17 to generate a list of 21 agreed-upon relevant ecosystem goods and services that can be reasonably ascribed to each feature or complex of features in the coastal landscape (presented alphabetically–no priority has been assigned with regards to value preferences):

1. Aesthetics—appreciation of natural scenery (other than through deliberate recreational activities); inspiration for culture, art, and design

2. Biological diversity
3. Carbon sequestration
4. Clean water provisioning (sediment, nutrients, pathogens, salinity, other pollutants)
5. Commercially harvestable fish and wildlife production
6. Cultural heritage and identity—sense of place and belonging; spiritual and religious inspiration
7. Education and scientific opportunities
8. Erosion protection and control (water and wind; any source)*
9. Habitat for fish and wildlife provisioning (e.g., nursery, refugium, food sources)
10. Increase or maintain land elevation, land building, sediment source reduction
11. Maintain background suspended sediment in surface waters
12. Nutrient sequestration or conversion
13. Property value protection*
14. Provision and storage of groundwater supply
15. Raw materials production (e.g., timber, fiber, fuel)
16. Recreation—opportunities for tourism and recreational activities
17. Reduce hazardous or toxic materials in water or landscape
18. Reduce storm surge and related flooding*
19. Reduce the peak flood height and lengthen the time to peak flood
20. Reduce wave attack*
21. TES species protection.

Note the goods and services highlighted with an asterisk (*)—these are primary services associated directly with traditional flood damage risk reduction assessments. This list is consistent with the ecosystem goods and services highlighted in the final report developed by President Obama's Hurricane Sandy Rebuilding Task Force (2013) (refer to page 74 therein). An abbreviated feature-service matrix is provided in Table 21 (see Appendix G's Table 76–Table 78 for the entire matrix). Individual feature tables decomposing the services and linking these to particular structural components of the ecosystem are presented in Appendix H (Table 79–Table 104).

A number of explicit assumptions apply to this exercise:

- This list is not intended to be comprehensive or exhaustive, but should be representative of the bulk of ecosystem goods and services reasonably ascribable to coastal systems.

Table 21. Feature-Services matrix for NNBF produced by the team for the study, based on literature and expert opinion.

| Ecosystem Goods and Services | Bluff or scarp | SAV or aquatic vegetation bed | Beach | Tidal flat (mud, sand) | Pond | Dune complex | Shrub-scrub wetlands (fresh) | Flooded swamp forest (fresh) | Terrestrial grassland | Terrestrial shrubland | Terrestrial forest | Maritime grassland | Maritime shrubland | Maritime forest | Riparian buffer | Emergent herbaceous marsh | Salt marsh | Shrub-scrub wetlands (brackish) | Flooded swamp forest (brackish) | Submerged breakwater (submerged berm/ artificial reef) | Living shoreline | Natural mollusk reef, intertidal or submerged | Island | Subaerial breakwater (with herbaceous vegetation) | Barrier island | Levee | Seawall / revetment / bulkhead | Groin | Storm surge barrier | Breakwater | TOTALS |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Aesthetics other than recreation | X | X | X | X | X | X | X | X | X | X | X | X | X | X | X | X | X | X | X | X | X | X | X | X | X | X | X | X | X | X | 30 |
| Biodiversity | X | X | X | X | X | X | X | X | X | X | X | X | X | X | X | X | X | X | X | X | X | X | X | X | X | | | X | X | X | 28 |
| Carbon sequestration | | X | | | | | X | X | X | X | X | X | X | X | X | X | X | X | X | | X | | X | X | X | | | | | | 18 |
| Clean water provisioning | | X | | X | X | X | X | X | X | X | X | X | X | X | X | X | X | X | X | | X | X | X | X | X | | | | X | X | 24 |
| Commercial fish and wildlife harvest | | | X | X | X | | | | | | | | | | | | | X | X | X | | X | X | X | X | | | | X | X | 12 |
| Cultural/spiritual heritage | X | X | X | X | X | X | X | X | X | X | X | X | X | X | X | X | X | X | X | X | | X | X | X | X | X | X | X | X | X | 29 |
| Education/scientific opportunities | X | X | X | X | X | X | X | X | X | X | X | X | X | X | X | X | X | X | X | X | X | X | X | X | X | X | X | X | X | X | 30 |
| Erosion protection and control | | | X | | | X | X | X | X | X | X | X | X | X | X | X | X | X | X | X | X | X | X | X | X | X | X | X | X | X | 26 |
| Habitat for fish and wildlife | X | X | X | X | X | X | X | X | X | X | X | X | X | X | X | X | X | X | X | X | X | X | X | X | X | | | X | | X | 27 |
| Increase deposition; reduce sediment source | | X | | | | X | X | X | X | X | X | X | X | X | X | X | X | X | X | X | X | | X | X | X | X | X | X | X | X | 25 |
| Maintain suspended sediment levels | | X | X | X | X | X | X | X | X | X | X | X | X | X | X | X | X | X | X | | X | X | X | X | X | | | | X | X | 25 |
| Nutrient sequestration or conversion | | X | X | X | X | X | X | X | X | X | X | X | X | X | X | X | X | X | X | X | X | X | X | X | X | | | X | | X | 26 |

| Ecosystem Goods and Services | Bluff or scarp | SAV or aquatic vegetation bed | Beach | Tidal flat (mud, sand) | Pond | Dune complex | Shrub-scrub wetlands (fresh) | Flooded swamp forest (fresh) | Terrestrial grassland | Terrestrial shrubland | Terrestrial forest | Maritime grassland | Maritime shrubland | Maritime forest | Riparian buffer | Emergent herbaceous marsh | Salt marsh | Shrub-scrub wetlands (brackish) | Flooded swamp forest (brackish) | Submerged breakwater (submerged berm/ artificial reef) | Living shoreline | Natural mollusk reef, intertidal or submerged | Island | Subaerial breakwater (with herbaceous vegetation) | Barrier island | Levee | Seawall / revetment / bulkhead | Groin | Storm surge barrier | Breakwater | TOTALS |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Property value protection | X | X | X | X | X | X | X | X | X | X | X | X | X | X | X | X | X | X | X | X | X | X | X | X | X | X | X | X | X | X | 30 |
| Provision/storage of groundwater | | | | | X | | X | X | X | X | X | X | X | X | X | X | X | X | X | | | | | | | | | | | | 14 |
| Raw materials production | | | | | | | | | | | X | | | | X | | | | | | | | | | | | | | | | 2 |
| Recreation/tourism | X | X | X | X | X | X | X | X | X | X | X | X | X | X | X | X | X | X | X | X | | X | X | X | X | | | X | | X | 26 |
| Reduce hazardous or toxic materials | | X | | X | | X | X | X | X | X | X | X | X | X | X | X | X | X | X | | X | X | X | X | X | | | | X | X | 23 |
| Reduce storm surge and related flooding | X | | X | X | X | X | X | X | X | X | | X | X | X | X | X | X | X | X | X | X | X | | X | X | X | X | | X | X | 26 |
| Reduce flood height, lengthen time to peak | | | | | X | X | X | X | X | X | X | X | X | X | X | X | X | X | X | | | | | | | X | X | | | | 17 |
| Reduce wave attack | X | | X | X | | X | | | | | | X | X | X | | X | X | | X | X | X | X | X | X | X | X | X | | X | X | 20 |
| TES species protection | X | X | X | X | X | X | X | X | X | X | X | X | X | X | X | X | X | X | X | X | X | X | X | X | X | | | | X | X | 27 |
| Total Goods and Services per Feature | 10 | 14 | 14 | 15 | 15 | 17 | 18 | 18 | 18 | 18 | 18 | 19 | 19 | 19 | 19 | 19 | 19 | 19 | 20 | 14 | 15 | 16 | 17 | 18 | 18 | 9 | 9 | 10 | 14 | 17 | |

- Not every project or management program will seek to provide the full suite of ecosystem goods and services as described. More realistically, each project or location will have a discrete set of objectives that guide recovery actions—it is these objectives that will dictate which benefits are desired and help NACCS teams select appropriate features that deliver desired ecosystem goods and services.
- Not every individual NNBF or structural feature of a type will necessarily provide each ecosystem goods or services identified as provided by that feature. In other words, there may be examples of a specific type of feature that do provide the ecosystem goods and services listed and other examples of the same type of feature that do not. The study team erred on the side of inclusion, where if an ecosystem good or service could in any instance be ascribed to a feature, it is, even if there are examples team members could cite that do not. There are many elements that influence whether a specific beach, breakwater, or barrier island can provide specific benefits derived from ecosystem goods and services—these are details best evaluated at a project or feature scale. The performance metrics are designed to provide this level of detail.

Appendix G crosswalks the individual features with the services they provide (based on an extensive literature and an expert elicitation exercise conducted with the team during the third spiral).

### Decomposition

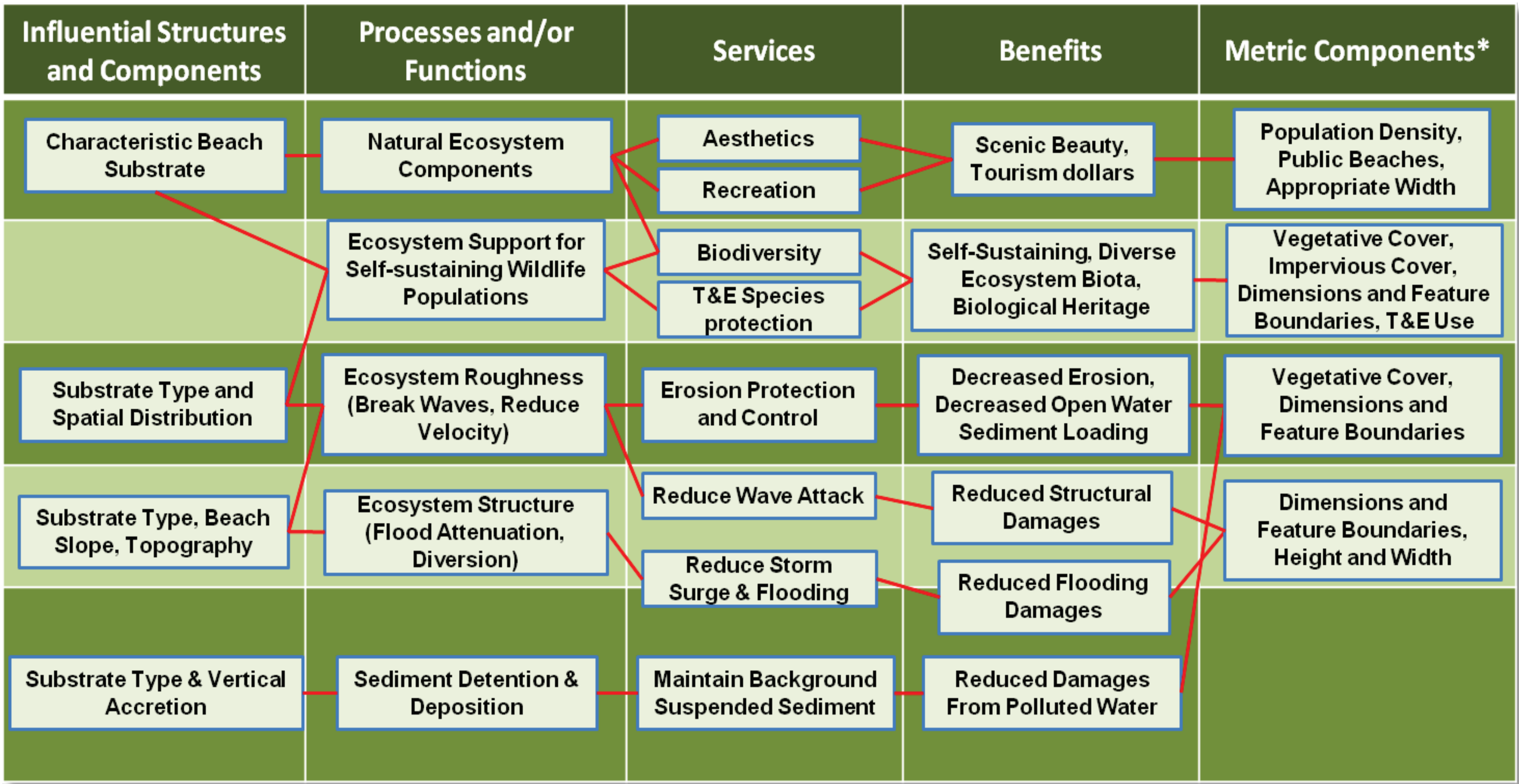
As a final step to develop and articulate performance metrics, each feature was decomposed, identifying the functions and processes that generated the ecosystem goods and/or services and the benefits that were derived from these productions (for details refer to Appendix H). Performance metrics were derived on a row-by-row basis to characterize these ecosystem states and the ecosystem goods and services producing these benefits. These data and the mathematical functions that describe specific metrics (refer to Appendix J) were developed for the services and benefits identified by the team and matched to each applicable feature (recreation metrics for breakwater features, for example, would not be measured by available public beaches). Though this report presents a coherent strategy and methodology for developing and firmly linking all of the elements leading to metrics that can be assessed using widely available and primarily geospatial data, doubtless there are additional or even better metrics or data sources that could be applied, depending on location, objectives, data availability or other factors applied to recovery efforts and restoration of coastal resilience.

Each service was considered separately to enable the team to develop metrics in a clear and traceable process. For each service, influential structures and components, processes and functions leading to it, and benefits and associated metrics proceeding from it, were carefully identified and articulated. Mapping the causal pathways through these tables revealed some overlap, similarity, or cross-linkages that were not readily apparent at the onset from the tables alone. For example, the characteristic substrate (sediment and its properties) is an influential component of beaches that forms a critical basis for 8 of the 14 services ascribed to beaches, ranging from aesthetics and commercially harvestable wildlife to maintenance of property values and maintaining water quality (Table 79 in Appendix H). Ecosystem functions and processes associated with beach substrate generate appropriate habitat conditions for sustainable shellfish populations that sequester nutrients or provide a harvestable food crop, provide roughness elements that attenuate energy, reduce erosion or encourage further deposition, and provide aesthetic natural scenery and valuable recreation and tourism opportunities.

As further illustration of specific linkages and resultant pathways, 8 of the 14 ecosystem goods and services from the NNBF beach illustrate the linkages and correspondence within and across ecosystem goods and services and associated influential structures, processes, benefits and metrics (Table 22).

Four structural components are largely influential, with each of them relying on some specific characteristics of the sediment and its spatial arrangement within the feature. Some of the linkages and resulting pathways from the critical structure to the benefit and associated metric are very simple, such as those that describe maintaining background suspended sediment for water quality, and some are more complex, such as those that lead to and proceed from biodiversity or reduction in storm surge. The benefits arising from erosion protection and control and from maintaining background suspended sediment can be assessed with the same metric components including the type of vegetation present and the size and other dimensions of the beach. Aesthetics and recreation benefits that include scenic beauty and tourism profit benefits can both be assessed using metrics based on population characteristics and the availability of

Table 22. Feature decomposition - NNBF example using the beach feature to demonstrate the process. Note that only 4 of the 14 structural components and associated processes, ecosystem services, benefits, and metrics associated with beaches are shown here. Refer to Appendix H (Table 79) for the entire suite of ecosystem goods and services associated with this feature.



public beaches of a certain width. In general, depending on project objectives, restoration actions that result in the provision of several ecosystem services and benefits are considered the most effective. Similarly, metrics capable of assessing more than one ecosystem service will reduce the level of effort and time required to evaluate existing conditions, predict future conditions, and determine project success.

### Three levels of characterization

The level of investment planners and managers make in formulating recovery plans will be dictated by any number of constraints (e.g., time, money, resources, data availability). With this in mind, a multi-level assessment approach was devised to utilize the information developed in this study. The intent was to provide options in deploying these tools ranging from a low-fidelity, best-professional-judgment exercise in ranking of services/benefits with regards to planning alternatives to a high-fidelity approach that involved quantification of metrics using sophisticated GIS protocols and economic benefit transfer methodologies including the following:

1. A best-professional-judgment (BPJ) voting matrix
2. A semi-quantitative causal mapping exercise
3. A series of quantitative performance metrics.

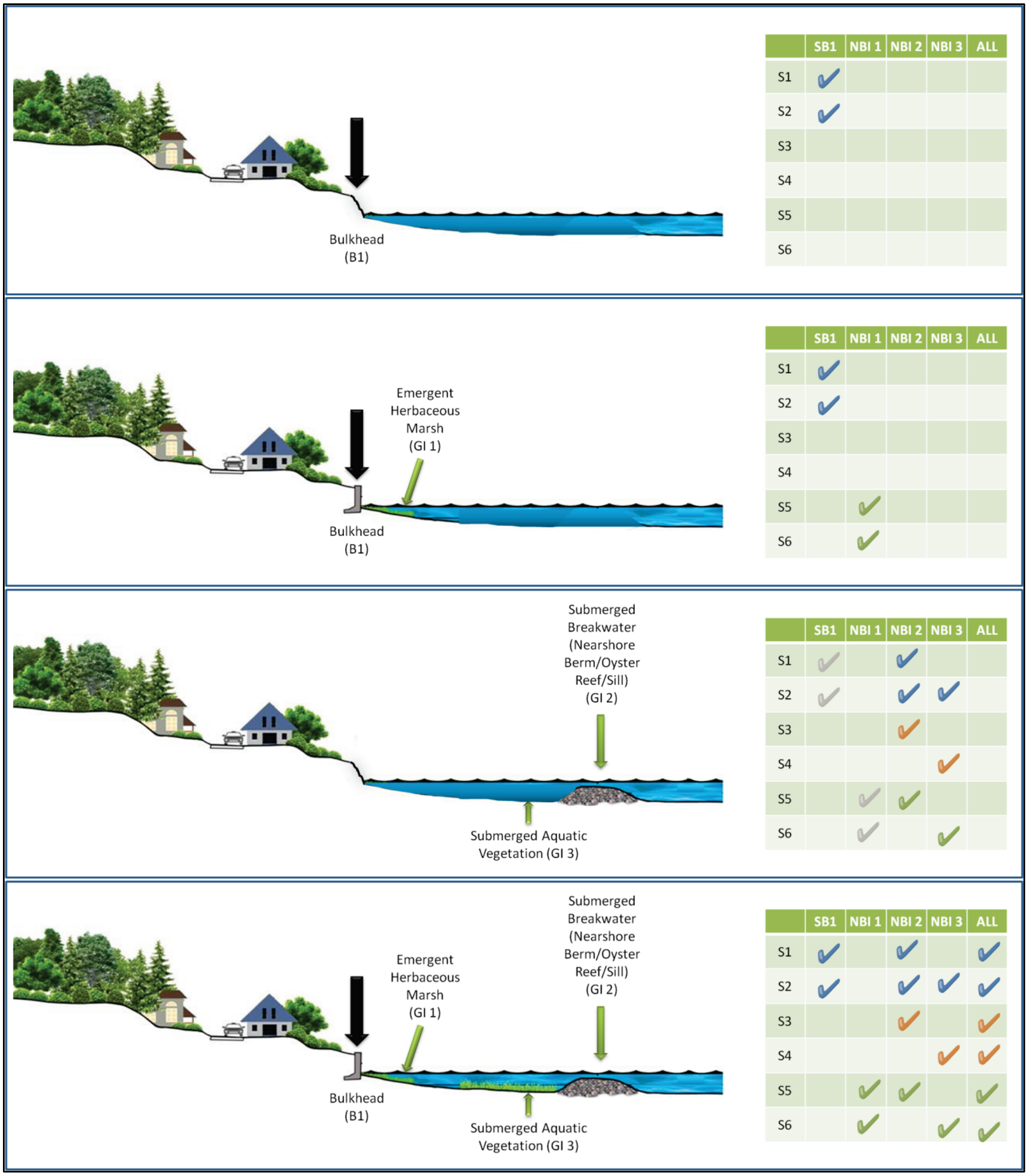
Supporting documentation for the latter two approaches can be found in Appendices D and E respectively.

#### *Qualitative—Best professional judgment (BPJ) preference matrix*

The qualitative BPJ matrix [modeled after Balmford et al. (2011)] is a simple table that allows planners and managers to elicit expert opinion from a panel of SME or from a broader stakeholder quorum. The idea is to present the stakeholders and decision makers with the various design options and provide them with details of services generated in Appendices B and C. The idea was to devise a service-feature matrix that could be used to indicate when and where ecosystem goods and services would be produced if features were deployed on the landscape (Figure 20).

As the figure illustrates, the goal was to show the cumulative effects of combining both NNBF and structural features into a system's perspective of risk reduction measures, offering a full accounting of the return on

Figure 20. Example of a communication product generated through this exercise. In each successive panel (starting at the top and moving down), new features are deployed, and their corresponding benefits (generated by goods and services tied to functions/processes driven by ecosystem states tied to feature components) are checked off as they are produced.



investment (i.e., the full suite of environmental, economic, and sociological benefits) generated by the individual plans. Each successive panel offers a conceptual recovery alternative with one or more features (NNBF and structural solutions) that generate the ecosystem goods services represented in the check-box matrix. One plan could include the construction of a structural feature (in this case a bulkhead, SB1) that in turn generates two hypothetical services (e.g., storm surge reduction, and wave attack reduction noted as S1 and S2 respectively) as noted in the top panel. A second recovery option (refer to the next panel down), could include a combination of the bulkhead feature and the establishment of emergent herbaceous marsh (an NNBF) (NBI 1). This solution would hypothetically produce both the first two services, and an additional two services (e.g., improvements in habitat for fish and wildlife and nutrient sequestration).

A third option could include an entirely different set of NNBF (NBI 2) as shown in the third panel (e.g., oyster reefs and submerged aquatic vegetation), with associated ecosystem goods and services per feature. As the matrix suggests, each successive option offers a different combination of goods and services (some have already been produced by earlier solutions, and some novel outputs). Use of this medium will offer planners and managers a platform from which to compare and contrast competing plans in a transparent fashion.

Obviously, not all situations call for the deployment of 21 ecosystem goods and services characterization. In all likelihood, problem context along with the establishment of particular goals and objectives will narrow the focus to a few key benefits for any given study. Moreover, the involvement of numerous stakeholders with disparate agendas, varying preferences, and conflicting interests will likely complicate the streamlining efforts.

To address this concern, the team suggests using formal expert elicitation activities to extract preferences from stakeholders and inform decision makers along these lines. To demonstrate the process, the team participated in a stakeholder workshop in Washington, DC, in November 2013, where 78 experts from across the NACCS region (and abroad) came together to discuss the utility of NNBF in coastal sustainability and resilience. During the meeting, an elicitation exercise was used to query the participants by posing the following:

> From the perspective of the organization you are representing, on a scale of 0 to 100, indicate how important it is to consider each of the following ecosystem goods and services when determining whether and how to include NNBF into NACCS recovery efforts.

The participants were then given a list of the ecosystem goods and services derived in this study and asked to rank their importance. Of the 63 participants in the room on the first day of the workshop, 48 experts agreed to share their opinions (78% response rate). These stakeholders ranged from Federal employees actively involved in the NACCS (18), to academics associated with various universities in the study area (8), to consultants who have used or are using NNBF solutions to address coastal storm protection and flooding concerns (13), and to non-governmental organizations with regional interests in post-Sandy recovery efforts (9).

Table 23 provides the results of the elicitation exercise. The results suggest some interesting interpretations. First, the average rankings of the stakeholder preferences suggest that “Reduce storm surge and related flooding” is the most important ecosystem service provided by NNBF, and that “Raw materials production” is the least important service. Probably more interesting is that a consensus was not evident—there were only a few points of difference among each of the categories, and every type of good or service was identified as having some value by one or more participants (note the Max/Min Scores of 100 and 0, respectively).

Although not comprehensive, the team found this exercise to be both useful and meaningful. Future studies can use this same approach to streamline their efforts using stakeholder preferences to narrow their focus and direct research and planning toward selecting, characterizing, and possibly even quantifying priority ecosystem goods and services to compare and contrast recovery efforts for the NACCS. For example, these outputs generated by potential recovery plans (quantified using the various ecosystem goods and services performance metrics described herein) can be relatively weighted[1] in a BPJ matrix for comparison purposes using these value preferences (refer to the hypothetical example of a BPJ matrix offered in Table 24.

[1] Facilitators can limit or remove biases (e.g., anchoring, group think) and address issues of double counting or institutional bias (i.e., having more than one contribution coming from the same agency) using techniques described in the collective works of Gregory et al. (2012), Innes and Booher (2010), and Meyer and Booker (2001) who offer in-depth guidance to eliciting opinions/judgments and debiasing results and to Malczewski (1999), Linkov and Moberg (2012), and Riabecke et al. (2012) who offer guidance on performing multiobjective trade-offs.

Table 23. Statistical results of the November 2013 expert elicitation exercise.

| Metric | Mean | Stdev | Max | Min | Median |
|---|---|---|---|---|---|
| Reduce storm surge and related flooding | 81.6 | 25.8 | 100 | 0 | 95 |
| Reduce wave attack | 80.0 | 26.6 | 100 | 0 | 90 |
| Erosion protection and control | 79.1 | 24.6 | 100 | 15 | 87.5 |
| Reduce the peak flood height and lengthen the time to peak flood | 75.9 | 29.0 | 100 | 0 | 85 |
| Habitat for fish and wildlife provisioning | 69.7 | 32.1 | 100 | 0 | 85 |
| TES species protection | 65.8 | 32.5 | 100 | 0 | 77.5 |
| Clean water provisioning | 63.3 | 32.3 | 100 | 0 | 75 |
| Biological diversity | 64.4 | 31.7 | 100 | 0 | 70 |
| Recreation | 60.5 | 27.5 | 100 | 5 | 60 |
| Property value protection | 56.7 | 33.0 | 100 | 0 | 70 |
| Reduce hazardous or toxic materials in water or landscape | 55.3 | 32.1 | 100 | 0 | 60 |
| Nutrient sequestration or conversion | 51.9 | 31.2 | 100 | 0 | 60 |
| Increase or maintain land elevation and land building | 51.1 | 33.1 | 100 | 0 | 50 |
| Education and scientific opportunities | 49.0 | 31.0 | 100 | 0 | 50 |
| Commercially harvestable fish and wildlife production | 48.8 | 32.4 | 100 | 0 | 50 |
| Aesthetics | 47.6 | 28.5 | 100 | 0 | 50 |
| Provision and storage of groundwater supply | 46.9 | 31.2 | 100 | 0 | 50 |
| Carbon sequestration | 46.3 | 30.0 | 100 | 0 | 50 |
| Maintain background suspended sediment in surface waters | 44.5 | 26.5 | 80 | 0 | 50 |
| Cultural heritage and identity | 44.2 | 28.8 | 100 | 0 | 50 |
| Raw materials production | 22.7 | 25.5 | 100 | 0 | 10 |

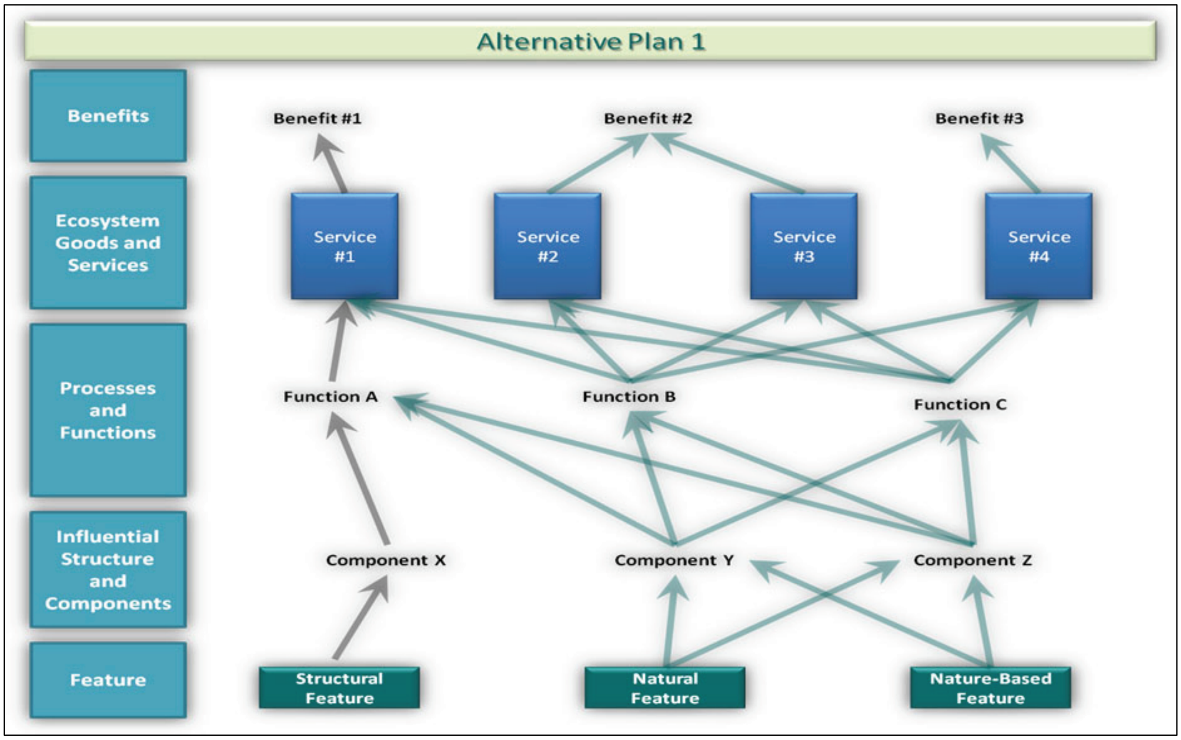
Table 24. Hypothetical example of a BPJ voting matrix. Stakeholders and/or decision makers provide their perceived benefits in the body of the table on the basis of benefits (e.g., B1, B2, B3) tied to ecosystem goods and services given a particular design option (e.g., Plan A, Plan B, Plan C) and offer their perceived values in terms of which benefits are the most important to them (top row shown in dark green indicating highest scores). The columns on the right relatively value the outcomes based on the weights and benefits recorded.

| | 1 | 2 | 4 | 3 | 5 | | |
|---|---|---|---|---|---|---|---|
| | B1 | B2 | B3 | B4 | B5 | Unweighted | Weighted |
| Plan A | 10 | 8 | 5 | 1 | 0 | 4.8 | 49 |
| Plan B | 10 | 10 | 0 | 0 | 0 | 4 | 30 |
| Plan C | 10 | 5 | 5 | 9 | 7 | 7.2 | 102 |
| Plan D | 6 | 10 | 10 | 8 | 5 | 7.8 | 115 |
| Plan E | 5 | 5 | 5 | 10 | 10 | 7 | 115 |
| Plan F | 7 | 7 | 3 | 4 | 7 | 5.6 | 80 |

*Semi-quantitative—a system dynamics approach using causal mapping*

Qualitative methods in systems thinking (Kim and Andersen 2012; Kopainsky and Luna-Reyes 2008; Luna-Reyes and Andersen 2003) were used to develop causal maps based on arguments among variables in each of the five main sectors: Feature, Influential Structure and Components, Processes and Functions, Ecosystem Goods and Services, and Benefits (Figure 21).

Figure 21. A generic illustration of the causal map construct used in this study.




As defined for this study, an argument is a series of causal relationships that link a Feature with a Benefit. As the figure illustrates, a collection of causal arguments for several Features and Benefits can be presented on one causal map. This qualitative causal mapping approach provides added value for analyzing causal relationships. Even a cursory review of the diagrams reveals how several features converge to support a given benefit. The causal maps developed for this study identified over 400 causal relationships (refer to causal maps in Appendix I for more details). These causal maps can potentially be used by planners and managers to develop both a qualitative analysis of potential leverage points in the systems as well as offer an opportunity to engage in semi-quantitative analysis of system dynamics in the future.

*Quantitative*

This section describes two approaches for estimating the value of ecosystem services. These approaches can inform understanding of the rough magnitude of ecosystem services of NNBF.

**Benefit transfer approach.** The first option is to employ a benefit transfer approach. The benefit transfer approach involves using previously published area-based estimates of the value of ecosystem services for a specific ecosystem or NNBF. Multiplying the area of the feature of interest by these published values allows one to estimate the value of the existing or new features. This approach has been used to estimate the value of ecosystems in the NACCS study (Costanza et al. 2006; Liu et al. 2010; Weber 2007) (Table 25 and Table 26).

Table 25. Ecosystem goods and service values based on peer-reviewed original research in temperate North America/Europe [2012 $/(acres*yr)].

| Ecosystem Goods and Services | Coastal Shelf | Beach | Estuary | Saltwater Wetland | Forest | Grass/ Rangelands | Cropland | Freshwater Wetland | Open Fresh Water | Riparian Buffer | Urban Greenspace | Urban/ Barren |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Gas/climate regulation | | n/a | | | 72 | 6 | | | | | 404 | |
| Disturbance regulation | | 32,794 | | 1 | | | | | | 106 | | |
| Water regulation | | | | | | | | 7,162 | | | 7 | |
| Water supply | 745 | | 59 | | 11 | | | 1,396 | 492 | 2,310 | | |
| Soil formation | n/a | n/a | | | | 7 | | | n/a | | | |
| Nutrient cycling | | n/a | | | | | | | | | | |
| Waste treatment | | n/a | | 7,322 | | | | | | | | |
| Pollination | n/a | n/a | | | 195 | | 10 | | n/a | | | |
| Biological control | | n/a | | | | | | | | | | |
| Habitat/refugia | | | 438 | 277 | 1110 | | | 6 | | | | |
| Aesthetic/recreation | | 17,851 | 364 | 31 | 156 | 1 | 18 | 1,889 | 428 | 1,647 | 2,562 | |
| Cultural/spiritual | | 29 | | 216 | | | | | | 5 | | |

* n/a = not applicable; if blank, then no studies available at this time

Table 26. Ecosystem goods and service values based on peer-reviewed original research, grey literature, and meta-analysis studies in temperate North America/Europe [2012 $/(acres*yr)].

| Ecosystem Goods and Services | Coastal Shelf | Beach | Estuary | Saltwater Wetland | Forest | Grass/ Rangelands | Cropland | Freshwater Wetland | Open Fresh Water | Riparian Buffer | Urban Greenspace | Urban/ Barren |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Gas/climate regulation | | n/a | | | 65 | 4 | | 161 | | | 404 | |
| Disturbance regulation | | 32,794 | 344 | 373 | | | | 4,397 | | 106 | | |
| Water regulation | | | | | | 2 | | 3,590 | | | 7 | |
| Water supply | 626 | | 59 | | 196 | | | 1,856 | 492 | 2,310 | | |
| Soil formation | n/a | n/a | | | 6 | 4 | | | n/a | | | |
| Nutrient cycling | 869 | n/a | 12814 | | | | | | | | | |
| Waste treatment | | n/a | | 6,508 | 53 | 53 | | 1,008 | | | | |
| Pollination | n/a | n/a | | | 195 | 16 | 10 | | n/a | | | |
| Biological control | 24 | n/a | 47 | | 2 | 14 | 14 | | | | | |
| Habitat/refugia | | | 378 | 242 | 1,110 | | 999 | 136 | | | | |
| Aesthetic/recreation | | 17,851 | 351 | 31 | 147 | 1 | 18 | 1,690 | 428 | 1,647 | 2,562 | |
| Cultural/spiritual | 42 | 29 | 18 | 216 | 1 | | | 1,070 | | 5 | | |

* n/a = not applicable; if blank, then no studies available at this time

The use of benefit transfer methods should be employed with forethought and consideration. The NRC (2005) noted that benefit transfer methods generally are a "second-best" valuation method and should be used with caution. The value estimates presented here for example, are presented as single values, but in reality represent a mean or average value with an associated range of variance about the mean. It has been shown for example that saltwater marshes have a considerable range of values in terms of their ability to buffer communities against hurricanes. In a 2008 study (Costanza et al. 2008), the authors present the mean annual values at "almost $40,000/hectare (ha), with a range from $126 ha (for Louisiana) to $586,845 ha (for New York) and a median value of $1,700, indicating a quite skewed distribution." For purposes of the NACCS, these values can serve as a starting point for detailed assessment or for a comparative reference. Unfortunately there are many ecosystem services presented in Appendix H for which there is no literature on value estimates.

**Metric-based approach.** The second option for quantifying ecosystem services values involves the use of metrics in the context of estimating ecological production that satisfies economic demand. The relationship between natural features and human welfare requires the understanding of the magnitude of ecological outputs, as characterized by ecological production functions, and the human preferences for those outputs, as characterized by economic demand functions (Tazik et al. 2013). Ecological production functions relate ecological attributes to ecological endpoints, and ecological demand functions account for human preferences based on access, scarcity, and reliability.

One of the study objectives is to “develop performance metrics relevant to human welfare benefits attributed to ecosystem goods and services arising from the presence of natural, nature-based and structural features acting alone or in concert.” Ecosystem services are dependent on ecosystem structure of the habitat and the linkages with surrounding systems including stressors (NRC 2005). Ecosystem structure is the foundation of ecosystem functions and associated services. Ecosystem structure depends on factors such as height of vegetation, size of the habitat, percent cover, and related attributes. Linkages with surrounding systems have supporting or suppressing effects on ecosystem functions. Linkages with surrounding systems include the extent of alterations in adjacent lands, proximity to other natural features, connectivity, and other attributes. Generally, metrics for human values or preferences were not considered except for a few cases. Complete characterization of services would require consideration of socio-economic factors outside of the provided metrics.

Metric development used numerous ecosystems indicators that could be developed and analyzed with a GIS. Table 27 provides a list of the raw data used to generate the indicators for the metrics for the NACCS study area. Indicators considered include those previously identified for use in national assessments (NRC 2000) and other indicators that have been recently developed with a spatial extent covering the entire NACCS study area. The focus was on landscape-level indicators that measure ecosystem structure and indicators that measure linkages with surrounding systems. Furthermore, additional data layers (Table 28) were generated to facilitate the development of metrics.

Table 27. Geographic information system (GIS) data used to develop metrics for ecosystem services.

| Data Layer | Source | Date | Scale/Spatial Resolution | Useful Fields/ Attributes | Comments |
|---|---|---|---|---|---|
| **Boundary Data Layers** | | | | | |
| NACCS_Planning_Reach_Polygons | Baltimore District | 2013 | | | This data layer was used to select subsets of national data layers. |
| **Land Cover Data Layers** | | | | | |
| Coastal Change Analysis Program (C-CAP) | NOAA | 2006 | 30 m | Land cover | Even though other datasets have land cover, C-CAP has more wetland classes (freshwater vs. saltwater; herbaceous vs. shrub vs. tree) |
| National Land Cover Dataset (NLCD)-Impervious Cover | Multi-Resource Land Characteristics Consortium (MRLC) | 2006 | 30 m | % impervious cover | |
| Landfire-type | USGS | 2008 | 30 m | Vegetation type | Vegetation type field has information on introduced or disturbed classes. This data layer can be used to estimate how much of an area has introduced or disturbed vegetation. Conversion to polygon would facilitate analysis. |
| Landfire-cover | USGS | 2008 | 30 m | Vegetation cover | Vegetation cover field has information on tree, shrub, and herb cover in 10% increments. Conversion to polygon would facilitate analysis. |
| Landfire-height | USGS | 2008 | 30 m | Vegetation height | Vegetation height field has information on height (m) of forests (0-5, 5-10, 10-25, 25-50), shrub (0-0.5, 0.5-1, 1-3, >3), and herb (0-0.5, 0.5-1, >1). For some wetlands, there is no associated heights and the middle class should be used. Conversion to polygon would facilitate analysis. |

| Data Layer | Source | Date | Scale/Spatial Resolution | Useful Fields/ Attributes | Comments |
|---|---|---|---|---|---|
| Gap Analysis Program Land Cover | USGS | 2001 | 30 m | Land cover | Data layer used solely for identification of maritime and dune land cover classes. |
| **Physical Geography Data Layers** | | | | | |
| National Elevation Dataset (NED) | USGS | 2013 | 10 m | Elevation | Elevation in ms (NADV88 datum). USACE Baltimore District (NAB) created one Digital Elevation Map (DEM) for the entire study area. |
| NACCS_shorelines | NOAA | 2000–2007 | 1:24,000 | NACCS Shoreline Type | NACCS Shoreline Types' to aggregate fields into the following categories: Rocky shores (exposed), Rocky shores (sheltered), Beaches (exposed), Man-made structures (exposed), Man-made structures (sheltered), Scarps (exposed), Scarps (sheltered), Vegetated low banks (sheltered), wetlands/marshes/swamps/ (sheltered). |
| us_medium_shorelines | NOAA | 2000 | 1:10k–1:60k | | |
| Coastal Barrier Resources System Polygons | USFWS | 2012 | 1:24,000 | | Polygons do not cover just the barrier island. |
| National Hydrography Dataset (NHD)-Flowline | USGS | 2012 | 1:24,000 | Type | Useful line feature types include stream/river and canals/ditches. These subsets can be used for other analyses. |
| National Hydrography Dataset (NHD)-Area | USGS | 2012 | 1:24,000 | Type | Useful polygon feature types include stream/river, submerged stream, and canal/ditch. These subsets can be used for other analyses. |

| Data Layer | Source | Date | Scale/Spatial Resolution | Useful Fields/ Attributes | Comments |
|---|---|---|---|---|---|
| National Hydrography Dataset (NHD)-Waterbody | USGS | 2012 | 1:24,000 | Type | Useful polygon feature types include lake/pond and reservoir. These subsets can be used for other analyses. |
| **Ecological Data Layers** | | | | | |
| TES species | USFWS | 2013 | n/a | | County counts of TES species gathered from www.fws.gov/endangered/index.html |
| Eelgrass | The Nature Conservancy (TNC) | 2008 | 1:24,000 | percent coverage | Data layer contains other vegetation besides eelgrass. |
| **Socio-economic Data Layers** | | | | | |
| Census | United States Census Bureau | 2010 | n/a | Pop | |
| Private schools | Oak Ridge National Laboratory | 2011 | n/a | Enrollment | |
| Public schools | Oak Ridge National Laboratory | 2011 | n/a | Enrollment | |
| Colleges and universities | Oak Ridge National Laboratory | 2011 | n/a | Tot_enroll | |
| Beaches | Environmental Protection Agency | 2010 | 1:24,000 | | |

Table 28. Data layers derived from sources in Table 27.

| Original Data Layer | Product Data Layer | Processing Operation | Useful Fields/ Attributes | Comments |
|---|---|---|---|---|
| C-CAP | Morphological Spatial Pattern Analysis (MSPA) Raster | Guido software | MSPA Class | Identifies core, bridges, edges, and islets of forest and wetlands. For sensitive biota, information useful for identifying valuable habitat (core) and habitat not as valuable (islets, edges). Defined edge as 30-m zone between forest/wetland and other land cover classes. |
| NHD Flowine | NHDDitches | Select Ftype = 336 | | Selects ditches and canals to help identify these features in wetlands. |
| NHD Flowine | 100 m buffer of stream lines | Select Ftype = 460, Buffer 100 meters | | Narrow streams are shown as lines in NHD Flowlines. Prior to buffer operation, need to insure data layer is projected to avoid distortions. |
| NHD Area | 100 m buffer of stream polygons | Select Ftype = (460,461), Buffer 100 meters | | Wide streams are shown as polygons in NHD Area. Prior to buffer operation, need to insure data layer is projected to avoid distortions. |
| us_medium_shoreline | NACCS_Islands | 1. Select by Location; select Features from us_medium_shorelines intersecting NACCS_Planning_Reach_Polygons<br>2. Feature to Polygon | | Removed Delmarva Peninsula and Long Island. Tried using NACCS_shorelines to generate island polygons, but most lines did not form closed polygons. |

Understanding the role of ecosystem structure and linkages on ecosystem functions and processes informed construction of a metric. For example, greater wetland vegetation height and cover are indicative of a positive influence on habitat for some fish and wildlife functions, depending on species of vegetation, which can have a negative effect (e.g., invasive exotics). In addition, lack of forest cover and modified land uses are indicative of a negative influence on habitat for fish and wildlife functions. A final metric for habitat functions of wetland would involve indicators for vegetation height, vegetation cover, and surrounding land uses. Also, the metrics need not be excessively complex. As an example, for the southeastern U.S., recreational catch in salt water could be estimated by just one indicator for ecosystem structure (acres of salt marsh) and just one socio-economic indicator for access (number of fishing trips) (Bell 1997).[1]

Socio-economic indicators were only used for socio-economic metrics where there was not substantial ecological output. Services related to aesthetics, cultural heritage, education and scientific opportunities, and some types of recreation are not intimately tied to ecosystem structure or functions, especially for most human populations. For example, a Minnesota community valued wetlands that were well cared for and were good places for children to play more than the wetland plant biodiversity (Nassauer 2004). Recreation value of beaches was associated with attributes of NNBF such as beach width and proximity to amusement parks (Parsons et al. 1999). Metrics for socio-economic services required inclusion of socio-economic indicators such as population density and proximity to schools that reflected the probability of use by human populations.

The general form of the metric includes up to two types of indictors. The first indicator type captures the foundational ecosystem production attributes of the feature. Attributes related to vegetation height, vegetation cover, percent native vegetation, vegetation type, soil type, and other indicators provide the basic information on the structure of the feature. Each of these indicators would use normalized values based on the maximum value within the NACCS study region for that indicator for that ecosystem feature with scores ranging from 0 to 1.0. The second indicator type represents linkages with surrounding systems. Attributes such as adjacent modified land cover, proximity to other habitats, and alterations

[1] Approximately 88% of the variance of fish catch weight was explained by number of trips and salt marsh acreage. This example also illustrates the need for socio-economic data on access to account for the service the salt marsh provides for recreational fishermen.

to hydrology provide basic information on supportive resources or stressors. Moderate to high levels of stressors can be controlling with high stressor levels such as impervious cover determining the level of certain functions regardless of the amount of vegetation or cover in the system (Schueler et al. 2009).

Some functions are not affected by altered landscapes as adversely. As an example, nutrient sequestration or conversion would not be affected by altered landscapes (Richardson et al. 2011; Verhoeven et al. 2006) and may even require altered surrounding areas to maximize its functions. Each of these indicators would also use normalized values based on the maximum value within the NACCS study region for that indicator for that ecosystem feature with scores ranging from 0 to 1.0. The final metric combining the two indicator types (through a geometric mean or another representative mathematical expression) would be a normalized value ranging from 0 to 1.0.

In addition to the metric, decision-makers need to consider the dimensions of the feature. Larger features with high scores for a metric would provide different amounts of functions and services than smaller features with high scores. To translate the metric to a value that has more utility for decision-makers, the metric score for a feature would need to be multiplied by the dimension of the feature. In most cases, this would be area, length, or width of the feature. Note that some services exhibit non-linear responses (e.g., biodiversity, species richness has been shown to be related to the log of area) (NRC 2000; Barbier et al. 2011; Koch et al. 2009).

Table 29 provides a synopsis of the GIS operations used to extract the features of interest while Appendix J provides a synopsis of the construction of the metrics for the different NNBF. For a given metric, similar indicators were used across the various NNBF. These metrics are meant to be an initial start with further refinement occurring based on availability of local data and better local knowledge of ecosystem processes.

**Considerations of Peer-Reviewed Studies in Developing Metrics.** A few metrics were informed by peer-reviewed studies. For metrics related to wave attenuation, different natural ecosystems would have different attributes included in the metric based on the documented attribute importance. For herbaceous coastal wetlands, vegetation density, biomass production, and marsh size could minimize adverse damage from waves

Table 29. GIS operations for identifying and/or extracting NNBF.

| Feature | Source Data Layer(s) | GIS Operation | Comment |
|---|---|---|---|
| Beach | NACCS_Mainland_Shoreline_Type<br>NACCS_Island_Shoreline_Type<br>C-CAP | 1. From either NACCS_Shorelines, Select NACCS Shoreline Type = "Beaches (exposed)"<br>2. Select by Location; select Features from C-CAP (polygon) intersecting NACCS_Shorelines<br>3. From CCAP, Select Value = 20 (Bare Land) | This operation works best if the C-CAP data layer has been converted to polygons |
| Mudflat/sandflat | C-CAP | Select Value = 19 (unconsolidated shore) | If data layer is in polygon format, can use Select tool. If data layer is in raster format, can use Con tool to set the non-target cells to null values and then export to polygon. |
| Bluff | NACCS_Mainland_Shoreline_Type<br>NACCS_Island_Shoreline_Type | Select NACCS Shoreline Type = "Scarps (exposed) and/or Scarps (sheltered)" | The output is a line file. Bluffs often do not show up as bare land and may be vegetated. |
| Dune | Gap Analysis Program Land Cover | Select INTLSGAPMAPCODE = (7503,7507) (Atlantic coastal plain southern dune and maritime grassland, northern Atlantic coastal plain dune and swale) | |
| Salt marsh | C-CAP | Select Value = 18 (estuarine emergent wetland) | See mudflat/sandflat. |
| Scrub wetland (brackish) | C-CAP | Select Value = 17 (estuarine scrub/shrub wetland) | See mudflat/sandflat. |
| Forest wetland (brackish) | C-CAP | Select Value = 16 (estuarine forested wetland) | See mudflat/sandflat. |
| Maritime grassland | Gap Analysis Program Land Cover | Select INTLSGAPMAPCODE = 7503 (Atlantic coastal plain southern dune and maritime grassland) | An alternative is to select C-CAP grasslands within 100 m of the NACCS shoreline. |
| Maritime shrubland | Not available | | An alternative is to select C-CAP shrublands within 100 m of the NACCS shoreline. |
| Maritime forest | Gap Analysis Program Land Cover | Select INTLSGAPMAPCODE = 4211 (Atlantic coastal plain northern maritime forest) | An alternative is to select C-CAP forests within 100 m of the NACCS shoreline. |

| Feature | Source Data Layer(s) | GIS Operation | Comment |
|---|---|---|---|
| Submerged aquatic vegetation | The Nature Conservancy | None | |
| Riparian | 100 m buffer of NHD Flowline<br>100 m buffer of NHD Area<br>C-CAP | 1. Merge 100 m NHD Flowline buffer and 100-meter NHD Area buffer<br>2. Raster clip C-CAP with buffered layers<br>3. Select Value = (9,10,11) (deciduous, evergreen, or mixed forest) | Processing of NHD buffers were described in Table 28. |
| Herbaceous marsh | C-CAP | Select Value = 15 (palustrine emergent wetland) | See mudflat/sandflat. |
| Scrub wetland (fresh) | C-CAP | Select Value = 14 (palustrine scrub/shrub wetland) | See mudflat/sandflat. |
| Forest wetland (fresh) | C-CAP | Select Value = 13 (palustrine forested wetland) | See mudflat/sandflat. |
| Pond | NHD Waterbody | Select FType = 390 (lake or pond) | This operation may select impoundments. |
| Terrestrial grassland | C-CAP | Select Value = 8 (grassland/herbaceous) | See mudflat/sandflat. |
| Terrestrial shrub | C-CAP | Select Value = 12 (scrub/shrub) | See mudflat/sandflat. |
| Terrestrial forest | C-CAP | Select Value = (9, 10, 11) (deciduous, evergreen, or mixed forest) | See mudflat/sandflat. |
| Reef | Not available | | |
| Island | NACCS_Islands | None | |
| Barrier island | CBRS_polygons<br>NACCS_Islands | Select by Location; select Features from NACCS_Islands intersecting CBRS_polygons | |
| Living shoreline | Not available | | |
| Structural levee | Not available | | |
| Structural surge barrier | Not available | | |
| Structural seawall | Not available | | |
| Structural groin | Not available | | |
| Structural breakwater | Not available | | |

and stabilize shorelines (Shepard et al. 2011). Note that even unvegetated sandflats have the ability to attenuate waves, albeit at a lower rate than vegetated habitats (Möller et al. 1999). For seagrasses, vegetation height up to the depth of water attenuates waves in a manner comparable to salt marshes (Fonseca and Cahalan 1992). For both salt marshes and seagrasses, attenuation of waves diminishes at greater water depths, especially when the water surface exceeds the height of the vegetation (Koch et al. 2009).

For metrics related to reducing storm surge, similar attributes have a role. For wetlands, increased roughness due to vegetation type, moderate marsh elevations, and marsh continuity all have a role in minimizing storm surges (Loder et al. 2009). Wetland roughness increases as one progresses from sand, to herbaceous, to shrubs, to woods. However, when storm surges increase water levels above the height of the vegetation, low-lying vegetation such as seagrasses and salt marshes are expected to have less of an effect on mitigating storm surges (Koch et al. 2009).

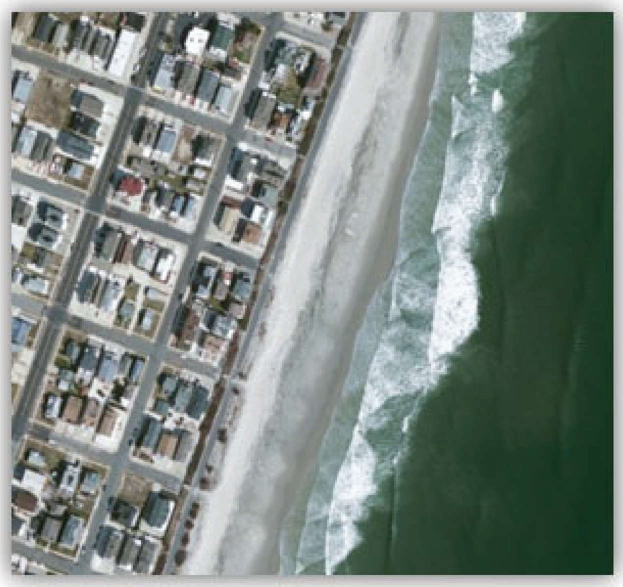
Non-vegetated NNBF could also provide storm surge protection services. Beaches and dunes serve as sacrificial structures that reduce wave energy and serve as barriers to storm surges (NRC 1995). Nevertheless, there are limits to the effectiveness of beaches and dunes by themselves in providing full protection. In Hurricane Sandy in the Boroughs of Bay Head and Mantoloking in New Jersey, beach/dune complexes with an elevation of 6 m above MSL were overwhelmed with water levels 4.2 m above MSL accompanied by wave crest elevations reaching 6.5 m above MSL, resulting in one home in Bay Head and over 30 homes in Montoloking being destroyed (Irish et al. 2013). For Bay Head, a forgotten buried seawall (crest 4.8 m above MSL) appears to have contributed to reducing the number of homes damaged or destroyed (Irish et al. 2013).

Figure 22 shows an example of a metric for storm surge protection for a beach based on maximum height of the beach above sea level and the width of the beach.[1]

[1] These dimensions are not meant to be design standards. Upon further analysis, design standards can be developed and used for metric construction. In addition, there are other factors that need to be considered such as design profile of the beach, information that cannot be obtained using landscape indicators.

Figure 22. Metric for storm surge protection by beaches based on height and width.

$$BEACH_{STSURGE} = (90^{th}\ Perc\ Height/17.3 \times Width/200)^{1/2}$$



**90th Perc Height:** 0 – 1 score, based on the 90th percentile beach height value in feet above mean sea level (10-meter DEM)

**Width:** 0 – 1 score, based on width in feet (C_CAP)

Metrics for surge protection services of beaches would be based on the height of the feature relative to the desired protection for a specified storm surge height. Table 30 shows the peak surges for notable storm events in the Northeast Atlantic in the past 100 yr and the additional height added by a mean higher high water (MHHW) tidal event. Storm surges from Hurricane Sandy were the second highest on record in the table. For metric development, the peak surge from Hurricane Sandy at MHHW tide (5.3 m or 17.3 ft) was used to form the metrics, with the understanding that there has been and will probably be greater storm surges. Wider beaches would be preferable to allow sufficient amount of sand to erode, but the needed width of the beach would require more consideration. Lacking more information, the width objective was 200 ft (an arbitrary value that can be adjusted based on planning goals and objectives). Beaches that are at least 200 ft wide and 17.3 ft high would receive the highest score (1.0) based on its ability to provide a high level of confidence in the protection.

Table 30. Major storms and associated storm surge elevation in the North Atlantic in the past 100 yr (from Needham and Keim 2012; http://surge.srcc.lsu.edu/data.html).

| Year | Storm Name | Location | State | Peak Surge (m) | MHHW elevation above MSL (m)1 |
|---|---|---|---|---|---|
| 1903 | Vagabond | The Battery | NY | 2.07 | 0.76 |
| 1936 | | Sewells Pt | VA | 2.83 | 0.43 |
| 1938 | Great New England | Fairhaven | MA | 6.49 | 0.54 |
| 1944 | | Providence | RI | 3.2 | 0.79 |
| 1953 | Carol | Bristol | RI | 2.99 | 0.75 |
| 1956 | Flossy | Sewells Pt | VA | 1.34 | 0.43 |
| 1971 | Doria | Providence | RI | 1.22 | 0.79 |
| 1976 | Belle | Manhattan | NY | 1.37 | 0.76 |
| 1985 | Gloria | Battery Park | NY | 2.1 | 0.76 |
| 1986 | Charley | Nantucket | MA | 1.22 | 0.55 |
| 1991 | Bob | Willets Point | NY | 2.13 | 1.06 |
| 1996 | Edouard | Nantucket | MA | 1.22 | 0.55 |
| 2003 | Isabel | Smithfield | VA | 3.28 | 0.43 |
| 2011 | Irene | Long Beach | NY | 2.16 | 0.81 |
| 2012 | Sandy | Bergen Point | NJ | 4.45 | 0.83 |

[1] Additional high elevation was based on historical MHHW records above MSL from http://tidesandcurrents.noaa.gov/tide_predictions.shtml. For Smithfield, the closest datum station is Sewells Point. For Long Beach, the closest datum station is Sandy Hooks. For Willets Point, the closest datum station is Port Morris.

For recreation on beaches, some attributes make beaches conducive to human use. Beach length and width appear to be important factors in recreational use (Parsons et al. 1999). However, beach width exhibits a more complicated relationship where widths greater than 75 ft are desirable, but widths greater than 200 ft decrease beach use due to the extra effort it takes for people to reach the water's edge. In addition, nonecological attributes such as proximity to amusement parks and boardwalks increase use.

Figure 23 presents an example of a metric for beach recreation based on indicators for beach access, width, length, and population density including a graph showing the non-linear relationship between beach width and recreational beach use. Because beach recreation is primarily a socio-economic service, an additional indicator for population density within the NACCS planning reach was factored, although other types of geographies (e.g., 5 km buffer, county) could be used.

Figure 23. Metric for beach recreation based on length, beach access, width, and population density.

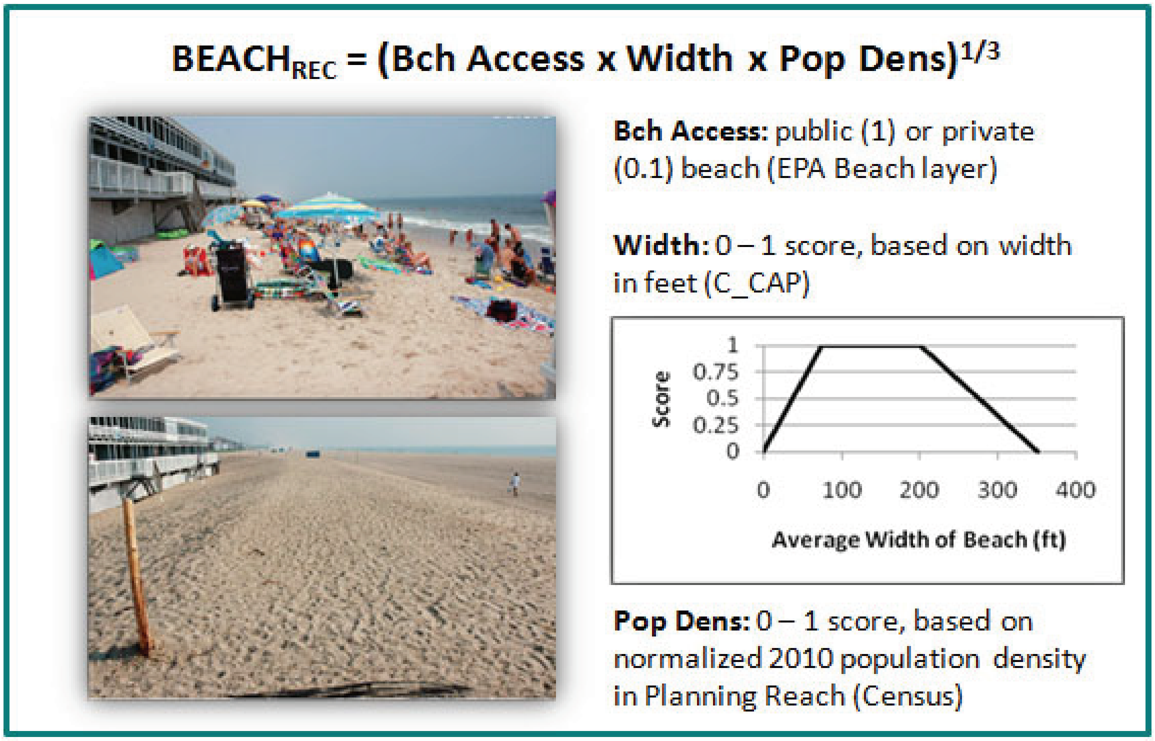



Figure 24 presents an example of a metric for palustrine scrub shrub wetland biodiversity based on indicators of vegetative cover, height, nativeness, tree cover, wetland cover and ditch densities. For mid-Atlantic wetlands, understanding wetland functions may require just a few explanatory landscape indicators (Weller et al. 2007). For flat wetlands, habitat hydrogeomorphic (HGM) scores were explained mostly by forest cover within 100 m of the wetland. For riverine wetlands, habitat, biogeochemistry, and hydrology HGM scores were explained mostly by natural, disturbed, and excavated streams from higher resolution National Wetland Inventory (NWI) maps (USFWS 2013). Impervious cover and other land uses did not have as great of an effect as ditch density. However, higher resolution NWI maps for determining ditch density are unavailable for most of the NACCS study area. In the absence of higher resolution NWI maps, HGM scores of riverine wetlands were explained by the amount of woody wetlands in the vicinity, suggesting that a riverine wetland's functions are influenced by proximity to woody wetlands. Because there were no region-wide data on HGM class, landscape condition of wetlands would rely on forest cover in a 100 m buffer based on C-CAP data, total wetland cover in a 1 km buffer based on C-CAP data, canal/drainage ditch map based on NHD Flowline data (Table 29). Nevertheless, approximately half or more of the variance was unexplained in these models, showing that landscape indicators do not fully account for ecosystem condition.

Figure 24. Metric for biodiversity of shrub wetlands based on vegetation cover and proportion natives in the wetland, tree cover within 100 m of wetland, proximity to other open water and wetlands within 1 km, and ditch density in the wetland.

$$PSSV_{BIODIV} = (\text{Veg Cover} \times \text{Veg Height} \times \text{Prop Native} \times \text{Tree Cover-100m} \times \text{OW/Wet-1km})^{1/5} \times \text{Ditch Density}$$

**Veg Cover:** 0 – 1 score, based on normalized vegetation cover in wetland (USGS Landfire)

**Veg Height:** 0 – 1 score, based on normalized vegetation height in wetland (USGS Landfire)

**Prop Native:** 0 – 1 score, based on normalized native vegetation type in wetland (USGS Landfire)

**Tree Cover-100m:** 0 – 1 score, based on normalized vegetation cover within 100 meters of wetland (blue) (USGS Landfire)

**OW/Wet-1km:** 0 – 1 score, based on normalized open water/wetland cover within 1 km of wetland (purple) (C-CAP)

**Ditch Density:** 0 – 1 score, based on normalized ditch density in a wetland (higher density = lower score) (NHD Flowline and C-CAP)

For other types of aquatic resources besides freshwater wetlands where region-specific studies were not available, aquatic resource condition was based on known general relationships between landscape indicators and aquatic resource condition. Figure 24 presents an example of a metric for palustrine scrub shrub wetland biodiversity based on indicators of vegetative cover, height, nativeness, tree cover, wetland cover and ditch densities. There has been documentation that streams and other aquatic resources are affected by impervious cover (Allan 2004; Schueler et al. 2009) and agriculture (Allan 2004). It was assumed that these effects would be similar for aquatic resources near estuaries such as mudflats, submerged aquatic vegetation, reefs, and other tidally influenced aquatic resources. Although it would be more appropriate to look at impervious cover in the contributing watersheds, the amount of GIS analysis to identify contributing watersheds in relatively flat topographies would be prohibitive and counter-productive, so impervious cover in the 100 m buffer was used instead. Because agriculture seems to have less of an effect on aquatic resources (Stewart et al. 2001), agriculture was treated as having half of the effect of impervious cover in a manner similar to landscape development indices used by Brown and Vivas (2005). Figure 25 shows the metric for salt marsh provisioning services based on vegetation cover and proportion native vegetation and stressor indicators such as impervious cover, agricultural land cover, and ditch density. As noted before, agriculture has less of an impact than impervious cover, and the scaling reflects its reduced effect.

Figure 25. Metric for provisioning by salt marshes based on vegetation cover and proportion natives in the salt marsh, impervious cover and agriculture within 100 m of the salt marsh, and ditch density in the salt marsh.

$$SLTMARSH_{PROV} = (\text{Veg Cover x Prop Native x NPP Coef})^{1/3} \text{ x}$$
$$(\text{Imp Cover-100m x Agric Cover x Ditch Dens) 1/3}$$

**Veg Cover:** 0 – 1 score, based on normalized vegetation cover in wetland (blue) (USGS Landfire)

**Prop Native:** 0 – 1 score, based on normalized native vegetation type in wetland (blue) (USGS Landfire)

**NPP Coef:** 0 – 1 score, based on normalized NPP coefficients

**Imp Cover-100m:** 0 – 1 score, ((25 - % imp cover in 100-m radius (purple))/15 (NLCD2006)

**Agric Cover:** 0 – 1 score, ((50 - % ag in 100-m radius (purple))/25 (C-CAP)

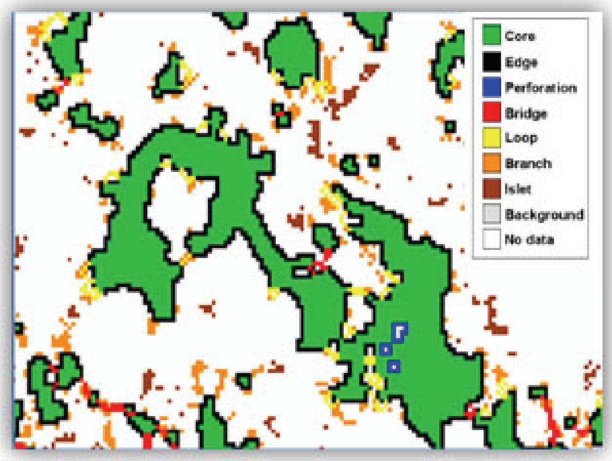
**Ditch Density:** 0 – 1 score, based on normalized ditch density in a wetland (higher density = lower score) (NHD Flowline and C-CAP)

For upland habitat types, disturbance sensitive functions such as habitat and biodiversity used the results of an MSPA (Wickham et al. 2010). A morphological spatial planning analysis (MSPA) was performed using the 2006 C-CAP data, identifying core, edge, bridges, islets, and other features (Figure 26). Central to MSPA is the understanding that configuration of natural ecosystems affect the usefulness as habitat, particularly for edge- and disturbance-sensitive species such as migratory neotropical songbirds. Coefficients based on MSPA-derived features were used in the indices for habitat-related functions of upland habitats. Coefficients for core, edge/perforation, bridge/loop/branch, and islets were 1, 0.7, 0.4, and 0.1, respectively.

For all NNBF, overall productivity has a role in some of the metrics. Mean net primary productivity (NPP) provides insights on the ecological capacity of a natural feature (Table 31).

Figure 26. Metric for forest biodiversity based on vegetation cover, proportion natives, and morphological spatial pattern analysis.

$$FOREST_{BIODIV} = (\text{Veg Cover} \times \text{Veg Height} \times \text{Prop Native} \times \text{MSPA Factor})^{1/4}$$




**Veg Cover:** 0 – 1 score, based on normalized vegetation cover in feature (USGS Landfire)

**Veg Height:** 0 – 1 score, based on normalized vegetation height in feature (USGS Landfire)

**Prop Native:** 0 – 1 score, based on normalized native vegetation type in wetland (USGS Landfire)

**MSPA Factor:** 0 – 1 score, Morphological spatial pattern analysis factor (Core = 1, edge/perforation = 0.7, branch/bridge/loop = 0.4, and islet = 0.1)

Table 31. NPP estimates for ecosystems in the NACCS study area.

| Ecosystem | Net Primary Productivity (g dry weight m-2 yr -1) | Source |
|---|---|---|
| Forest (upland or maritime) | 1200 | Cronk and Fennessy (2001) |
| Shrub (upland or maritime) | 600 | |
| Grassland (upland or maritime) | 500 | |
| Bluffs | 3 | |
| Freshwater herbaceous wetland | 2500 | |
| Saltwater herbaceous wetland | 2500 | |
| Sand | 3 | |
| Ponds | 500 | |
| Riparian | 1200 | Used upland forest value |
| Wetland forest (saltwater or freshwater) | 1200 | |
| Wetland shrub(saltwater or freshwater) | 500 | |
| Submerged aquatic vegetation | 700[1] | Roman et al. (1990) |
| Mudflats | 350[2] | |

1 Rounded it down to 700

2 Used the average value

Although vegetation height and cover do provide similar information, knowledge of the published literature values for NPP for various ecosystems complements knowledge of the structure. Because NPP varies depending on site-specific condition of the ecosystem, season, seral stage, and other unaccounted factors, published values for net primary productivity would not be indicative of the actual ecological processes. NPP values are best used as a complement to structural indicators, especially when comparing services across habitats where all habitats are based on the same normalized scale. As Table 31 presents, beaches do not have as much ecological productivity and mudflats have ecological productivity that may not be fully acknowledged by decision-makers.

## Conclusions

Thoughtful attention to design, location, and construction of NNBF which are resilient and self-repairing, while providing a suite of goods and services, can ensure successful ecosystem recovery in the aftermath of Superstorm Sandy (or other storms in the future). Considerations of the full spectrum of functions, services, and benefits potentially produced by these coastal recovery initiatives are critical to managing coastal resilience over the long term. To effectively utilize ecosystem goods and services in the decision-making process requires a clear understanding of the concept and context (definitions and problem space). Here a new definition is offered couched within a new context—that of managed ecosystems composed of natural and engineered features embedded within a socioeconomic environment operating at the systems level.

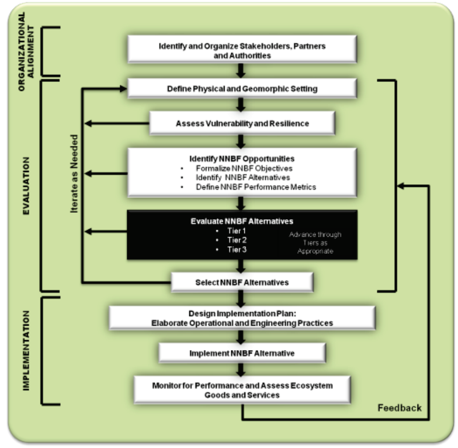
From this new perspective, the development of a procedure was sought that would transparently and concisely identify key ecosystem-based goods and services associated with these systems and use this process to develop a suite of clear and concise performance metrics that planners, engineers, and managers can use to transparently compare and contrast competing recovery design plans. These metrics target not only reductions of coastal storm damages, but the full spectrum of environmental, social, and economic benefits associated with these systems.

Both nature-based approaches and ecosystem goods and service valuations are on the frontiers of both ecology and engineering, and thus many, many research questions still remain unanswered. The lists presented herein should be considered a good start, but not all inclusive or the end-all solution to the problem of quantifying ecosystem response to proposed recovery plans. In other words, it is entirely likely that new NNBF will be added to this list as the NACCS recovery efforts unfold and new technologies are developed. Moreover, the services these provide will likely expand and adapt over time upon review and reflection by the stakeholder community.

Further, the quantitative (and semi-quantitative) methodologies presented in the appendices are only now coming to fruition. These techniques will need to be fine tuned (or new approaches be devised) to address specific planning objectives as feasibility-level studies come online, and uncertainties surrounding their production will need to be acknowledged and addressed. The spiral-based approach presented here can be used to revise and derive new metrics sensitive enough to discriminate amongst proposed recovery plans. The approach accommodates all three levels of hierarchical characterization, which should facilitate its use in the field. Moreover, the spiral is flexible and adaptive and will lend itself well to both the USACE planning process as well as other stakeholders' recovery planning procedures and methodologies.

Recommendation Number 22 of the President's Hurricane Sandy Rebuilding Task Force (2013) calls for the development of a "consistent approach to valuing the benefits" of NNBF and structural features to advance their broad integration and application (refer to page 78)—the approach presented herein directly addresses this need. The final product is a scientifically informed and defensible toolset that will transparently and consistently estimate benefits for the NACCS and support them in their efforts to recover from Superstorm Sandy. These metrics can now be deployed in all three tiers of the NNBF assessment framework (Chapter 5), to which this study provides a critical link.

# 5 Framework for Assessing and Ranking NNBF Alternatives

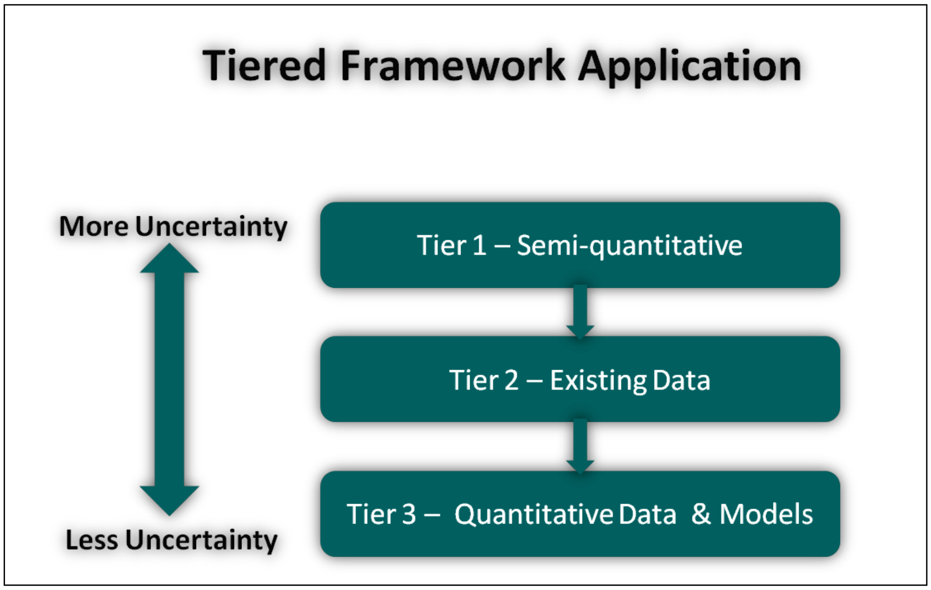



## Introduction

This chapter describes a tiered evaluation framework for analyzing the contribution of NNBF to system vulnerability, resilience and other study objectives, while accounting for other services generated by the NNBF. Described here are the steps of analysis using the objectives and associated vulnerability and performance metrics developed as part of the NACCS and described in prior chapters. The framework provides a structured, repeatable, and easily understood (i.e., transparent) means of evaluating natural, nature-based, and structural feature vulnerability and performance. The NNBF may be variously assessed categorically, as specific projects, or as groups of projects reflecting a particular alternative. Given that the framework needs to be flexible to take advantage of any new information that may become available during the decision-making process, the framework is necessarily tiered. The tiers of analysis, beginning with evaluation based primarily on expert elicitation, progress through stages employing greater levels of quantitative and engineering analysis. Each successive tier is more quantitative and less uncertain, and can build on a previous tier(s) (Figure 27). It is not necessary to execute all three tiers; rather, the approach permits analysis with the best available data and may be implemented at whatever tier(s) needed to support sound decisions.

The decision framework represents integral components of Evaluation as shown in Figure 2. The framework is compatible with evaluations of other management actions and alternatives undertaken by the NACCS project delivery team (PDT), and supports alternative screening, prioritization, and benefit and cost analyses, depending on the tier. The framework provides a means to define the decision space for evaluation based on NACCS objectives. This chapter is a narrative describing how the approach applies, how to use stakeholder preferences, how the consequence tables can be derived across the tiers, and the inherent characteristics that make the framework suitably appropriate and flexible.

Figure 27. Conceptual diagram of the NNBF decision framework showing options for operating across tiers that represent a decision-making continuum. A study can be implemented at any level or repeated when more data is available to lower uncertainty.




## Structured decision-making process

The framework by design supports a structured decision-making process. It is intended to complement the USACE planning process and is readily recognizable by many resource agencies that use it to structure their complex decisions. It is based on the five steps as described by Hammond et al. (1999):

- **Problem**–Identify the overarching problem (can be regarded as the goal).
- **Objectives**–Describe the desired outcomes and have associated performance measures.
- **Alternatives**–Can be any reasonable actions that achieve the objectives, ranging from specific projects to types of NNBF to alternatives with multiple actions.
- **Consequences**–Describe how well alternatives meet objectives.
- **Trade-offs**–Evaluate consequences across the range of alternatives.

These five steps of the framework serve as a construct for analyzing a complex decision by dividing it into components that separate science from policy. Unlike decisions made intuitively by focusing on available alternatives, structured decision making focuses on early definition of objectives (values), which subsequently drive the remainder of the assessment framework. It enables deliberative, thorough, transparent, explicit, and replicable decision-making process (enabling new information to be incorporated into the decision without having to start from the beginning). It also exposes uncertainty and its impact on the decision.

## Basic framework construct

To help understand the framework structure, a basic construct of the framework was developed (Table 32). It is populated by proxy objectives and metrics for illustrative purposes. This information could be derived through a variety of mechanisms including a vulnerability assessment (refer to Chapter 3), an assessment of ecosystem goods and services (refer to Chapter 4), or even analyses that address risk reduction and economic viability. Objectives are generated by the stakeholders [e.g., Federal and State agencies, nongovernmental organizations (NGO)] and reflect their values, but are also informed by an understanding of the potential roles of NNBF (Chapter 1). Metrics associated with the objectives are discussed in Chapters 3 and 4. The measures associated with each metric will vary depending on the availability of data and tools and are informed by an understanding of the processes affected by NNBF (Chapter 2). Alternatives are formulated from lists of NNBF and an understanding of their function and a recognition of the types of features appropriate given the geomorphic setting (Chapter 2).

Table 32. Basic construct of the framework showing objectives, metrics and alternatives for NNBF. Table populated by proxy information and is designed to be sufficiently flexible as to be used in all three tiers of the framework.

| | | | Alternative Performance | | | | |
|---|---|---|---|---|---|---|---|
| Objective | Metric | Measure | 1 | 2 | 3 | 4 | Etc. |
| Reduce storm impacts | Average annual damages avoided | ↑/no change/↓ | | | | | |
| | Recovery time | Months | | | | | |
| | Employment impacts | % of workforce unemployed | | | | | |
| Sustain ecosystem services generated by coastal systems | Fish and wildlife habitat provision | Habitat quality index | | | | | |
| | Maintain water quality | Water quality index | | | | | |
| Promote resilient coastal communities | Pop | No. residents | | | | | |
| | Vulnerability to coastal storms | Exposure and sensitivity | | | | | |

## Stakeholder preference surveys

Stakeholder preference surveys, while not required, can be an important element of the tiered framework, especially in Tier 1 when data and other information is lacking for the alternatives being considered. Stakeholder preferences can be applied to objectives or to alternatives (e.g., NNBF categories) in order to weight objectives or help formulate alternatives. A matrix can be used to structure the decision problem and present to stakeholders. Table 33 builds on the basic construct presented in Table 32, but adds stakeholder preferences for the stated objectives. Table 33 presents hypothetical results from three stakeholders, with consequent weights applied to each of the proxy metrics in the second column. In this case, the stakeholders placed greater weight on the average annual damages avoided (0.20) and recovery time (0.18) metrics, indicating that they placed more value on these metrics than the other metrics in the matrix. This weighting process is not necessary but is a powerful mechanism to address trade-offs with complex objective sets.

Table 33. Stakeholder preference survey matrix. The objectives and metrics are carried over from Table 32, with preferences for objectives and consequent weighting of objectives.

| Objective | Metric | Importance to Stakeholder 1 | Importance to Stakeholder 2 | Importance to Stakeholder 3 | Objective Weighting |
|---|---|---|---|---|---|
| Reduce storm impacts | Average annual damages avoided | 7 | 10 | 7 | 0.20 |
| | Recovery time | 9 | 8 | 5 | 0.18 |
| | Employment impacts | 5 | 6 | 3 | 0.11 |
| Sustain ecosystem services generated by coastal systems | Fish and wildlife habitat provision | 5 | 3 | 10 | 0.15 |
| | Maintain water quality | 3 | 4 | 9 | 0.13 |
| Promote resilient coastal communities | Pop | 2 | 5 | 3 | 0.08 |
| | Vulnerability to coastal storms | 5 | 9 | 5 | 0.15 |

## Framework construct across tiers

The measures and alternatives used in the framework may vary across tiers. What will not change are the objectives and metrics used to inform those objectives. In Tier 1, the measures for each metric are likely to be semi-quantitative and geared toward expert elicitation (Table 34). If more detailed data or modeling results are available, they can be used. In many cases the framework will be focused on categories of NNBF or specific projects. In the example shown in Table 34, the measures for each metric provided in the third column are based on simple scales or are index-based, reflecting the relative lack of data available at early stages of the project for the same proxy objectives and metrics listed in Table 32 and Table 33. For example, the measure for average annual damages avoided is a simple scale expressed as positive change, no change, or negative change relative to current conditions. These are applied to each of the alternatives— presented in this case as categories of NNBF (columns on the right side of the table). In order to apply the decision framework, these response vectors must be converted to a numeric scale (e.g., ↑ = 3, no change = 2, ↓ = 1).

Table 34. Example construct for Tier 1 of the framework. The objectives and metrics are carried over from Table 32 and Table 33.

| Objective | Performance Metric | Measure | Dune and Beach | High Marsh | Oyster Reef | Barrier Island | Etc., |
|---|---|---|---|---|---|---|---|
| Reduce storm impacts | Average annual damages avoided | ↑/no change/↓ | | | | | |
| | Recovery time | % change | | | | | |
| | Employment impacts | ↑/no change/↓ | | | | | |
| Sustain ecosystem services generated by coastal systems | Fish and wildlife habitat provision | Habitat quality index | | | | | |
| | Maintain water quality | Water quality index | | | | | |
| Promote resilient coastal communities | Pop | % change | | | | | |
| | Historical districts protected | ↑/no change/↓ | | | | | |

As the decision-making process progresses to more rigorous evaluation and less uncertainty in later tiers, more quantitative measures, generally involving numerical analysis are employed (Table 35). In later tiers more information will be available from project data, numerical models, and engineering analyses, providing greater resolution in the performance of alternatives under consideration. Table 35 illustrates this point by providing measures that have been updated to reflect increased availability of data, models and analytical tools to evaluate the alternatives under consideration. It is this aspect of the later tiers that provides more alternative-specific data and quantitative rigor, as well as improved prediction of outcomes and substantial reduction of uncertainty in the decision-making process.

Table 35. Example construct for Tier 3 of the framework. The objectives and metrics are carried over from Table 32 to Table 34.

| Objective | Performance Metric | Measure | Consequences | | | | |
|---|---|---|---|---|---|---|---|
| | | | Alt 1 | Alt 2 | Alt 3 | Alt 4 | Etc. |
| Reduce storm impacts | Average annual damages avoided | $M/yr | | | | | |
| | Recovery time | Months post category 3 storm | | | | | |
| | Employment impacts | Employment rate | | | | | |
| Sustain ecosystem services generated by coastal systems | Fish and wildlife habitat provision | Pop structure species diversity | | | | | |
| | Maintain water quality | Water quality index, salinity | | | | | |
| Promote resilient coastal communities | Pop | # Residents | | | | | |
| | Historical districts protected | # Properties | | | | | |

## Example matrix

To help facilitate a more complete understanding of the proposed framework for assessing and ranking NNBF alternatives, a series of consequence tables were developed that more completely relates alternatives to objectives/metrics. The intent is to capture and organize the types of objectives and metrics used for the NACCS and include evaluation criteria derived from relevant NNBF study tasks.

An example matrix of objectives, metrics and alternatives for NNBF is provided in Table 36. It is designed to be sufficiently flexible as to be used in all three tiers of the framework. The table has been populated by objectives and metrics that address resilience and environmental benefits (consistent with the NACCS) provided by NNBF and captured in the form of ecosystem goods and services (de Groot et al. 2002; van Oudenhoven et al. 2012). Objectives from the NACCS related to impacts to coastal populations and infrastructure were woven into the three objective categories of resilience, vulnerability, and ecosystem goods and services. Each of these categories contains multiple objectives related to these three categories. Objectives associated with resilience include ecological, social, economic, institutional, and infrastructure (structural features and NNBF).

Table 36. Example Tier 1 stakeholder preference survey (SH = Stakeholder).

| Objective Category | Objective | Metric | Preferences | | | | | | Weight |
|---|---|---|---|---|---|---|---|---|---|
| | | | SH1 | SH2 | SH3 | SH4 | SH5 | SH6 | |
| Resilience | Increase ecological resilience | Fish and wildlife habitat | 9 | 4 | 7 | 8 | 8 | 1 | 5.9 |
| | Improve social resilience | Storm-related mortalities over 10 yr | 10 | 9 | 10 | 10 | 8 | 10 | 9.1 |
| | | Historical districts protected | 1 | 3 | 5 | 4 | 2 | 1 | 2.6 |
| | | Pop change | 4 | 3 | 5 | 3 | 2 | 1 | 2.9 |
| | Increase economic resilience | Recovery time | 7 | 5 | 6 | 8 | 10 | 7 | 6.9 |
| | | percent of Pop that is employed | 8 | 7 | 8 | 5 | 3 | 10 | 6.6 |
| | Improve institutional resilience | percent of Pop covered by flood insurance | 2 | 3 | 4 | 2 | 4 | 6 | 3.4 |
| | Improve structural feature resilience | Average annual damages avoided | 9 | 6 | 8 | 7 | 5 | 10 | 7.2 |
| | | Density of commercial and industrial building infrastructure, including ports | 3 | 7 | 3 | 4 | 1 | 6 | 3.8 |
| | Increase nature-based infrastructure resilience | Storm protection | 8 | 4 | 5 | 4 | 3 | 1 | 4.0 |
| Vulnerability | Increase coastal protection | Susceptibility to Cat 3 or larger storms | 9 | 9 | 8 | 10 | 7 | 10 | 8.5 |
| | Reduce coastal Pop vulnerability | Exposure index | 7 | 9 | 9 | 6 | 8 | 9 | 7.7 |
| Ecosystem Goods and Services | Improve erosion protection and control | Vegetation index | 3 | 10 | 7 | 5 | 9 | 3 | 5.9 |
| | Increase TES species protection | Presence/Absence | 7 | 7 | 6 | 6 | 5 | 8 | 6.2 |
| | Maximize recreation opportunities | percent open space publically available | 5 | 8 | 7 | 9 | 5 | 6 | 6.4 |
| | Maximize education opportunities | # School field trips | 4 | 5 | 5 | 5 | 6 | 6 | 5.0 |
| | Increase carbon sequestration of NNBF | Tons carbon stored | 1 | 3 | 5 | 2 | 4 | 1 | 2.6 |
| | Sustain commercial fisheries | Catch per year | 10 | 3 | 4 | 6 | 6 | 5 | 5.4 |

Objectives coupled with vulnerability as defined in the vulnerability metrics (Chapter 3) include coastal protection and population vulnerability, which reflect the Composite Index developed by the NACCS. Objectives related to ecosystem goods and services include protecting TES species, recreation and education, among others.

Metrics assigned to each objective are either stated in the NACCS or are plausible proxies to inform each of the objectives in the resilience, vulnerability and ecosystem goods and services categories (refer to Chapter 4). Additionally the structural resilience objective and "Density of commercial and industrial building infrastructure, including ports" metric (in Table 36) incorporates an RSM strategy for placing dredged sediments beneficially for supporting and sustaining the use and value of NNBF (refer to Chapter 6). Two metrics have been developed to inform the vulnerability objective. The first is related to coastal storm damage susceptibility. The second vulnerability metric, the exposure (i.e., composite) index, was developed by the NAACS for addressing vulnerability to coastal populations related to population density and infrastructure, social, and environmental assets (refer to Chapter 3). Ecosystem goods and services objectives related to erosion and TES species are informed by metrics for NNBF that can characterize the benefits generated by these features (refer to Chapter 4). Units of measure are assigned to each metric. The concept of resilience is incorporated directly into the framework matrix through the use of metrics that inform the study objectives, such as time to recovery following a major storm.

Table 36 lists the results of a hypothetical preference survey involving six stakeholders that could be used to weight objectives and/or metrics. In the example, their weights are applied to each of the metrics in the third column. The weight data were then summarized as a simple average, but can be analyzed using simple statistics to identify trends in the weighting data.

Table 37 provides a basic construct of the framework indicative of a Tier 1 evaluation. The measures for each metric are semi-quantitative and based on expert elicitation. In this example, the measures for each metric are all based on simple scales or are index-based, reflecting the relative lack of data typical in an initial feasibility-level study. In this example, SME have provided input for each class of NNBF, but specific alternatives could be evaluated as well.

Table 37. Tier 1 framework matrix populated by information obtained from SME (Part I).

| Objective Category | Objective | Metric | Performance Measure | Beaches | Dune Complexes | Islands | Marsh Platforms | Mollusk | Fans | Drumlins/ Moraines | SAV Beds |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Resilience | Increase ecological resilience | Fish and wildlife habitat | Species diversity (extent to which diversity reflects historical values, using a scale from 0–10, with 10 being best) | 3 | 4 | 7 | 8 | 8 | 1 | 4 | 6 |
| | Improve social resilience | Storm-related mortalities over 10 yr | Number of mortalities averaged over 10 yr (0=10; 0–10=7; 11–50=4; 50–100=1; >100=0) | 1 | 4 | 4 | 4 | 2 | 1 | 1 | 1 |
| | | Historical districts protected | Number of properties (0–10=3; 11–50=5; 50–100=7; >100=10) | 1 | 3 | 5 | 4 | 2 | 1 | 1 | 1 |
| | | Pop change | Expected 10 yr avg. Pop change as a percentage (any decrease=0.0; 0–1% = 3; 1–3% = 5; 3–5% = 7; >5% = 10) | 4 | 3 | 5 | 3 | 2 | 1 | 1 | 2 |
| | Increase economic resilience | Recovery time | Estimated # months to recover following a Cat 3 storm (0–10 scale; 0–3 mos=10; 4–6 mos=5; 7–12 mos=3; >12 mos=1) | 3 | 5 | 6 | 5 | 5 | 2 | 4 | 2 |
| | | percent of Pop that is employed | Estimated unemployment rate (<4%=10; 5–7%=5; >7%=3) | 4 | 3 | 5 | 3 | 3 | 1 | 1 | 2 |
| | Improve institutional resilience | percent of Pop covered by flood insurance | percent housing units covered by flood policies (0-20%=3; 21–50%=5; 51–75= 7; >75%=10) | 2 | 3 | 3 | 2 | 1 | 1 | 1 | 1 |
| | Improve structural feature resilience | Average annual damages avoided | Estimated relative to current condition (Scale 0-10; 0–much lower; 5–about same; 10–much higher) | 3 | 5 | 6 | 5 | 5 | 1 | 3 | 2 |
| | | Density of commercial and industrial building infrastructure, including ports | Density of commercial infrastructure (higher density is better; structures/1000 residents) (<1000=3; 1001–1500=5; 1500–2000=7; >2000=10) | 3 | 2 | 3 | 2 | 1 | 1 | 1 | 1 |

| Objective Category | Objective | Metric | Performance Measure | Beaches | Dune Complexes | Islands | Marsh Platforms | Mollusk | Fans | Drumlins/ Moraines | SAV Beds |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | Increase nature-based infrastructure resilience | Storm protection | percent land area that is NNBF<br>(0–2%=2; 3–5%=4; 6–8%=6; >8%=8) | 2 | 4 | 5 | 4 | 3 | 1 | 2 | 1 |
| Vulnerability | Increase coastal protection | Susceptibility to Cat 3 or larger storms | Scaled 0–10 based on expert opinion with 10 being least susceptible | 2 | 3 | 4 | 5 | 7 | 7 | 7 | 7 |
| | Reduce coastal Pop vulnerability | Exposure index | Scaled 0–10 based on expert opinion with 10 being least vulnerable | 3 | 4 | 4 | 6 | 7 | 8 | 7 | 8 |
| Ecosystem Goods and Services | Improve erosion protection and control | Vegetation index | Estimate of vegetative quantity * quality, scaled 1–10 relative to current conditions (0–much worse; 5–same; 10–much better) | 7 | 7 | 6 | 6 | 5 | 5 | 5 | 5 |
| | Increase TES species protection | Presence/Absence | percent area with TES habitat, scaled 1–10 relative to current conditions (0–much worse; 5–same; 10–much better) | 7 | 7 | 6 | 6 | 5 | 5 | 5 | 5 |
| | Maximize recreation opportunities | Available open space publically available | Acres available for outdoor recreation<br>(0–10 scale where 10 is greatest number of acres) | 5 | 5 | 5 | 5 | 6 | 6 | 6 | 6 |
| | Maximize education opportunities | School field trips | Number of school field trips (no./yr)<br>(0–10 scale where 10 is greatest number of trips) | 4 | 5 | 5 | 5 | 6 | 6 | 6 | 6 |
| | Increase carbon sequestration of NNBF | Tons carbon stored | Carbon stored in plants and soil (kg/ha/yr)<br>(0–10 scale where 10 indicates the greatest carbon stored) | 5 | 5 | 5 | 5 | 7 | 7 | 7 | 7 |
| | Sustain commercial fisheries | Catch per year | Total dollar take by commercial fishermen per year | 3 | 3 | 3 | 3 | 6 | 6 | 6 | 6 |

Table 38 builds on Table 36 and Table 37, presenting alternatives focusing on a particular region, and represents one alternative that is a single structural feature (breakwater), one that is entirely nature-based (oyster or artificial reef), two that combine NNBF and structural features (breakwater + reef and seawall + living shoreline), as well as a No Action alternative. Cost and responses can be obtained for each alternative. In this manner single as well as multiple features can be scaled and integrated into the framework. The alternatives can be obtained via stakeholder input, alternative formulation, from existing lists of proposed NNBF projects, or other sources. The cells in a column below each alternative are referred to as consequences and measure the performance of each alternative relative to the stated objectives. The consequences can be populated with information derived from expert elicitation (Table 38) or quantified using existing data or models (Table 39), depending upon the evaluation tier (or more generally the availability of analytical tools to quantify consequences).

## Structured decision-making framework case study application

The framework as structured using the five steps described by Hammond et al. (1999) has been widely applied, especially to address complex problems related to conservation actions. Such well-documented examples can show how the framework can be applied for assessing and ranking NNBF alternatives consistent with agency policy and guidance. The example provided here synopsizes the structured decision-making process as applied to a project concerned with controlling non-native fish on the lower Colorado River (Runge et al. 2011). The USGS undertook this structured decision-making project to provide input to the Bureau of Reclamation (BoR) for preparing an environmental assessment (EA) for controlling non-native fish below Glen Canyon Dam. A process was developed that allowed diverse stakeholder groups, including tribes, to discuss, articulate, and document their respective values, to develop and evaluate a broad set of potential alternatives using the best available science, and to define individual preferences of each group on how to manage the inherent trade-offs in this complex environmental problem, goals consistent with NACCS objectives for developing the framework.

Table 38. Tier 1 framework matrix populated by information obtained from SME (Part II).

| Objective Category | Objective | Metric | Performance Measure | No Action Alternative | Structural Feature (Breakwater) | Oyster or Artificial Reef | Breakwater + Reef | Seawall + Living Shoreline |
|---|---|---|---|---|---|---|---|---|
| Resilience | Increase ecological resilience | Fish and wildlife habitat | Species diversity (extent to which diversity reflects historical values, using a scale from 0–10, with 10 being best) | 2 | 3 | 4 | 6 | 5 |
| | Improve social resilience | Storm-related mortalities over 10 yr | Number of mortalities averaged over 10 yr (0=10; 0–10=7; 11–50=4; 50–100=1; >100=0) | 1 | 4 | 4 | 7 | 7 |
| | | Historical districts protected | Number of properties (0–10=3; 11–50=5; 50–100=7; >100=10) | 3 | 3 | 5 | 7 | 7 |
| | | Pop change | Expected 10 yr avg. Pop change as a percentage (any decrease=0.0; 0–1% = 3; 1–3% = 5; 3–5% = 7; >5% = 10) | 5 | 5 | 5 | 7 | 7 |
| | Increase economic resilience | Recovery time | Estimated # months to recover following a Cat 3 storm (0–10 scale; 0–3 mos=10; 4–6 mos=5; 7–12 mos=3; >12 mos=1) | 1 | 5 | 3 | 5 | 5 |
| | | percent of Pop that is employed | Estimated unemployment rate (<4%=10; 5–7%=5; >7%=3) | 5 | 5 | 5 | 5 | 5 |
| | Improve institutional resilience | percent of Pop covered by flood insurance | percent housing units covered by flood policies (0–20%=3; 21–50%=5; 51–75= 7; >75%=10) | 3 | 5 | 5 | 7 | 10 |
| | Improve structural feature resilience | Average annual damages avoided | Estimated relative to current condition (Scale 0–10; 0–much lower; 5–about same; 10–much higher) | 3 | 3 | 5 | 5 | 7 |
| | | Density of commercial and industrial building infrastructure, including ports | Density of commercial infrastructure (higher density is better; structures/1000 residents) (<1000=3; 1001–1500=5; 1500–2000=7; >2000=10) | 3 | 3 | 5 | 7 | 10 |
| | Increase nature-based infrastructure resilience | Storm protection | percent land area that is NNBF (0–2%=2; 3–5%=4; 6–8%=6; >8%=8) | 2 | 2 | 4 | 6 | 8 |

| Objective Category | Objective | Metric | Performance Measure | No Action Alternative | Structural Feature (Breakwater) | Oyster or Artificial Reef | Breakwater + Reef | Seawall + Living Shoreline |
|---|---|---|---|---|---|---|---|---|
| Vulnerability | Increase coastal protection | Susceptibility to Cat 3 or larger storms | Scaled 0–10 based on expert opinion with 10 being least susceptible | 2 | 3 | 4 | 5 | 7 |
| | Reduce coastal Pop vulnerability | Exposure index | Scaled 0–10 based on expert opinion with 10 being least vulnerable | 3 | 4 | 5 | 7 | 8 |
| Ecosystem Goods And Services | Improve erosion protection and control | Vegetation index | Estimate of vegetative quantity * quality, scaled 1–10 relative to current conditions (0–much worse; 5–same; 10–much better) | 7 | 7 | 6 | 6 | 5 |
| | Increase TES species protection | Presence/Absence | percent area with T/E habitat, scaled 1–10 relative to current conditions<br>(0–much worse; 5–same; 10–much better) | 7 | 7 | 6 | 6 | 5 |
| | Maximize recreation opportunities | Available open space publically available | Acres available for outdoor recreation<br>(0–10 scale where 10 is greatest number of acres) | 5 | 5 | 5 | 5 | 6 |
| | Maximize education opportunities | School field trips | Number of school field trips (no./yr)<br>(0–10 scale where 10 is greatest number of trips) | 4 | 5 | 5 | 5 | 6 |
| | Increase carbon sequestration of NNBF infrastructure | Tons carbon stored | Carbon stored in plants and soil (kg/ha/yr)<br>(0–10 scale where 10 indicates the greatest carbon stored) | 5 | 5 | 5 | 5 | 7 |
| | Sustain commercial fisheries | Catch per year | Total dollar take by commercial fishermen per year compared to past 10 yr (0–10 scale; 0–much worse; 5–same; 10–much improved) | 3 | 3 | 3 | 3 | 6 |

Table 39. Tier 2 framework matrix informed by numerical models and/or data from existing similar projects in the region.

| Objective Category | Objective | Metric | Performance Measure | No Action Alternative | Structural Feature (Breakwater) | Oyster or Artificial Reef | Breakwater + Reef | Seawall + Living Shoreline |
|---|---|---|---|---|---|---|---|---|
| Resilience | Increase ecological resilience | Fish and wildlife habitat | Species diversity (Shannon Index) | 0.5 | 0.4 | 0.6 | 0.6 | 0.5 |
| | Improve social resilience | Mortalities prevented | Number of people | 0 | 30 | 5 | 40 | 40 |
| | | Historical districts protected | Number of properties | 0 | 40 | 0 | 60 | 55 |
| | | Pop | Pop change( %/yr) | -2 | 2.5 | 0 | 3 | 3.5 |
| | Increase economic resilience | Recovery time | # of Months post Cat 3 | 15 | 8 | 15 | 8 | 6 |
| | | percent of Pop that is employed | Unemployment rate | 7.5 | 7.5 | 7.5 | 7.5 | 7.5 |
| | Improve institutional resilience | percent of Pop covered by flood insurance | percent housing units covered by flood policies | 10 | 10 | 10 | 9 | 8 |
| | Improve structural feature resilience | Average annual damages avoided | $M/year | 0 | 10 | 0 | 12 | 30 |
| | | Density of commercial and industrial building Infrastructure, including ports | Density of commercial infrastructure (SFI/SFT) | 0.8 | 0.9 | 0.9 | 1 | 1.1 |
| | Increase nature-based infrastructure resilience | Storm protection | percent land area that is NNBF | 2 | 2 | 5 | 8 | 12 |
| Vulnerability | Increase coastal protection | percent emergent wetlands | Acres non-developed wetlands | 33,000 | 32,000 | 34,000 | 32,000 | 31,000 |
| | Reduce coastal Pop vulnerability | Exposure index | Composite exposure index includes Pop density and infrastructure, social and environmental components; scaled 0-10 with 10 being least vulnerable | 2 | 4 | 5 | 7 | 8 |

| Objective Category | Objective | Metric | Performance Measure | No Action Alternative | Structural Feature (Breakwater) | Oyster or Artificial Reef | Breakwater + Reef | Seawall + Living Shoreline |
|---|---|---|---|---|---|---|---|---|
| Ecosystem Goods and Services | Improve erosion protection and control | Quantitative vegetation index | Vegetation cover, vegetation height, and bathymetry (area weighted index on 0-1 scale, with 1 much better) | 0.4 | 0.5 | 0.6 | 0.7 | 0.8 |
| | Increase TES species protection | Presence/absence | Habitat suitability index (area weighted on a 0-1 scale) | 0.6 | 0.5 | 0.7 | 0.6 | 0.6 |
| | Maximize recreation opportunities | Availability of open space publically available | Composite recreation index based on available area, census data, and market size<br>(0-1 scale with 1 being much better) | 0.3 | 0.4 | 0.4 | 0.5 | 0.4 |
| | Maximize education opportunities | School field trips | Composite education index based on learning kiosks, accessibility and field visits<br>(0-10 scale with 10 being much better) | 3 | 3 | 4 | 4 | 6 |
| | Increase carbon sequestration of NNBF | Tons carbon stored | Carbon stored in plants and soil (kt/ha/yr) | 200 | 200 | 200 | 200 | 240 |
| | Sustain commercial fisheries | Catch per year | Total dollar take by commercial fishermen per year ($M) | 500 | 510 | 510 | 515 | 510 |

The project utilized two face-to-face workshops. The first workshop was used to develop a diverse set of objectives representing the range of stakeholder concerns and to develop a set of alternatives. The second workshop examined the trade-offs inherent in the problem, allowing stakeholders to express their individual judgments about how those trade-offs should best be managed in the selection of a preferred alternative. The set of objectives identified and defined reflected desired future conditions over 30 yrs (cultural and spiritual dimensions, ecological aspects including both species and ecosystem level components, recreational interests and uses, and operational and economic components). The use of trade-off analysis evaluated the alternatives against the objectives, documenting the values of stakeholders along the way.

The weights unique to each participating stakeholder group were used as input into the trade-off analysis to produce individual rankings of the alternatives (Table 40). All stakeholders identified either D1 or D3 as their preferred alternative, and neither alternative was ranked lower than number 3 by any stakeholder group.

The USGS used principle components analysis (PCA) to explore the sensitivity of the best-performing alternative to the weights on the objectives to help explain the difference in preferences among stakeholders (Figure 28). Alternative D1 was favored at the average objective weight and continued to be favored as more weight was given to sport fishery and cost objective, or the desire to reduce non-native fish below the Glen Canyon dam. As more weight is given to cultural objectives or humpback chub (HBC) objectives, alternative D3 is favored. Stronger weightings towards cultural objectives and power generation results in J1 rising as preferred. The result of the sensitivity analysis is that the top-ranking alternatives (D1 and D3) are fairly robust to variation in the stakeholder weights. Such plots of the scores for these components for each stakeholder group used by the USGS not only helps illustrate the diversity of views expressed through this process, but can be similarly applied to assessing and ranking NNBF alternatives.

Evaluating the effects of uncertainty on the highest ranking alternatives allowed the USGS project team to complete a value-of-information analysis, which led to an adaptive strategy that included three possible long-term management alternatives for controlling non-native fish species below Glen Canyon dam.

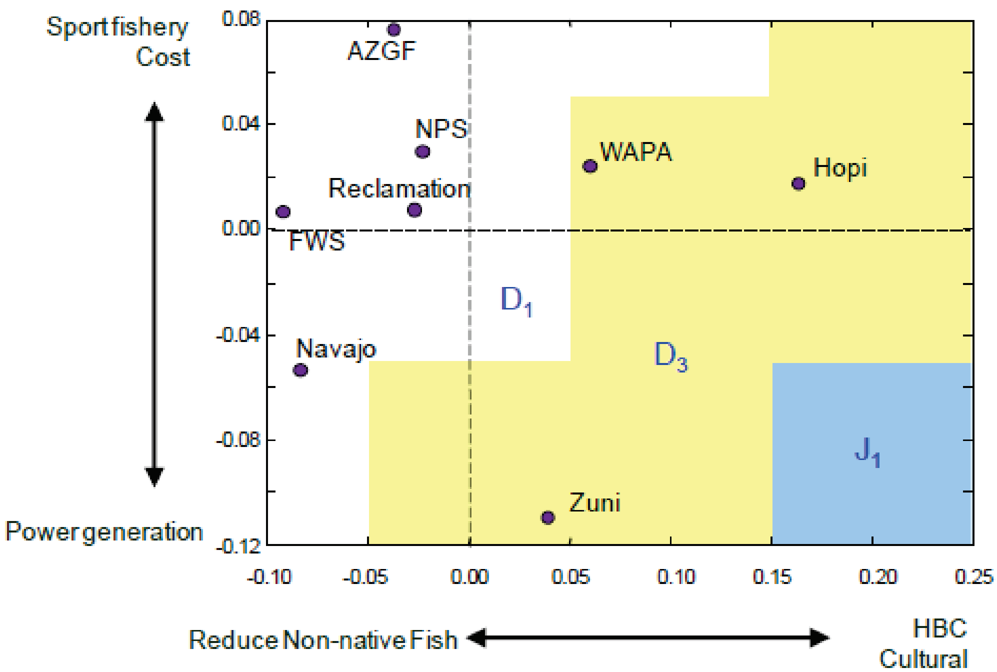
Table 40. Composite scores from trade-offs for each alternative, using weights of participating stakeholders. Green shading indicates the highest ranking alternative for each stakeholder group, representing the top two ranked alternatives (D1 and D3) (from Runge et al. 2011).

| Alternative | AZGF* | BoR* | USFWS* | Hopi | Navajo | NPS* | WAPA* | Zuni | Average |
|---|---|---|---|---|---|---|---|---|---|
| A | 0.598 | 0.527 | 0.497 | 0.563 | 0.498 | 0.647 | 0.432 | 0.462 | 0.501 |
| C2 | 0.505 | 0.418 | 0.418 | 0.450 | 0.428 | 0.474 | 0.308 | 0.314 | 0.402 |
| C3 | 0.427 | 0.380 | 0.373 | 0.419 | 0.397 | 0.443 | 0.280 | 0.267 | 0.361 |
| C4 | 0.478 | 0.440 | 0.428 | 0.545 | 0.458 | 0.512 | 0.353 | 0.370 | 0.437 |
| C5 | 0.444 | 0.404 | 0.397 | 0.527 | 0.433 | 0.483 | 0.326 | 0.366 | 0.411 |
| D1 | 0.672 | 0.589 | 0.649 | 0.571 | 0.648 | 0.629 | 0.557 | 0.504 | 0.606 |
| D2 | 0.584 | 0.538 | 0.596 | 0.525 | 0.610 | 0.598 | 0.519 | 0.457 | 0.554 |
| D3 | 0.610 | 0.578 | 0.623 | 0.618 | 0.645 | 0.651 | 0.565 | 0.558 | 0.603 |
| J1 | 0.522 | 0.496 | 0.567 | 0.586 | 0.553 | 0.503 | 0.501 | 0.519 | 0.539 |
| J1’ | 0.610 | 0.525 | 0.583 | 0.528 | 0.537 | 0.508 | 0.523 | 0.481 | 0.545 |
| J2 | 0.439 | 0.452 | 0.519 | 0.559 | 0.522 | 0.474 | 0.472 | 0.471 | 0.497 |
| J2’ | 0.524 | 0.479 | 0.532 | 0.497 | 0.503 | 0.473 | 0.491 | 0.433 | 0.500 |
| K | 0.365 | 0.387 | 0.426 | 0.459 | 0.436 | 0.472 | 0.293 | 0.346 | 0.390 |
| Rank | | | | | | | | | |
| 1 | D1 | D1 | D1 | D3 | D1 | D3 | D3 | D3 | D1 |
| 2 | J1' | D3 | D3 | J1 | D3 | A | D1 | J1 | D3 |
| 3 | D3 | D2 | D2 | D1 | D2 | D1 | J1' | D1 | D2 |
| 4 | A | A | J1' | A | J1 | D2 | D2 | J1' | J1' |
| 5 | D2 | J1' | J1 | J2 | J1' | C4 | J1 | J2 | J1 |

* Stakeholders: AZGF = Arizona Game and Fish Department; BoR = Bureau of Reclamation; USFWS = Fish and Wildlife Service; NPS = National Park Service; WAPA = Western Area Power Administration

The USGS project case study was essentially an example of a Tier 1 effort, where SME and value scales were used for several metrics where empirical and modeling data were largely absent. However, the underlying message is that this process is consistent with the evaluation framework and is applicable to the NACCS: The best available information should be used regardless of the assessment tier. The results of such assessments can assist decision makers by helping them structure a complex decision problem and inform the final decision in a transparent and understandable manner.

Figure 28. Graph of principle components analysis of the objective weights. The shaded regions of the graph show the alternatives (D1, D3, and J1) favored under the analysis (from Runge et al. 2011).




## Example objective addressed through the tiered framework

An demonstration is provided here building on information presented earlier in Table 38 and Table 39 to illustrate the capability of the framework for integrating information across tiers of evaluation. This example addresses the contributions of NNBF to coastal resilience. The metric used to inform the objective is storm protection. The storm protection metric needs to be quantified to be useful in decision making, so measures across the three tiers of evaluation need to be identified. Given the level of information available to quantify performance of NNBF in terms of storm protection can vary considerably over time (the measure identified to inform the objective may also vary) giving rise to the application of the framework in tiers that become increasingly quantitative and certain.

### Tier 1: Semi-quantitative

In this Tier 1 example, the measure for the storm protection metric is semi-quantitative and geared toward expert elicitation (Table 41).

Table 41. Consequence table for the Tier 1 evaluation using a hypothetical simple semiquantitative scale to inform the storm protection metric where the matrix was populated by information obtained from SME.

| Objective Information | Performance Metric | Measure | Consequences | | | | |
|---|---|---|---|---|---|---|---|
| | | | No Action Alternative | Structural Feature (Breakwater) | NNBF (Oyster Reef) | Structural Feature + NNBF (Breakwater + Oyster Reef) | Structural Feature + NNBF (Seawall + Living Shoreline) |
| **Objective Category** Resilience<br><br>**Objective** Contribution of NNBF to coastal resilience | Storm protection | Scale from −10 to 10, where −10 = significantly increases damages, −5 = increases damages, 0 = no change, 5 = decreases damages, 10 = significantly decreases damages | 0 | 5 | 1 | 7 | 9 |

The measure is the impact of NNBF on damages incurred from a Category 3 storm based on expert opinion, reflecting the lack of data or predictive models available at this early stage of the project. The measure for the metric presented in the third column of Table 36 through Table 41 is based on a simple scale from –10 to 10, where –10 is significantly increased damages relative to current conditions, –5 = increases damages, 0 = no change, 5 = decreases damages, and 10 = significantly decreases damages. These are applied to each of the alternatives presented as categories of NNBF (consistent with alternatives presented in Table 38 and Table 39). Information from SME is then used to populate the matrix. In this example, the No Action alternative is given a score of 0 (no change)[1],the Structural Features (breakwater) alternative scored 5 (decreased damages), the NNBF (Oyster Reef) alternative was scored 1 (slight decrease in damages), and Structural Features + NNBF (Breakwater + Reef) and Structural Features + NNBF (Seawall + Living Shoreline) alternatives were scored 7 and 9, respectively, because they decrease damages. Note that the combination of Breakwater (5) and Oyster Reef (1) features are non-additive result of 7, indicating a degree of synergy.

[1] A No Action Plan by USACE planning guidance definitions (USACE 2000) is automatically set at zero, and all other plans are compared to the No Action through relative comparisons. Any issues surrounding impacts or loss of functionality due to sea level rise must first be addressed in the No Action Plan, and all subsequent planning alternatives must be relativized to this future condition.

### Tier 2: Existing data

As the availability of information improves, the performance of these alternatives can be revisited by modifying the performance measure and using this new information to populate the consequence tables (i.e., a Tier 2 analysis). In this example, the availability of project data to inform the resilience objective and the storm protection metric provided an opportunity to reduce the uncertainty surrounding the quantification of the storm protection metric. These data were compiled in terms of observed storm damages relative to acres of NNBF per mile of coastline, so this becomes the logical measure for performance in the framework. These data were applied to each of the same alternatives presented as categories of NNBF in Tier 1 (Table 41).

Populating the consequences matrix using the data from NNBF acres per mile of coastline requires converting the acreages to a storm damage performance. In this hypothetical example, assume the data show that < 10 acres/mile NNBF have no effect on storm damages and the alternative is scored as a 0; 10–20 acres/mile NNBF (the current condition) slightly reduced damages and the alternative is scored as a 3; 20–40 acres/mile NNBF showed moderate reduction in damages and the alternative is scored 5; 40–80 acres/mile showed significant damage reduction and the objective is scored as a 7. Alternatives with densities > 80 acres/mile are scored as a 10. Because the data do not directly account for structural features, both seawalls and breakwaters were assigned an equivalent value of 10 acres of NNBF/mile of structure. The new data resulted in the values presented in Table 42. These values are assumed more accurate than for the Tier 1 assessment since they are based, in part, on measured performance data.

While the availability of data in the region improved the accuracy and reduced the uncertainty surrounding the quantification of this metric, the quality of NNBF was not accounted for in this Tier 2 example and it still relied on judgment to score structural features.

Table 42. Consequence table for the Tier 2 evaluation using a hypothetical quantitative measure to inform the storm protection metric from regional data.

| Objective Information | Performance Metric | Measure | Consequences | | | | |
|---|---|---|---|---|---|---|---|
| | | | No Action Alternative | Structural Feature (Breakwater) | NNBF (Oyster Reef) | Structural Feature + NNBF (breakwater + Oyster Reef) | Structural Feature + NNBF (Seawall + Living Shoreline) |
| **Objective Category** Resilience **Objective** Contribution of NNBF to coastal resilience | Storm protection | Acres of NNBF per mile of coastline | 3 | 5 | 5 | 7 | 7 |

### Tier 3: Quantitative data and models

It became possible to progress to Tier 3 in this example because numerical models that could capture the performance of NNBF and other infrastructure contributing to coastal resilience. While necessarily maintaining the same resilience objective and storm protection metric, the Tier 3 measure was quantified by applying a numerical model to assess the potential of NNBF features for reducing storm surge and waves for hurricanes with varying intensity. The Wamsley et al. (2009b) model was used because it quantifies the degree to which NNBF creates frictional resistance and affects storm surge and wave energy. This results in lower surge and wave height for a given storm with consequent reduction in storm damages.

The results of the model indicated that restoration of marsh resulted in decreases in both surge and wave magnitudes at the NNBF. Conversely, model results indicated that degradation of marsh resulted in increases in both surge and wave magnitudes at the NNBF. In general, the model output indicated that wave change patterns were consistent with water level changes. The waves may be controlled by increased frictional resistance in the shallower water, nonlocal depth-limited breaking (e.g., at the edge of the marsh) or be depth limited at the marsh.

Results indicated that coastal marsh and other NNBF have the potential to reduce surge and wave magnitudes. Alternatives incorporating NNBF having the ability to reduce water level and wave height scored greater than other alternatives considered. Alternatives lacking infrastructure providing frictional resistance provided the least benefit. The alternative with the greatest amount of submerged and emergent vegetation providing the most frictional resistance as exemplified by the Structural Features + NNBF (Seawall + Living Shoreline) outperformed the other alternatives under consideration for this metric (Table 43).

Table 43. Consequence table for the Tier 3 evaluation using a numerical model to assess storm surge and wave height under several alternatives including NNBF. Results of the modeled water level and wave height for a standard storm are presented along with a value for average annual damages avoided based on a suite of storms.

| | | | Consequences | | | | |
|---|---|---|---|---|---|---|---|
| **Objective Information** | **Performance Metric** | **Measure** | No Action Alternative | Structural Feature (Breakwater) | NNBF (Oyster Reef) | Structural Feature + NNBF (Breakwater + Oyster Reef) | Structural Feature + NNBF (Seawall + Living Shoreline) |
| **Objective Category**<br>Resilience<br><br>**Objective**<br>Contribution of NNBF to coastal resilience | Storm protection | Peak water level (m), maximum wave height (m), (Average Annual Damages Avoided $M)* | 2.1,0.5 ($0) | 2.1,0.3 ($1) | 1.7,0.3 ($2) | 1.7,0.2 ($2.2) | 1.4,0.2 ($2.3) |

*Values presented characterize distributions with an accompanying range of uncertainty.

The Tier 3 analysis provides valuable information representing the state of the science with regards to trends and relative performance. Nevertheless, some uncertainty remains with regards to the application of the model, so the results should not be taken as an absolute quantitative assessment of surge and wave reduction. Additional examples of quantitative engineering and modeling tools that can be used to quantify performance metrics in a Tier 3 analysis are provided in the following paragraphs.

NNBF such as barrier islands, beaches, dunes, and wetlands provide important services in the form of erosion control and reduced flooding by reducing wave and storm surge energy. The degree to which the range of NNBF contribute to reducing damages caused by storm surge and waves depends on a number of factors including the characteristics of the storm, the geomorphic context, the spatial configuration of the features, and associated infrastructure. For example, the wave and storm surge attenuation provided by wetlands has been shown to be strongly dependent on storm characteristics (e.g., forward speed and track) and the surrounding coastal landscape (Wamsley et al. 2010). Numerical models now exist that can be applied to quantify, with uncertainty, the interaction of storms with natural features. Wamsley et al. (2009b) presents a numerical model and its application to assess the potential of both barrier islands and wetlands for reducing storm surge and waves for hurricanes of varying intensity. Realistic coastal storm modeling such as this requires the integration of several complex and sophisticated numerical models. The Coastal Storm Modeling System (CSTORM-MS) (Massey et al. 2011) developed by ERDC is an example of a state of the art system developed for this purpose. CSTORM-MS includes the following models:

- a tropical planetary boundary layer model, MORPHOS-PBL (Thompson and Cardone 1996), to generate the cyclone wind and pressure fields, an ocean hydrodynamic model
- an ocean hydrodynamic model, ADvanced CIRCulation Model (ADCIRC) (Westerink et al. 2008; Bunya et al. 2010), to generate the surge and currents fields
- a regional and a nearshore ocean wave models, WAve Prediction Model (WAM) (Komen et al. 1994) and Steady-State Spectral Wave Model (STWAVE) (Smith et al. 2001), to generate the wave fields.

In addition to these models that simulate the oceans response to a storm in the form of waves and surge, a bed morphology model, such as C2SHORE (Wamsley et al. 2013), is needed to simulate landscape changes due to the surge and wave effects. This morphology model is presently being integrated into the CSTORM-MS. The models are tightly coupled through the CSTORM-MS work flow and, where appropriate, apply the Earth System Modeling Framework (ESMF).

The C2SHORE model is an extension of the one-dimensional (1D) sediment transport model CSHORE (Kobayashi et al. 2009; Johnson et al. 2012). CSHORE predicts beach profile evolution over the nearshore region, including erosion of the beach berm and dunes. CSHORE is an example of a phase-averaged model based on the nonlinear shallow water wave (NLSW) equations. The primary advantage of NLSW surf zone dynamics models is that they incorporate many of the important physical processes, run very quickly, and are very stable. The CSHORE model provides ample flexibility for calculating wave runup for a wide range of beach settings, beach/structure situations, and wave conditions. CSHORE also can be used to predict cross-shore beach morphology change, dune erosion, the steepening of beaches during storms, and the resulting influence on runup which is sensitive to beach slope. In addition, CSHORE can be used to predict wave overtopping of dunes.

Beach and dune evolution can also be quantified through application of Beach-FX (Gravens et al. 2007), a comprehensive analytical framework for evaluating the physical performance and economic benefits and costs of beach nourishment. Beach-FX relies on databases that describe the environmental forcing, infrastructure inventory, and estimates of coastal morphology response. The morphology response database is calculated with models such as CSHORE, or SBEACH (Larson and Kraus 1989), and GENESIS (Hanson and Kraus 1989). Beach-FX is implemented as an event-based Monte Carlo life-cycle simulation tool for sandy shore and dune evolution prediction.

## Framework attributes

Perhaps the most significant attribute of the proposed framework is its flexibility. That flexibility extends to evaluating (within the same framework) the performance of variously crafted alternatives using just expert opinion as well as the results of detailed model and engineering analyses. This gives rise to the tiered implementation concept discussed previously, which reasonably reflects likely implementation for the NACCS. Early application of the framework in the NACCS will likely reflect the Tier 1 analysis and will be the most qualitative and most uncertain. Index scales will likely be required to generate relative units of measure for most objectives.

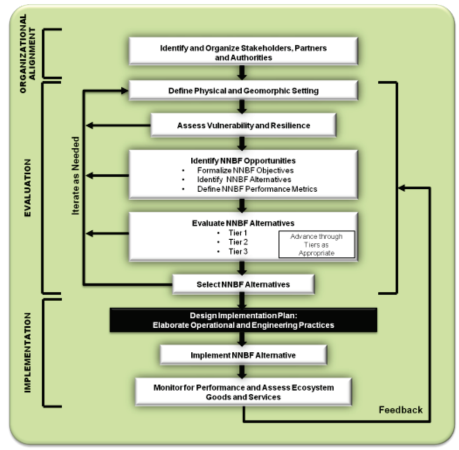
A key capability of the framework in these early tiers is the ability to focus the assessment of alternatives (Gregory and Keeney 2002). The matrix can be used to screen and rank NNBF alternatives via statistical summaries of scores, as needed. Separate matrices can be prepared for each of the climate change scenarios defined in the NACCS (2018, 2068, 2100, and 2118), providing insight into the robustness of any alternative. Information used in an early tier, such as stakeholder input (Table 36), can be carried forward to subsequent tiers (if employed) or may be replaced with input from data or quantitative analyses (Table 37).

In Tier 1 (Table 38), it is anticipated that the performance measures will take the form of semi-quantitative scales reflecting stakeholder or SME opinion. For Tier 2 type analyses (Table 39), the performance measures can presumably be more readily quantified using numerical models, engineering analysis, or performance data from existing projects in the region. This would potentially result in different performance metrics with different units. Stakeholder preferences (or other sources) can be used to weight objectives, if desired, for any tier.

It should be emphasized that although three tiers of analysis for decision making are described in this report, there is no requirement to implement them sequentially or to employ all three. The three tiers simply reflect the reality that available information will vary over time (and perhaps geographically) and an assessment strategy must be adaptable. Which tier is used to initiate the framework and the number of tiers used in decision making ultimately depends on the time, resources, data, and other information available to inform the decision-making process.

The framework was developed in a manner that supports rigorous engineering analysis and sound science while offering the flexibility to rely entirely or partly on expert opinion should results be required prior to the availability of more rigorous assessment methods. Models, tools and techniques to assess coastal systems, such as Beach- FX, ADCIRC, CSHORE and CSTORM-MS as described in Section 5.8.3, can be applied to quantify performance and populate the consequences table at any point (i.e., tier) after which the model/tool becomes available. The framework can be used collaboratively with multiple stakeholders or agencies, lends itself to the elicitation of preferences, and can be developed in an understandable manner that can be shared broadly so that the decision-making process is transparent.

# 6 Regional Sediment Management (RSM) Strategy for Beneficial Use of Dredged Materials (BUDM) on Construction of NNBF




## Introduction

Implementing NNBF as a part of an integrated network of actions that combines such features with structural and nonstructural measures will involve the use of sediment as a construction resource. Barrier islands, beaches, dunes, wetlands, and other forms of NNBF are constructed, either naturally or through human engineering, through the use of sediment. Processes influencing both the supply and delivery of sediment affect the feasibility and sustainability of NNBF.

In the context of RSM[1], navigation dredging projects represent a source of sediment that can be applied beneficially to the construction of NNBF. Many factors, (e.g., regulations, policies, engineering considerations, costs, stakeholder perspectives) will shape opportunities for beneficial use of dredged sediment. In this chapter, relevant approaches and tools are described that can be applied in developing regional strategies for applying dredged sediment for NNBF.

A life-cycle RSM strategy for placing dredged sediments beneficially in the Long Island Sound (LIS) region was developed as a demonstration to support the objective of contributing to the wider scope of implementing NNBF. The LIS demonstration methods outlined in this chapter can be applied to other regions in the Sandy study area. The intent was to produce a generalized approach for comprehensively developing dredging and placement options in a technically appropriate and consistent manner in context of stakeholder views. This approach would be applicable to any study area with sufficient data. Relevant information and input was

[1] http://rsm.usace.army.mil/

gathered from NACCS study team members and SME in the field of dredging and sediment placement. The team reviewed this information and conceptualized an approach for developing RSM strategies for BUDM. Exercising this approach, a demonstration-of-method was developed for the LIS. With the executable approach developed and demonstrated in this limited-scope vignette, next steps will be scoped for holding an actual stakeholder engagement using the approach and reflecting on its outcome as a bench test to refine it for comprehensive application over the entire study area. This chapter is specifically designed to optimize BUDM in RSM strategies. Separate analysis must be performed to determine if dredged material provides sufficient sediment to achieve NNBF goals. If additional sediment is required, BUDM can be combined with other practices (e.g., diversions, mining, reservoir flushing) to achieve overall requirements.

## Preparatory tasks

A multi-disciplinary development team was established to support the development of NNBF through RSM. Several preparatory tasks were undertaken support to development of this strategy. Preparatory tasks included review of established practices, definition of key terms, and literature review. Following these tasks, SME dredging managers were engaged during a field site visit by the development team. Finally, the RSM strategy development approach was conceptualized and designed.

### Present BUDM practice

BUDM is a long-established practice within the study region. However, the practice is presently employed by a small group of SME with limited coordination between projects. Little guidance exists for those who are not familiar with the practice. Although application of BUDM is ongoing, it is unlikely that the placement option will be reviewed after BUDM placement site selection until the site reaches capacity or dredged material is no longer needed at the site. BUDM practice is often not optimized, but rather it is opportunistic. Therefore, more beneficial or cost-effective BUDM practices for these dredged sediments may not have been considered. A screening methodology for strategic placement opportunities (SMSP) can improve present dredged material management practices even for projects with existing BUDM plans by identifying options that are lower cost or produce greater benefit.

### Definition of terms

In order to ensure clarity in communication as methods were developed, a number of key terms required definition. The main focus of this study was to develop a dredged sediment SMSP in the context of a natural systems approach. For the purpose of this study, the term strategic placement was defined as locating dredged sediments in such a way that either (1) they enable natural systems, processes, and resources to create, restore, or improve environmental habitat or (2) they provide protection and stability for natural and built infrastructure. The natural systems approach indicates that the natural setting and environmental forcings will be harnessed as much as feasible to mobilize sediments and achieve design goals. Some examples of the natural systems approach include using nearshore berms that provide a wave break or feeder beach, creating and enhancing wetlands, and positioning of dredged mounds to reduce channel shoaling.

Both strategic placement and the natural systems approach are key components within RSM and Engineering With Nature (EWN) practices. RSM is a systems approach for efficient and effective management of sediments in the coastal, estuarine, riverine, and watershed environments. The main concepts of RSM include managing local projects and sediments within a regional context, considering sediments as a regional resource, supporting sustainable solutions that address multiple disciplines, communication, and collaboration. These disciplines include navigation and dredging, flood and storm damage reduction, ecosystem restoration, and other issues. Within USACE, EWN is defined as the intentional alignment of natural and engineering processes to efficiently and sustainably deliver economic, environmental, and social benefits through collaborative processes. EWN practices often include using engineering and science to produce operational efficiencies; using natural processes to maximize benefit; broadening and extending the benefits provided by projects; and using science-based collaborative processes.

### Literature review

A review of relevant literature was performed prior to developing the site-specific SMSP. This was not a scientific literature review in the traditional sense, but rather a review geared towards the defined project requirements. The review included Permanent International Association of Navigation Congresses (PIANC) reports related to strategic placement of dredged sediments. The first report, International Navigation Association (INA)

(2000), describes general requirements for planning, executing, interpreting, and reporting a site investigation for a proposed dredging project. INA (2000) describes required information related to dredged material and environmental conditions, and identifies survey techniques that should be conducted during the preliminary site investigation. PIANC (2009a) presents a review of several categories of management practices applied to dredging projects that protect the environment. This report also describes the process of a dredging project from beginning to end and explains where management practices should be applied (PIANC 2009a). PIANC (2009b) introduces the reader to various potential uses of dredged material that are classified into engineering uses and environmental enhancement. This report also describes important factors for the success of using dredged material and provides recommendations for designing BUDM practices. The last report provides guidance on successful wetland restoration (International Navigation Association 2003). The report includes sections describing project strategic plan, evaluation and site characterization, design, implementation, and monitoring. Although the PIANC reports covered a wide variety of topics, they provide background of the present state of dredged material uses and restoration. The reports also provide the framework to begin the SMSP.

Team expertise is not isolated to LIS. Team members were concurrently working on other studies involving beneficial use and living shorelines. Within the USACE, there is nominal guidance for concepts where dredged material is used to support living shorelines in lieu of hard protective structures. Although some districts have been implementing these concepts, there are few reports that describe the work. The Baltimore District of USACE (CENAB) (Blama 2012) describes how BUDM is applied to mitigate chronic shoreline erosion and establish wetlands at Barren Island in Chesapeake Bay. Team members and NAB staff discussed the Barren Island project and the general concepts of beneficial use and living shorelines. Team members and NAB staff also discussed other ongoing BUDM projects, including Battery Island, the Anacostia River, the Blackwater Wildlife Refuge, and the Isle of Wight. An upcoming Dredging Operations and Environmental Research Program (DOER) tech note will discuss aspects of these BUDM projects including design and stakeholder engagement.

Additionally, the NACCS encompasses a large number of efforts, and the ERDC has led several of these tasks. Several members of this specific study team have also been engaged in other tasks including NNBF and the

Conceptual Regional Sediment Budget (CRSB). The NNBF coastal classification and feature descriptions (Chapter 2) were used in the first step of the ecosystem restoration side of the SMSP. In addition, another study team focused on a CRSB from Maine to Virginia. This team reviewed and collected existing sediment budgets for the region and incorporated them into the Sediment Budget Analysis System (SBAS) and a visual web-portal. Another requirement was to compile existing Dredging Information System (DIS)[1] data from 1990 to 2013 and calculate shoaling rates for dredged channels which were added to the SBAS and web-portal. These rates were added to the SBAS and the web-portal. The DIS data analysis was helpful for this team, because the information was then applied to the LIS scoping example of D2M2 (the Dredged Material Management Decisions model) in conjunction with other local data. These tasks are discussed briefly here because it is important to understand how the various tasks overlap and become integrated. Familiarity with these other tasks was crucial in integrating tasks and leveraging the work already completed to produce a higher quality final comprehensive product.

The SMSP requires a searchable library to integrate the techniques on the ecosystem restoration and the navigation-operations sides. Instead of developing a new technique library, one member of the team identified ongoing work on a technique library (Thomas et al., forthcoming). Given the short timeframe for this study, using the existing technique library allowed the team to focus efforts on the SMSP development and the LIS D2M2 example. While presently insufficient for application, the existing techniques library is acceptable for demonstration as described in this text.

### Description of the Dredged Material Management Decisions Model (D2M2)

D2M2 is an existing dredging optimization model that was applied here to demonstrate a strategy for optimizing RSM for BUDM and construction of NNBF. In addition to D2M2, the efforts described herein draw on a body of recent analyses performed by and for USACE in support of the LIS Dredged Materials Management Plan (DMMP).

D2M2 is a powerful planning tool for allocating dredged materials among multiple sites with differing attributes and constraints[2]. D2M2 brings transparency, flexibility, and mathematical rigor to the planning process

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[1] Available at: https://dis.usace.army.mil

[2] http://el.erdc.usace.army.mil/dots/

through mathematical optimization. The model is designed to analyze millions of combinations of dredging and placement sites to allocate specific quantities of dredged material along various possible routes, over time. D2M2 optimizes management value with consideration of the data for and trade-offs among multiple objectives. In this process, D2M2 accounts for spatial site distribution, dredging equipment, transportation paths, storage needs, beneficial uses, environmental concerns, and other factors. The management value being maximized is user defined and can consist of any mix of economic, environmental, storm protection, habitat, social, or other objectives envisioned by project management. D2M2 was developed for the purpose of (1) supporting dredging plan optimization for multiple objectives, (2) engaging in dredging scenario and sensitivity analysis, and (3) developing DMMP and enabling ongoing, near-real-time operational support

D2M2 was originally developed in 1984 by USACE Hydrologic Engineering Center to support the USACE Philadelphia District (CENAP) in their dredged-material management of the Delaware River. It was jointly funded by the CENAP, the Water Resources Support Center, and the Waterways Experiment Station (now ERDC). The original software was updated for the San Francisco District in 1994 and 2008 to be adapted for a Windows environment. Recently, the D2M2 model has been completely rewritten and expanded by ERDC to be a user-friendly Java-based tool with an array of powerful new dredging planning features and functions.

Developing an RSM optimization case study using D2M2 requires a large body of technical data potentially across multiple management objectives. To accommodate these data requirements for the current demonstration, a benefit is derived from a variety of detailed dredging-related reports and studies commissioned by USACE to support the LIS DMMP[1]. Development of the LIS DMMP was requested by the governors of Connecticut and New York after the Environmental Protection Agency (EPA) designated two open water dredged material disposal sites in LIS. The overall goal of the LIS DMMP is to develop a comprehensive dredged material management plan that recommends practicable, implementable solutions to manage dredged material in an economically sound and environmentally acceptable manner in the LIS region. Data developed for the LIS DMMP include in-depth analyses of all potential dredged material

[1] http://www.nae.usace.army.mil/Missions/ProjectsTopics/LongIslandSoundDMMP.aspx

management alternatives including open water placement, beneficial use, upland placement, and innovative treatment technologies that can be used by dredging proponents in developing alternatives analyses for dredging in the LIS vicinity. While not necessarily representative of the entire North Atlantic region, these data provide a suitable basis to demonstrate integrated, multiobjective optimization for RSM.

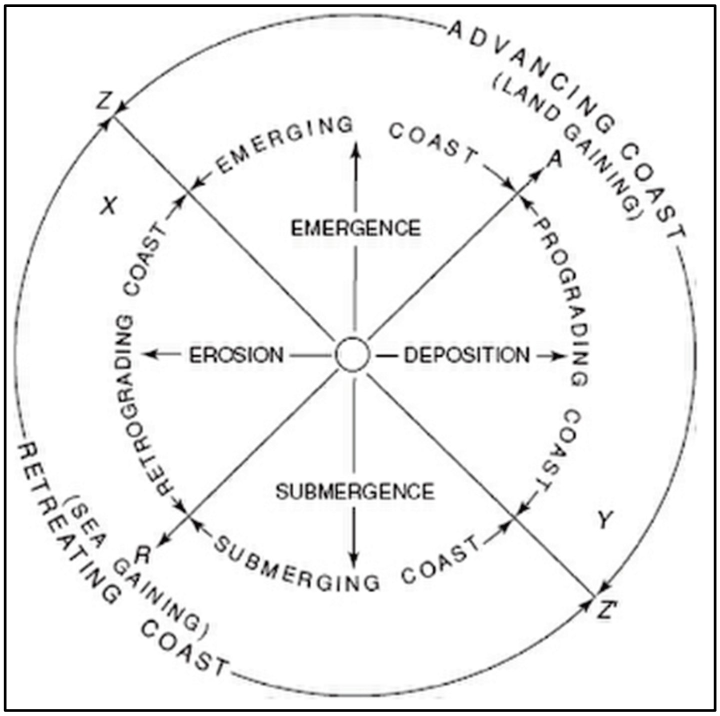
In parallel with the technical investigations for the LIS DMMP, USACE New England District (NAE) established a stakeholder working group comprised of representatives from Federal, State, regional, and local agencies, and various other organizations that have an interest in the management of dredged material in the LIS region. Over the past several years, the working group has iterated through a process to establish a list of potential evaluation criteria reflective of stakeholder interests and concerns. This was done in a series of working sessions to identify and coalesce criteria, subcriteria, and metrics, and through individual interviews to identify organizational trade-offs and preferences. Again, while not necessarily entirely representative of the entire North Atlantic region, these criteria align well with those present elsewhere in this report. The D2M2 demonstration draws from criteria for which data are available in the LIS DMMP technical analysis that reflect both the priorities identified by the LIS DMMP working group and the criteria identified in this report as relevant for RSM.

## Screening methodology for SMSP

SMSP is described by a decision flow diagram (Figure 29) that integrates the goals of dredging with ecosystem restoration. Sediment is an integral component of natural coastal systems, and the integrated approach moves towards acknowledging the role of sediment as a resource rather than a waste product requiring disposal.

Coastlines are dynamic features, evolving in response to time-varying coastal processes such as waves and currents. Static coastlines are fairly uncommon, typically occurring in areas with highly resistant geology such as rocky cliffs. Coastlines can be categorized as advancing (emerging or prograding) or retreating (eroding or submerging) (Figure 29). Identifying where each coastal reach of interest lies on the continuum of advancing or retreating coasts can help prioritize coasts. Identification of vulnerable coast permits focus of actions to help mitigate negative change.

Figure 29. Continuum of advancing and retreating coasts (Bird 2008).

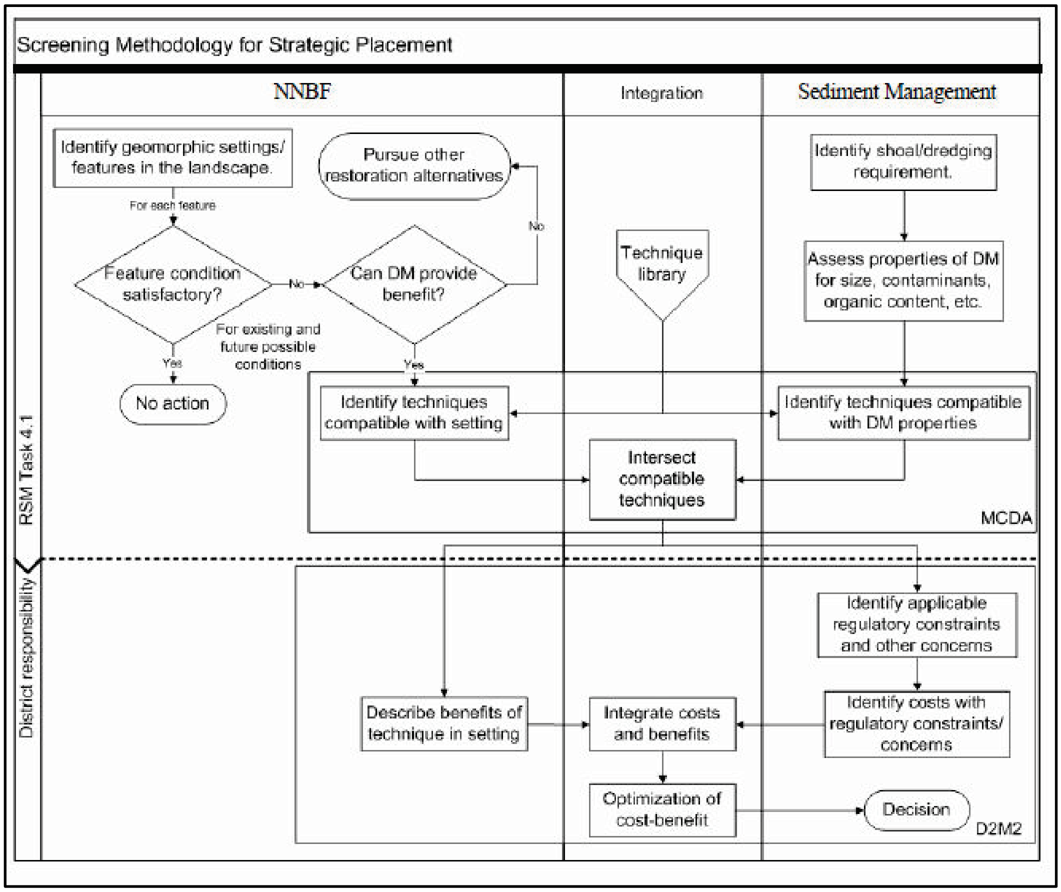



The SMSP uses a geomorphic framework developed as part of the NACCS NNBF efforts to identify appropriate geomorphic settings along the coast that could potentially serve—or benefit from use—as dredged material placement areas. The SMSP is designed to be flexible; in its simplest implementation, it serves as a basic decision tree to identify potential dredged material placement areas. More complex implementations of the SMSP rely on a variety of data resources such as geospatial data, the SEDiment MANagment Technologies (SEDMAN) database (Thomas et al. forthcoming), and D2M2.

### NNBF opportunity identification

The SMSP flowchart is shown in Figure 30. The flowchart is divided into two main parts: (1) The top portion is designed to determine the suite of appropriate geomorphic dredged material placement areas given the physical constraints of the dredged material properties within the area of interest. (2) The bottom portion is designed to filter the suite of possible placement areas given regulatory and user-specified value constraints (e.g., environmental windows, costs).

Figure 30. SMSP flowchart.




*Identification of coastal geomorphic landscape features*

The ecosystem restoration section of the SMSP is designed to identify potential placement sites within the area of interest that are sediment deficient. The geomorphic framework used is described in the NNBF to classify the features within the area of interest. Features that are compatible with dredged sediment placements include beaches, dune complexes, tidal flats, wetlands (sometimes referred to as marsh platforms), and islands (excluding predominantly rocky islands found along the glacially derived coasts in the north of the study area). The SMSP is designed to identify potential placement areas for dredged material within the littoral zone and coastal areas influenced by marine processes; upland beneficial uses and open water disposal are not considered until all other options are eliminated. Features with small areas of interest (i.e., beaches and wetlands) can be easily identified manually from maps or aerial photos. For larger areas, geospatial datasets can be utilized to more easily identify features. Various datasets can be used, but many are state or site specific; the NOAA Environmental Sensitivity Index (ESI[1]) utilizes a standard methodology to identify shoreline geomorphology along all of the Nation's coasts. The ESI uses 15 standard shoreline types to categorize the landward and seaward shore based on the vulnerability to oiling. The geomorphic framework described in the NACCS study identifies only five feature types that are potential placement sites within the SMSP. Table 44 generalizes the ESI shore types to the NACCS geomorphic features.

Table 44. Cross-walk between ESI and NACCS.

| ESI Type | Description | NACCS Geomorphic Feature |
|---|---|---|
| 1 | Exposed rocky shores | Scarp |
| 2 | Exposed rocky platform | Platform, bank, etc. |
| 3 | Fine-grained sand beaches | Beach* |
| 4 | Coarse-grained sand beaches | Beach* |
| 5 | Mixed sand and gravel beaches | Beach* |
| 6a | Gravel beaches | Beach* |
| 6b | Riprap structures | Artificial |
| 7 | Exposed tidal flats | Tidal flat* |
| 8a | Sheltered rocky shores | Scarp |
| 8b | Sheltered manmade structures | Artificial |
| 9 | Sheltered tidal flats | Tidal flat* |
| 10a | Salt to brackish marshes | Marsh platform* |
| 10b | Freshwater marshes | Marsh platform* |
| 10c | Swamps | Marsh platform* |
| 10d | Mangroves | n/a |

* Indicates features that may benefit from sediment additions.

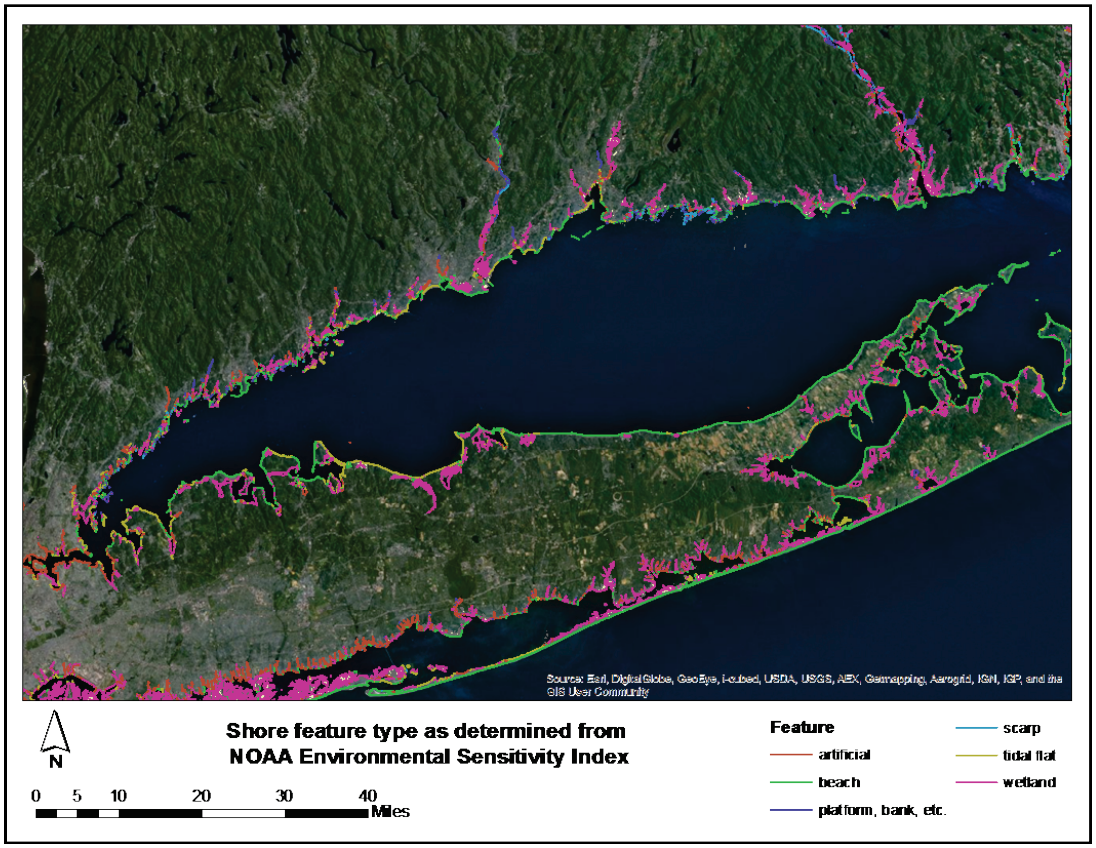
The ESI is not exhaustive; since it is a shore classification system, features such as dune complexes are not considered as they are above the legal definition of the shore as the mean high water line. The presence of dune complex features can be inferred from the USGS dune height dataset within the USGS National Assessment of Coastal Change Hazards: Hurricanes and Extreme Storms (2013b); if dune crest elevation is greater than 2 m, a dune complex is assumed to be present (Note the same dataset can be used to assess dune condition as part of the feature condition assessment step in the SMSP).

[1] http://response.restoration.noaa.gov/esi

Islands, while included in the NACCS report as separate features, are actually composed of multiple smaller scale features (USACE 2015). Islands placement sites are most common within the Chesapeake Bay (e.g., Poplar Island, Barren Island, Battery Island), and these placement sites are often ideal for large dredged material volumes. Along the majority of coastal sites in the NACCS study area, entire islands are not as likely to be identified as placement sites; rather, individual features of islands are identified as potential placement sites.

Figure 31 shows a map of NACCS feature types as determined from the ESI for LIS. While some islands exist in the study reach, analysis of the aerial photos indicated the islands were primarily rocky and not conducive to sediment placement so were removed from the initial analysis.

Figure 31. NACCS feature types for Long Island Sound as determined by ESI.




*Condition assessment of features*

Once the set of features to be considered within the area of interest is identified, the condition of those features is assessed. There are a number of ways to assess feature condition. Physical assessment methods primarily concentrate on the lateral and vertical changes in geometry of the geomorphic features over time. Other physical features are important to the character and function of coastal geomorphic features, but physical geometry is the simplest to rapidly assess from geospatial data sources. Ecological assessment methods concentrate on the vegetative condition or site-specific suitability for a species of concern. Few geospatial approaches currently exist to assess ecological function on a large scale, so such techniques are best suited for later stages of analysis when choosing among limited numbers of placement locations. Large-scale datasets containing ecologically relevant data such as the ESI or the National Wetlands Inventory (NWI) (USFWS 2013) can be used to examine some aspects of the ecological function of a feature such as the use of a shore by critical species or the dominant wetland vegetation community and anthropogenic modifications, but they are incomplete measures of ecological condition. Ecological condition is tied to physical condition, so measures of physical condition should be considered first before applying site-specific measures of ecological function.

To assess physical condition, lateral erosion or progradation rates and vertical accretion or subsidence rates should be considered. Many coastal features occupy narrow ranges of elevation, so vertical changes can be just as critical as aerial extent when assessing condition. Rapid, high-magnitude changes (on the order of 10 yr) should be prioritized since the risk of feature loss or conversion is the highest for rapidly changing features. Erosion rates (lateral changes) can be computed manually at a scale of interest for smaller study areas. Coarser estimates of shoreline change can be utilized if the area of interest is large. Tools for manually calculating erosion rates are available from USGS (2013c). USGS also compiled an analysis of shoreline change along the New England and mid-Atlantic coasts in 2010, calculating erosion rates for all outer-coast sites (not in lagoons, sounds, estuaries). Older erosion rate estimates that included some inner-coast sites are also included in the USGS Coastal Vulnerability Index (Hammar-Klose and Thieler 2001).

Erosion rate estimates from the USGS Coastal Vulnerability Index (Hammar-Klose and Thieler 2001) were used to identify a subset of feature types that could potentially benefit from sediment additions (wetlands, tidal flats, and beaches) within the LIS that were subject to high (>2 m/yr) erosion rates. The NWI (USFWS 2013) which includes both wetland and tidal flat feature types is also added to the map. The NWI includes wetland-type modifiers that can indicate potential degradation in ecological condition such as ditching.

Accretion/subsidence rates can be calculated from historical and current elevation datasets. The Joint Airborne Lidar Bathymetry Technical Center of Expertise (JALBTCX) provides imagery and elevation data typically on a 5 to 7 yr schedule through the USACE National Coastal Mapping Program (NCMP)[1] using the Compact Hydrographic Airborne Rapid Total Survey System (CHARTS) bathymetric and topographic Lidar system. Historical and current elevation datasets can be compared to detect both lateral and vertical changes in geomorphic features. Since natural coastal features that are formed by marine processes occupy narrow elevation ranges, physical properties of identified features can also be used to assess condition. For example, marsh platforms typically exist between mean tide level and mean high water. If a marsh platform feature subsides to an elevation lower than mean tide level, it will become unable to support wetland vegetation and will begin to convert to tidal flat. Such a feature could benefit from dredged material additions either through thin-layer placement or by strategic, shallow, open water placement, allowing hydrodynamic forces to deliver the sediment to the marsh in a manner more representative of natural processes.

*Assessment and benefit of dredged sediment applicability:*

Assessing benefits to geomorphic features from the application of dredged material is straight forward if the degraded condition is due to lateral erosion or subsidence. If the features are formed from sediment and are rapidly eroding or subsiding, dredged material will likely provide benefit. However, measures of ecological condition are not as clear. If ecological degradation is due to causes other than physical degradation, such as the presence of invasive species (e.g., Phragmites ssp), then other restoration alternatives should be pursued. Benefits from the application of dredged material depend on the placement method, the engineering design, and the full analysis of the environmental conditions that caused the degraded condition. The SMSP assumes the conditions that initially caused the degradation are mitigated for in the placement design. Specific information on designing placement areas is not considered explicitly within the SMSP.

[1] http://shoals.sam.usace.army.mil/Mapping.aspx.

Once a subset of degraded features is identified in the area of interest, the technique library can be queried to indicate which dredging and placement techniques are compatible with the placement location. The techniques library is described in more detail below.

*Identify dredging/placement techniques compatible with dredged sediment*

The next steps in the SMSP involve integrating the operations requirements with the ecosystem restoration requirements. This is the final step required to develop a set of placement areas that can be analyzed within the D2M2 framework. The goal of the integration is to assure dredged material is placed in appropriate areas based on physical properties such as grain size and organic content using appropriate techniques. For instance, while dredged material with a high proportion of fines is appropriate for placement on wetland features, it may not be appropriate for placement in more energetic environments such as beaches. The placement technique is also crucial for the environment. For instance, many wetlands have converted to shallow open water, and dredged material can be used as a resource to restore the wetland habitat. If the current bottom elevation is too far below the critical elevation for vegetation growth (approximately mean tide level), strategic placement techniques that rely on passive sediment transport such as shallow open water placement will not be effective as sediment accretion rates at subtidal elevations tend to be relatively low (Gunnell et al. 2013). The integration of the ecosystem restoration and operations/navigation sections of the SMSP could be subjected to further analysis if the area of interest contains many possible placement locations, and/or the dredged material properties are highly variable.

Once a final subset of placement areas is determined using the SMSP, input datasets for D2M2 can be developed for each option. The SMSP is designed to consider regulatory constraints within the D2M2 framework. If regulatory constraints such as environmental windows or avoidance of submerged aquatic vegetation are considered earlier in the process, potential placement sites may be screened out of the D2M2 analysis completely without examining the potential environmental merits of a placement site. D2M2 can optimize among the potential dredged material placement sites based on any set of objectives proposed for exploration by managers and decision makers (e.g., costs, environmental benefits, stakeholder concerns). Since the D2M2 optimization criteria are site specific and depend on management objectives and trade-offs, the implementation of D2M2 is best performed in coordination with USACE District staff having local expertise and knowledge of specific sites, costs, sediment volumes, etc. The LIS example is provided for demonstration, but the final implementation of D2M2 will differ based on the constraints and values of the USACE District and its stakeholders.

### Navigation channel operations and maintenance sediment source estimation

BUDM is incorporated into the overall SMSP flowchart (Figure 30). Specifically, the far right side of the SMSP flowchart relates to the sediment management in general and BUDM in particular. This section of the SMSP only differs from the traditional operations workflow in that it assumes that dredged sediment is a resource rather than a waste product. Figure 30 illustrates this segment of the overall SMSP flowchart. Each of the three boxes in Figure 30 identifies a specific, required evaluation for BUDM. These evaluations are described in the following.

*Estimate shoaling and dredging requirements:*

The first step in the Sediment Management section of the SMSP flow chart (Figure 30) is to identify shoaling and dredging requirements. This task was first conducted through the CRSB, and additional steps were taken to get the data in the proper format for this study. For the CRSB, it was necessary to determine the shoaling rate of USACE channels in the North Atlantic Division (CENAD). Short of contacting personnel at each District and requesting dredging data, the most comprehensive source of data is the DIS. DIS includes both contracted and in-house dredging projects between 1990 and July 2013. All projects along with the Channel Framework ID, name, dredged volume, date, and other relevant information were included in a spreadsheet. The CRSB team wrote a matrix laboratory (MATLAB) code to calculate the annual shoaling rate estimates for each project that experienced at least three dredging events between 1990 and 2013. Ninety projects in NAD were dredged at least three times, but many of the projects, especially in NAE were dredged only once or twice. Each of the projects that were dredged at least three times was incorporated in the CRSB for SBAS. The DIS spreadsheet gave only the names of projects and the Channel Framework ID, so the CRSB team had to determine the geographic location of each dredging project. Once the location of each dredging project was identified, the CRSB team created an SBAS cell and added the annual shoaling rate for dredging. Although the SBAS is an add-in for ArcGIS 10, the cells and fluxes are represented by shape files outside of the SBAS. Even if a user does not have SBAS installed on a machine, that person can view the shape files representing the cells and fluxes and determine where each dredging project was located. More information about the process for the shoaling calculations and the development of the CRSB can be found in the following.

All of the projects that were dredged at least three times are included in tables in CRSB analysis. For the purpose of this task, all of NAD was considered first. Projects near LIS were considered for use in the D2M2 example. Table 45 lists all of the projects in Rhode Island, Connecticut, and New York with more than three dredging events during the period of interest. The third column lists the total dredged volume in cubic yards from 1990 to 2013 while column 4 lists the total days between the beginning of the first events and the last day of the last event. Column 5 lists the calculated annual shoaling rate in cubic yards (CY).

Table 45. Projects in RI, CT, and NY with multiple dredging events (1990–2013)

| Job Name | District Code | Total CY | Total Days | Annual Rate (CY) |
|---|---|---|---|---|
| Block Island Harbor of Refuge, RI | NAE | 258,165 | 7,470 | 12,614 |
| Clinton Harbor, CT | NAE | 70,790 | 4,611 | 5,604 |
| New Haven Harbor, CT | NAE | 633,486 | 3,332 | 69,394 |
| Patchogue, CT | NAE | 23,230 | 726 | 11,679 |
| Buttermilk Channel, NY | NAN | 342,326 | 7,906 | 15,804 |
| East River, NY | NAN | 469,650 | 5,173 | 33,138 |
| East Rockaway Inlet, NY | NAN | 2,857,420 | 7,778 | 134,091 |
| Fire Island to Jones Inlet, NY | NAN | 8,020,733 | 4,901 | 597,341 |
| Flushing Bay and Creek, NY | NAN | 126,759 | 4,002 | 11,561 |
| Glen Cove Creek, NY | NAN | 74,220 | 3,646 | 7,430 |
| Gowanus Bay, NY | NAN | 465,205 | 8,377 | 20,270 |
| Gravesend Bay Anchorage, NY | NAN | 148,539 | 2,751 | 19,708 |
| Hudson River Channel, NY | NAN | 1,126,413 | 1,952 | 210,625 |
| Jamaica Bay, NY | NAN | 2,350,393 | 7,913 | 108,416 |
| Jones Inlet, NY | NAN | 1,644,673 | 6,539 | 91,804 |
| Lake Montauk Harbor, NY | NAN | 125,585 | 7,650 | 5,992 |
| Long Island Intracoastal, NY | NAN | 290,875 | 7,072 | 15,013 |
| NJ/NY Channels - Kill Van Kull | NAN | 6,379,412 | 5,144 | 452,660 |
| NYandNJ Channel-Arthur Kill | NAN | 4,124,940 | 5,668 | 265,632 |
| Port Jersey Channel | NAN | 4,079,500 | 3,437 | 433,232 |
| Shinnecock Inlet, NY | NAN | 1,804,199 | 7,110 | 92,621 |

It is important to note that DIS identified many additional projects that experienced dredging once or twice in the 23 yr period. It is prudent to believe that they will be dredged at some future date. While sites with little dredging are not included in this D2M2 demonstration, they can be incorporated into District D2M2 applications.

As a part of the LIS DMMP, dredging needs for all Federal and non-Federal projects were projected for 2008 to 2037 (Battelle 2009). These values are also used in the D2M2 example. Since the DIS data only included historical data from 1990 to 2013, the team thought future dredging needs could give additional information around LIS. The projections were developed in 2008, but the DIS data now includes 2008 to 2013. Therefore, it was possible to compare the projected volumes to the actual dredged volumes. Only a few of the projects were expected to be dredged during the first 5 yr block (Battelle 2009). It was determined that most of the actual volumes dredged were similar to the projected volumes. However, there were a few projects that were actually dredged that did not anticipate dredging while others were projected to be dredged, but dredging did not occur. For example, Bridgeport Harbor was expected to have more than 3 million CY removed between 2008 and 2012, but nothing was dredged during that time period. Several newspaper articles discussed an overwhelmingly negative public opinion toward dredging, so it is likely that opinion delayed dredging. Battelle (2009) only considers the need for dredging, but does not include any constraints that can cause dredging to be delayed or canceled such as the lack of funding, permitting issues, or negative public opinion. Since the D2M2 task considers future dredging and placement options, it makes sense to use the projected volumes from the Battelle report (2009). DIS data were used in locations that were not analyzed in the Battelle report (2009).

The CRSB team wanted to compile a list of placement sites, but there is no database similar to DIS that includes this information. The CRSB team attempted to contact each District in NAD to get a list of placement sites, but calls and e-mails went largely unanswered due to the immense workload in the Districts after Sandy. Existing placement sites would have been helpful for both this task and the CRSB study. For this task, the existing placement site would be the best place to start when working with the SMSP and the D2M2 LIS example.

*Assess properties of dredged sediments*

The next step in the Sediment Management section of the flow chart (Figure 30) is to assess the properties for dredged material. This includes the grain size, volume, shape, existence of contaminants, and the organic content of the material. All of these properties will limit where the material can be placed. For example, the average grain size will determine whether the dredged material is better suited for a nourishment project or a wetland restoration. Although the average grain size is important, the grain size distribution must also be considered. There are often restrictions on the placement of material that consists of a certain percentage of fine sediment. Additionally, the volume of material will affect where it can be placed. The options for strategic placement will change when dredging a couple thousand cubic yards versus over a million cubic yards. Finally, sediment with higher levels of contamination will have far fewer strategic placement options than cleaner material.

*Identify dredging/placement techniques compatible with dredged sediments*

The last step in the Sediment Management section of the flow chart (Figure 30) is to identify dredging and placement techniques compatible with the dredged sediments. This directly relates to the ecosystem restoration side and the integration into the technique library. Once all of the dredging requirements and constraints on the dredged material are compiled, the list of possible techniques will be refined. The list of techniques comes from the technique library which is discussed in the following. Techniques that are compatible with the ecosystem restoration side will be incorporated into the library. Once these are combined, a final list of techniques will be produced.

### An inventory of options for matching sediment sources with BUDM opportunities

Many different technologies and tactics are available to manage sediments. As previously discussed, a technique library will include the available options and make it possible for the evaluation system (Figure 30) to automatically recommend appropriate technologies. A technique library was previously developed to help screen sediment management tactics and technologies based on site conditions by the Navigation Systems and Dredging, Operations, and Environmental Research Programs (Thomas et al., forthcoming).[1] A total of 78 techniques is already included in the library. Although the list is extensive, it is not exhaustive. The system is designed to permit addition of new tactics and technologies with minimal effort.

The existing screening tool allows users to select parameters that best represent the site conditions at potential projects. The tool then ranks available tactics and technologies based on the selected parameters to recommend which should be further investigated. Links to the relevant references are provided on the website along with a short description of each tactic or technology to help users gather the background information needed for detailed design of sediment management projects.

In the SMSP, the existing library will be called by the evaluation tool to select techniques to place sediment. The evaluation tool will supply input to the screening tool describing the physical conditions, environmental restoration considerations, and properties of the dredged material. Then the screening tool will rank available techniques based on multiple parameters input to select techniques that satisfy both the ecosystem restoration and dredging requirements. Recommendations will provide input for D2M2.

A series of figures from the existing website is included to demonstrate the screening tool and technique library. Figure 32(A) shows the home screen of the technique library screening tool. Fields on the left represent categories of parameters that can be specified to identify options for managing sediment; available techniques that satisfy selected parameters are listed on the left. Figure 32 (B) illustrates selection of some parameters, reducing the number of suitable techniques. Selecting a technique activates a pop-up window that includes some basic information and links to detailed design documentation and other reports (Figure 33).

[1] The existing tool is located at http://SedMan.usace.army.mil/.

Figure 32. A) Home screen of the technique library screening tool; B) Techniques Library Screening tool with parameters selected.

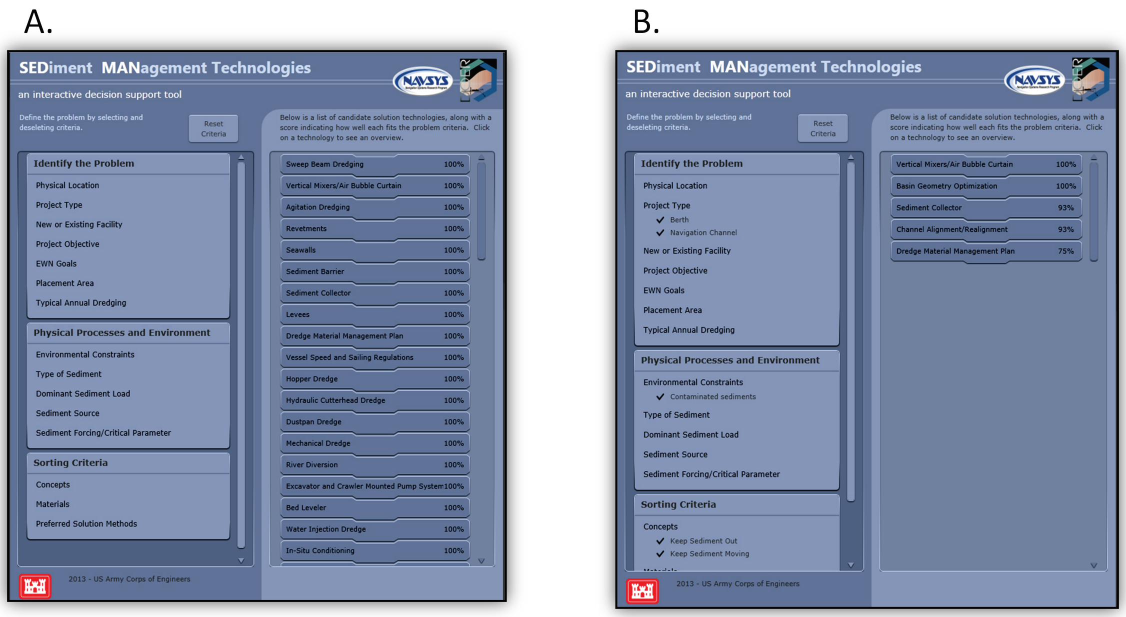



Figure 33. Example of technique-specific information included within the tool.

## Stakeholder involvement and development and selection of dredged sediments strategic placement designs

### Identification of interested and affected parties

RSM projects are often performed in complicated political environments where stakeholders are sensitive to different decision paths and actively engaged in championing for or against specific project alternatives. Inviting the participation of relevant stakeholder groups at the forefront of the decision process can avoid later conflict but is most effective if all parties feel that their views are being accurately and meaningfully incorporated in the process and if all groups feel they have a fair say in informing the final recommendations. In addition to this variety of public, nongovernmental, local, State, and Federal stakeholders, many projects attempt to achieve multiple (and sometimes conflicting) objectives through choices among different design and operational alternatives. These factors add complexity but if navigated successfully can lead to better-accepted and more technically sound solutions.

Transparent and quantitative decision-analytic tools can help streamline the decision-making process by rigorously and transparently incorporating divergent stakeholder views. To be most successful, the identification of stakeholders to participate in a working group should include both proponents and opponents of any particular issue and should especially seek to include organizations that have been vocal for past involvement in the region. Stakeholder organizations can be identified from past involvement, newspaper and internet searches, public solicitations, and through discussions with other stakeholders, etc. It is beneficial for a working group to include a balance of perspectives that reflect the major interests in the region and the diversity of views held by the public.

### A decision framework for structuring stakeholder engagement

A transparent evaluation framework can help in addressing these types of complex problems by structuring management-stakeholder engagement and technical expertise to inform respective components of the solution. This evaluation framework breaks the larger decision down into more tractable components. After the purpose of the project has been identified, a working group of decision makers and stakeholders might discuss and select a set of criteria that are relevant for decision making (e.g., costs, habitat restoration, environmental impacts, storm protection benefits). In parallel, technical experts, informed by management and the working group, can strive to identify alternative technical solutions to the problem. Each of these potential solutions is likely to impact or benefit many of the identified criteria. This provides a structure that technical experts can use to focus their scientific studies, as they work to analyze each alternative in terms of all relevant criteria.

With this data in hand, the working group will fully understand the scope of the problem and potential solutions and can concretely discuss preferences, trade-offs, and the relative importance of the various criteria involved in the decision. Either in a group setting or through individual interviews, facilitators can support working group members in identifying trade-offs between the importance of different criteria. If this is done individually, it gives a rich set of preference data that can be assessed to identify areas of relative agreement and disagreement. Decision support staff can then integrate the technical analyses with trade-off preference. The outcome of this integration can provide a set of relative total scores for all alternatives. These scores represent the net utility or total benefit of each potential design or operational plan, with the highest-scoring plan representing the most-preferred alternative.

There are several benefits of a structured evaluation approach in addition to providing a total score and rank for each alternative. The data-driven nature of the approach facilitates sensitivity and scenario analyses, where one can ask what if questions and assess the potential impact of uncertainty, changes in alternative performance, or differences in preferences in terms of decision outcome. The approach is also flexible and transparent, so interested parties can access and understand all assumptions leading to the final prioritization. This is especially important for continued understanding of the recommended plan over the coming decades, where re-evaluations can be made based on updated information without needing to reconvene all participants. For example, an analysis can be easily extended to consider new alternatives as they are developed. Because organizational values are relatively stable, the weightings can continue to be applied as data in the region develop over time. Last, this approach can be fair to all involved. If each member of the project delivery team or if some other organizations are allowed to influence the site prioritization through individual interviews, these discussions can take place either with or without discussion with other participants. Overall, these benefits are anticipated to improve the utility of an RSM plan or

DMMP and its public and political acceptance with the stakeholders involved. Ultimately, this is one of many ways that agencies organize and synthesize technical information and trade-off preferences for long-term and ongoing project planning and implementation. Like other methods, it must be performed to fit the goals of management and be consistent with the policies and authorities of the organization.

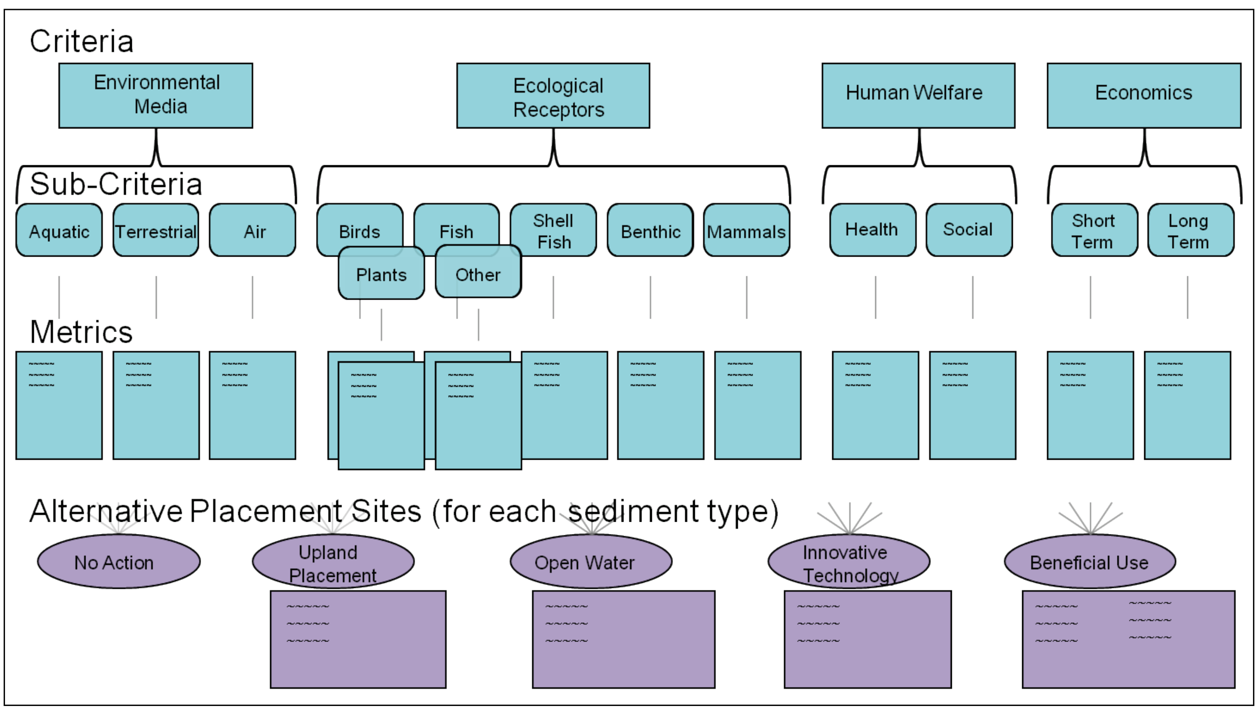
### An example framework for stakeholder engagement in the LIS DMMP

The use of this type of structured evaluation framework to organize stakeholder engagement in long-term regional planning has recently been demonstrated by USACE and ERDC to support the ongoing development of the LIS DMMP. The overall goal of the DMMP is to develop a comprehensive dredged material management plan for the USACE that recommends practicable, implementable solutions to manage dredged material in an economically sound and environmentally acceptable manner. The DMMP process calls for Federal agencies to seek public input regarding development of the management plan. This structured public input, along with the other analyses and studies, will be incorporated by the USACE project delivery team (the responsible party for the DMMP) as an important component of its planning recommendations. In total, these analyses and recommendations will provide a framework for dredging proponents to analyze dredged material processing, use, and placement-site alternatives in the LIS region for years to come.

This public involvement has been solicited through a multiobjective framework that is anticipated to improve the ultimate public acceptability of the DMMP and its recommendations. A working group of representatives from several dozen stakeholder organizations was compiled by CENAE to give input into sediment placement sites for each dredging center in the region. The working group consists of representatives from Federal, State, regional, and local agencies and various NGO interested in the management of dredged material in the LIS region and will be the primary mechanism for synthesizing stakeholder input and feedback to the project delivery team and broader planning community. Through the working group's involvement in the objective identification process, the DMMP team is seeking a way to identify management alternatives that protect the environment based on the best scientific data and analysis and meet society's need for safe and economically viable navigation for water-based commerce, transportation, national security, recreation, and other public purposes.

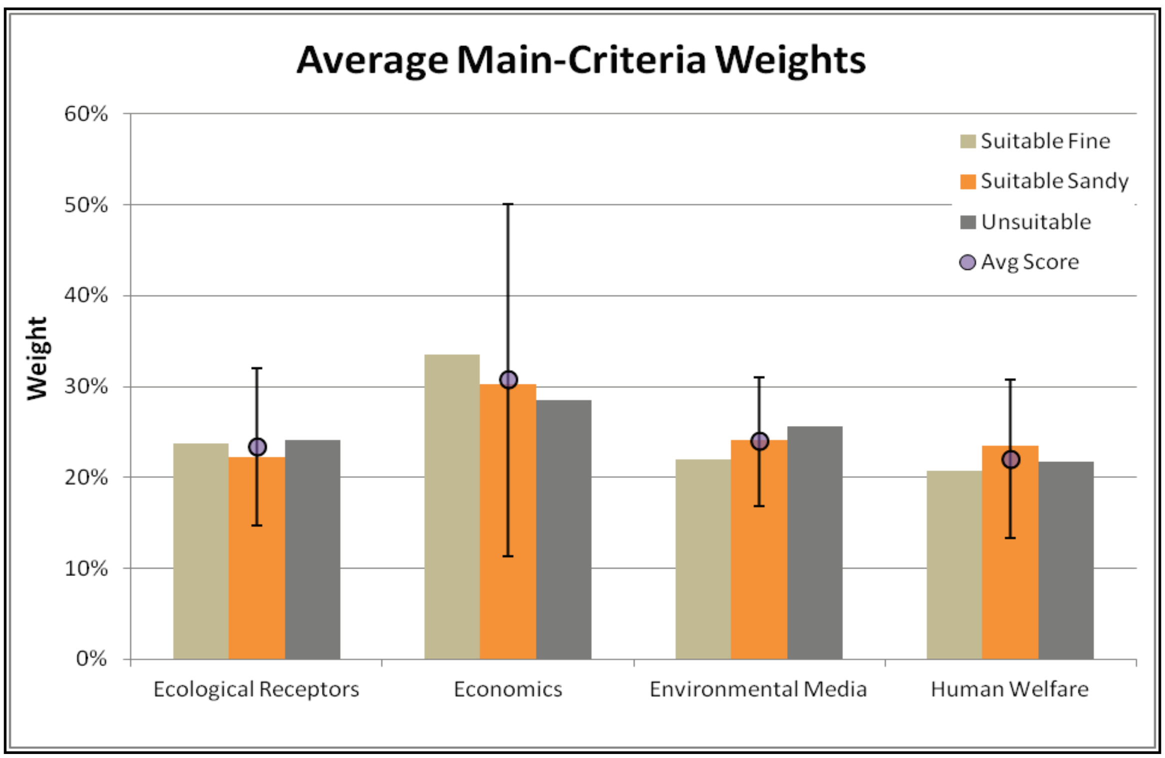
During a series of working group meetings, the stakeholders were tasked with collaboratively building a decision model. The resulting model included specified criteria, sub criteria, and metrics relevant to stakeholder interests in the LIS region (Figure 34). The group also suggested additions to the proposed list of alternative types. Individual interviews were then conducted to elicit judgments regarding the importance of the identified criteria. Through interviews and surveys, each representative of a stakeholder organization was able to contribute a personal view of the relative importance of criteria including environmental impacts, species habitats, health risks, social benefits, economic costs, etc. in the context of dredged materials placement. The elicitation process was conducted to inform USACE decision making in a way that fairly and transparently integrated divergent stakeholder views and allowed all participants to voice their preferences and concerns without a single stakeholder dominating the discussion.

Figure 34. A structured evaluation framework collectively developed by stakeholder representatives involved in the Long Island Sound Dredged Materials Management Plan Working Group. Through group discussion and individual interviews, this approach fairly, transparently, and quantitatively incorporates stakeholder preferences and concerns to inform the decision process.




While many stakeholders tended to identify criteria aligned with their mission space as having relative importance to their organization, they generally also recognized the importance of the other criteria outside of their primary interests. On average, results show strong relative balance among a diverse stakeholder group. The consensus view identifies a slight preference for the Economics criteria, with the Environmental Media, Ecological Receptors, and Human Welfare criteria all scoring at approximately equal levels of diminished preference (Figure 35). This seems to reflect a consensus belief that no criterion is singularly important and that coupled social-environmental systems are complex and interdependent, with balance across many criteria needed to ensure for the well-being of the LIS region as a whole. With the LIS DMMP working group, at least, the initial results were well received and prompted good discussion, with many participants voicing appreciation for their involvement in the process and the learning and exchange that took place along the way.

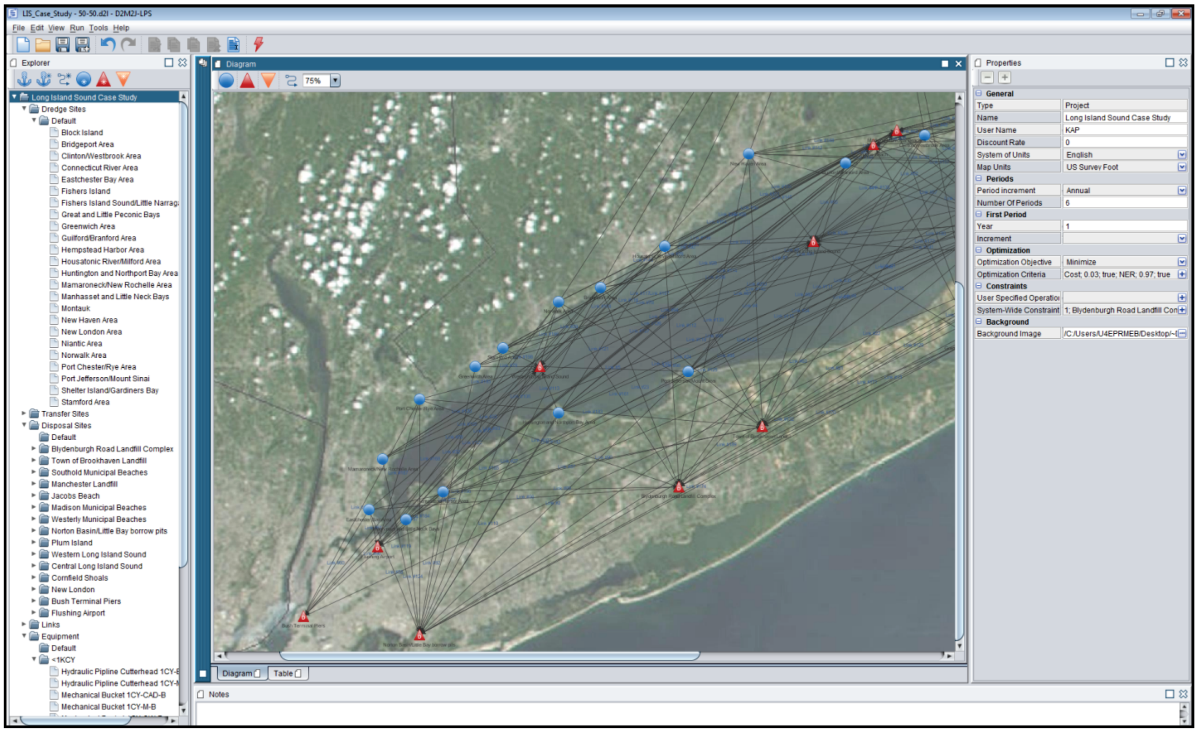
Figure 35. Results of the Long Island Sound DMMP working-group interviews. Relative preferences among criteria were elicited in the context of three different material types. Group averages are shown in the colored bars, individual responses are shown via the diamond, square, and circular dots. (Note: results for the four main categories are shown here, but preferences were also elicited for sub-criteria within each of these categories).



### Optimization of dredged sediment management with respect to multiple objectives

The results of stakeholder engagement to identify and weight criteria and technical studies commissioned to assess alternative plans with respect to those criteria provide actionable input for operational planning. Beyond simply ranking and scoring discrete alternatives, computational optimization solvers can be used by management to draw from these preference and technical data to evaluate a continuous range of alternatives, for example assessing thousands or millions of possible dredged material placement routes and volumes with respect to multiple criteria to identify a plan that maximizes net benefit, as defined to meet project goals and objectives. With regional sediment management often complicated by multiple stakeholders with opposing interests, public concern for environmental quality, high complexity in number of site variables, and limited annual budgets, optimization techniques can build on data developed in transparent evaluation framework to add consideration of operational constraints, regulatory issues, equipment-specific cost curves, and other factors not typically included in the prior scoring results. Here, multiobjective optimization allows the user to define goals, constraints, and relationships among the variables that drive the process, automatically inferring additional constraints and relationships from the spatial environment. Optimization algorithms can calculate the most beneficial combinations and quantities of sediments dredged, transported, stored, and placed of at each site in each year. In solvers like the USACE Dredged Material Management Decisions (D2M2) model (Figure 36), the optimization objective function can be flexible so that the software can seek to maximize the decision maker or stakeholder community's total value from sediment management (e.g., to minimize cost while maximizing environmental benefit). After D2M2 (in its role as a long-term planning tool) identifies a collection of preferable solutions that maximize sediment management value, these solutions can be refined by district staff supported by more detailed physical, operational, engineering, planning, and costing models.

Figure 36. Screenshot of the D2M2 model built using data prepared for the LIS DMMP.



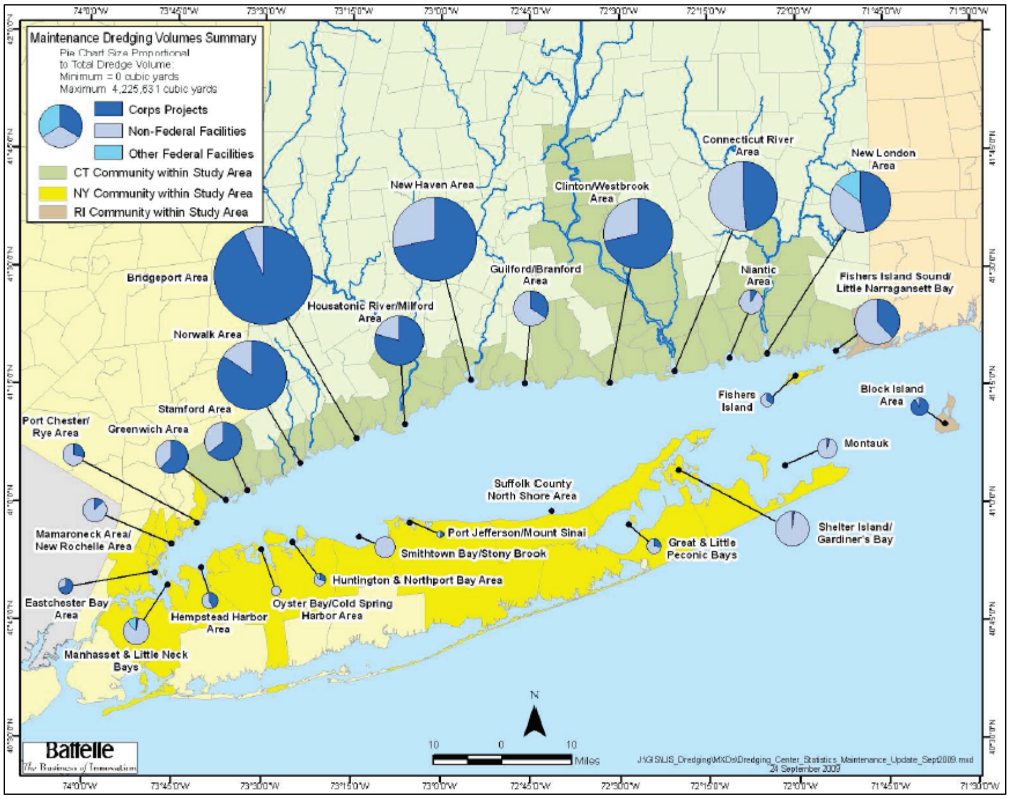

## Long Island Sound (LIS) Dredged Materials Management Plan (DMMP) D2M2 Demonstration

This vignette draws from technical reports prepared in support of the LIS DMMP to develop a demonstration-of-method cast study using the D2M2 dredging optimization planning tool. The D2M2 model considers 24 regional dredging sites and 15 placement sites (Figure 36) in the LIS region to determine an optimal long-term sediment management strategy based on consideration of cost, effect, and mixed objectives. These sites are linked in GIS to create a network of routes, to which dredging equipment cost curves could be applied.

### LIS input data development

The 24 LIS regional dredging centers are discussed in USACE (2009a). Data for each dredging center were derived from historical records and interviews to project dredging needs over a 30 yr span from 2008 to 2037 (Figure 37). The volumes of dredged material considered in the model reflect dredging needs for only the USACE navigation projects. The optimization is run for 5 yr time intervals over the 30 yr planning horizon.

Figure 37. Map of the LIS region identifying regional dredging centers and projected dredging needs of a 30 yr time horizon.




Of the 157 potential upland and beneficial use sites identified in the LIS DMMP Placement Site Inventory Report expressing a need for dredged material in the coming decades, 15 sites are selected for inclusion in this demonstration. Of the 15 placement sites included in the model, 6 are Upland sites, four are Beach Nourishment sites, three are Open Water sites, one is a Confined Aquatic Disposal (CAD) Cell site, and one is a Marsh Creation site. Data for the Open Water and CAD Cell placement sites were obtained from the USEPA (2011), and data for the Upland and Beneficial use (Beach Nourishment and Marsh Creation) placement sites were obtained from USACE (2009b)

The four Open Water and CAD Cell placement sites are estimated to be able to accommodate average annual dredged material disposal volumes as stated in the progress report. The annual volumes, in addition to time constraints identified for short-term, open water placement sites, were used to create the average 5 yr dredged material disposal volumes.

Additional constraints and considerations relevant for modeling these 15 placement sites included dredged material capacity, dredged material disposal frequency, variety of placement site location and type (e.g., marsh creation, beach replenishment, brownfields), and proximity to the dredge sites. Volumes per 5 yr interval had to be calculated based on the dredged material estimated quantity needed and the timeframe for use given in the Site Inventory Report. It is assumed that the beach nourishment sites will require nourishment with the specified volume once every 5 yr, and that the redevelopment and habitat restoration projects would be completed with the specified volume over several years.

Equipment cost curves are specified for 200 routes between pairs of potential dredging and placement sites. Equipment costs were derived from analyses by the NAE cost-estimating team, which estimated costs in the LIS region associated with transferring dredged material from dredge to placement sites via different methods. The costs varied based on the volume of dredged material, the type of placement site, the distance between dredge and placement sites, and the equipment used for transfer.

In this vignette, several types of effects of dredged material placement are considered and traded off as criteria in the D2M2 Model. Effect data was estimated from data provided in USACE (2012b, c). Both reports contain information about the effects that placement in the LIS DMMP study area are expected to have on the community. Berm sites referred to in the reports are similar to beach nourishment sites but with material placed nearshore. Containment sites refer to CAD cells, island confined disposal facility (CDF) sites, or shoreline CDF. A combination of expert judgment and report data are used to estimate effects for each potential material placement site in the LIS D2M2 model.

The four criteria identified in the reports included Cultural Resources, Environmental Resources, Infrastructure Resources, and Physical Resources. Each criterion and its respective subcriteria are listed in Table 46 that follows. The subcriteria are those applied for the LIS project and may require modification for other applications. There is good overlap between these criteria and their subcriteria (Table 46) and those identified by the LIS DMMP working group community. Values for each of these subcriteria were identified in terms of expected positive benefits or negative impacts to the relevant community.

Table 46. Effect input field criteria and subcriteria for impacts to the community.

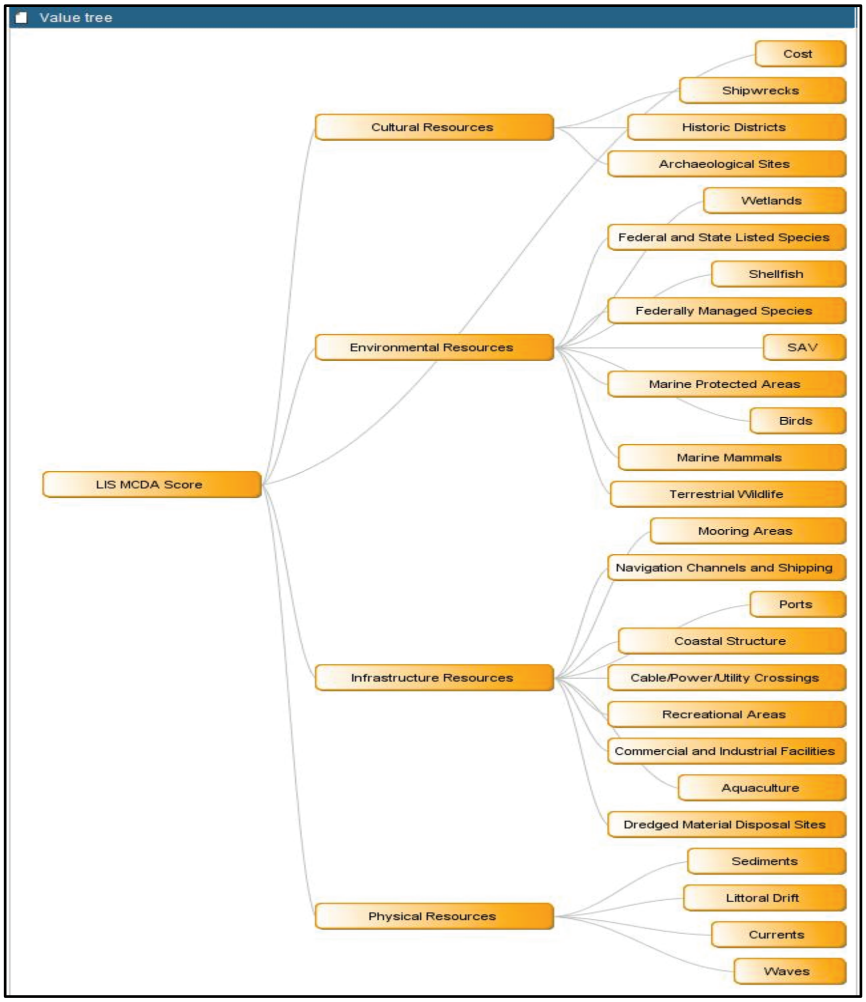
| Criteria | Subcriteria |
|---|---|
| Cultural impacts | Shipwrecks, historic districts, archaeological sites |
| Environmental impacts | Wetlands, Federal- and State-listed species, shellfish, Federally managed species, SAV, marine-protected areas, birds, marine mammals, terrestrial wildlife |
| Infrastructure impacts | Mooring areas, navigation channels and shipping, ports, coastal structure, cable/power/utility crossings, recreational areas, commercial and industrial facilities, aquaculture, dredged materials disposal sites |
| Physical | Sediments, littoral drift, currents, waves |

### Optimization sediment management planning

Next, the optimization objective to minimize the costs and the negative effect and maximize positive effects to the community is defined. Here, costs include fixed costs for using sites and equipment, per-unit disposal costs, and per-distance travel costs. Effects of the placement sites were evaluated using the previously mentioned nearshore and containment-site DMMP reports. A value tree shows trade-offs between the cost criterion and the four impact criteria (Figure 38). To evaluate and compare optimization results under varying criteria preferences, the optimization with three different weight sets was run, mimicking potential decision perspectives that could be investigated by management or valued by the stakeholder community. The first weighting scenario, All Cost, is used to calculate the optimal solution considering the lowest possible cost. The second weighting scenario, All Effect, optimizes the dredging solution considering the impacts to the community, including the cultural, environmental, infrastructure, and physical impacts, regardless of cost. Finally, the third scenario, 50/50, calculates the optimal solution under equal cost and effect considerations. Here, cost and effect data were each normalized over their respective ranges before trade-offs were evaluated. By varying the weights of the two composite optimization criteria, three different solutions are obtained through D2M2.

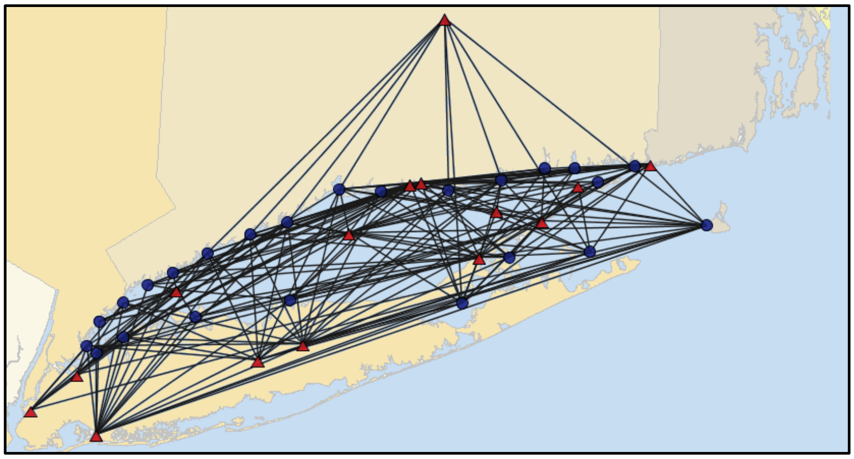
System-wide constraints for the project include allowable placement volumes for each placement site per 5 yr time interval. These volumetric constraints are derived from the placement site data reports. To further organize and constrain the optimization model, there were developed disposal site categories and equipment categories. With these categories in place, minimum or maximum amounts of material to be delivered to each type of disposal site could be set, and equipment use at each site could be constrained to a compatible category.

Figure 38. Evaluation tree of cost and effect criteria.




Main dredging site properties include name, location, and volume needed to be dredged in each time increment. Placement site properties include fixed-cost scaling factors (i.e., to modify average equipment cost curves based on site-specific details), wet-to-dry ratios (bulking factors), first possible periods, and site-capacity relationships. Four main equipment types are assigned to different routes, including small hopper dredges, mechanical bucket dredges, hydraulic pipeline cutterhead dredges, and pump-off hopper dredges. Equipment are identified for each route based on a comparison of expected costs for the volume to the dredged and placement site type. Based on the 24 dredge sites, 15 placement sites, and 200 links (Figure 39), 49 unique equipment cost curves are defined.

Figure 39. Map of LIS route network connecting dredging and placement sites used in the D2M2 optimization model.

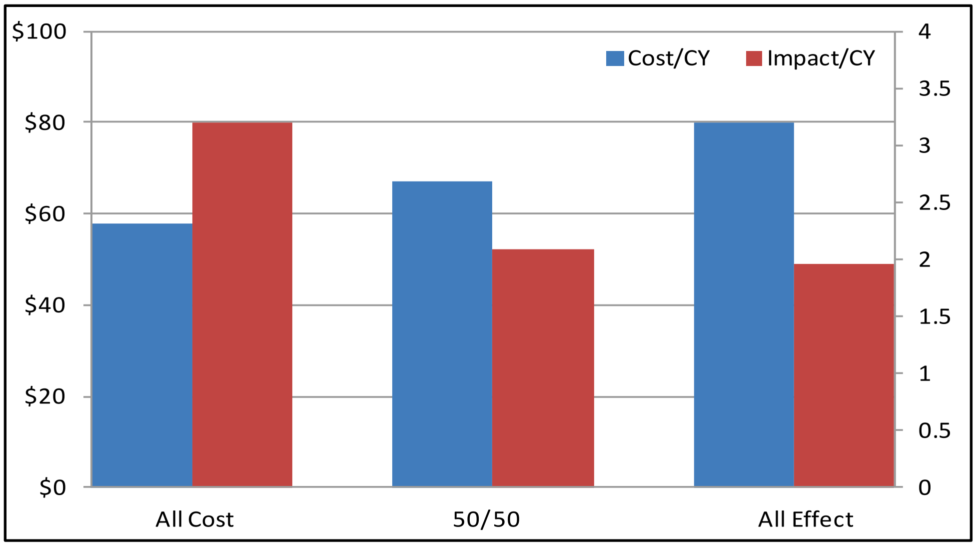


## Results and discussion

After running optimization for the three different trade-off scenarios, D2M2 produced reports that detailed the amount of dredged material to be transferred to each placement site in a given 5 yr period (Figure 40). Comparing and contrasting result sets like these can be useful as a project team explores the implications of different management trade-offs. The All Cost weighting scenario produces a least-cost dredging and material placement plan. Based on the equipment type, the distance from source to destination, and the constraints on the placement sites, the model identifies a least-cost plan predominantly involving open water disposal, with some beneficial and upland use, where those options are most cost effective. This management plan would cost approximately $58/CY transferred and a result in a relative impact score of 3.20 effect points per CY transferred.

The All Effect weighting scenario produces an optimal dredging and material placement plan that focuses on the non-monetary effects of material placement. These effects include cultural, environmental, infrastructure, and physical resources with multiple subcriteria, each having equal weights. Based on the impact scores (positive effect scores are represented as negative impacts) associated with each placement site, the model identifies a plan that focuses on beneficial uses, with many sites sending material for beach nourishment and brownfield or industrial site redevelopment. This management plan results in a relative impact score of 1.96 effect points per CY transferred at a cost of approximately $80/CY transferred.

Figure 40. Relative results of Cost, Effect, and Mixed D2M2 weighting schemes.




The 50/50 Cost and Effect weighting scenario produced an optimal dredging and material placement plan that considers cost and effect scores equally. This plan is perhaps most interesting, showing a mix of open water, upland, and beneficial placements of the dredged material. Here, the degree of benefit and the relative costs are traded off directly to inform the planning. The 50/50 scenario results in a relative impact score of 2.09 effect points per CY transferred at a cost of approximately $67/CY transferred.

This D2M2 vignette and demonstration, while not exhaustive, provides valuable insight into the types of analysis available with multiobjective optimization tools. In this example, the weighting scenario that minimized costs showed a trend of sending most dredged material to open-water sites or other placement sites that were in close proximity to the dredging site. Open-water sites are typically less costly than other placement sites because handling and transfer processes are minimized. The farthest distance that dredged material travelled was approximately 88 miles from Block Island to Central LIS. In addition, mechanical bucket dredges were predominantly used given the relatively lower-estimated fixed costs. However, the trade-off with minimizing cost is that the impact score is at its greatest. However, given the relatively higher impact score, this scenario may garner objections from the public or other stakeholder interests that value environmental and other factors in addition to cost savings.

The results from the All Effects scenario showed that dredged material went to redevelopment, brownfield, beach nourishment, and landfill sites. Most of these sites are beneficial use sites, where the dredged material is utilized to benefit the community or environment in some manner. Generally, beneficial use sites restore habitats, build recreation facilities, and increase overall aesthetics. Minimizing the impact score is key to positive public perception and for the USACE mission task to “protect, restore and enhance the environment.”[1] The farthest distance that dredged material travelled was approximately 96 miles from Manhasset and Little Neck Bays to Southold Municipal Beaches. In addition, a pump-off hopper is the dredging equipment that is being used most frequently for this scenario, and pump-off hoppers tend to have higher fixed costs. Even though this scenario would likely be rejected by project managers citing cost concerns, it is useful to understand project implications that could be more appreciable to some stakeholders.

The 50/50 Cost and Effect scenario showed that dredged material went to a wider variety of sites as compared to the other two scenarios. Neither open-water nor beneficial-use sites dominate material placement. The longest distance travelled was 75 miles from Stamford Area to Southold Municipal Beaches. An assortment of mechanical, hopper, and other types of equipment was used. As expected, the 50/50 scenario leads to an operational plan that balances aspects of the other two scenarios. In practice, it is expected that many operational plans that achieve buy-in from both project managers and the stakeholder community will implement a weighting scheme that has some consideration for both cost and effect criteria, and many additional scenarios and sensitivity analyses can be run to explore the full space of potential solutions.

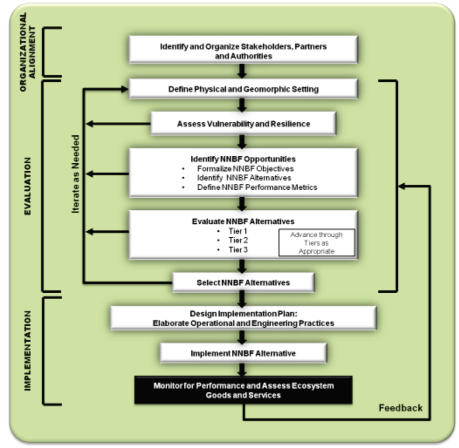
Path Forward

The proposed final product is a comprehensive analysis over the study area from Maine to Virginia using the methods demonstrated herein. The comprehensive analysis would identify the location and type of potential NNBF to support risk reduction and coastal resilience. However, insufficient testing of this new methodology requires an interim step before development of the final product. The proposed next step is to undertake a bench scale test (focused on a single planning reach) to exercise the range of developed capabilities described in this chapter. This step includes an NACCS stakeholder group to identify sediment sources and placement options that include not only dredged material but also

[1] USACE Campaign Plan, http://www.usace.army.mil/About/CampaignPlan

other sediment sources. Subcriteria and metrics may need to be expanded or modified for specific testing outside LIS. The results of bench scale testing will not be used in the study. Rather, the testing exercise itself (and its results) will be reviewed to determine aspects that are deemed successful and those that are problematic to make adjustments for final product application. Stakeholders who participate in this effort will be engaged in a review process to ensure needed refinement is satisfactorily identified. The refined methods will then be documented for advanced distribution to stakeholders prior to being incorporated into study methods for the entire NACCS area. A final request will be made of stakeholders to identify any remaining issues. A revised stakeholder group, including contact information, will be added to the documentation to be used in the final product. Data will be gathered and assembled based on the refined methods for use in the execution phase of the final product. The refined methods will then be exercised in the stakeholder setting for the NACCS area from Maine to Virginia.

# 7 Ecosystem Service Benefits of USACE Ecological Restoration Projects in the Coastal Northeast: Hurricane Sandy Case Study




## Introduction

Once NNBF have been integrated into the coastal system to support resilience and improve flood protection, it is necessary to monitor the performance of these features over time and assess the system's response to disturbance (e.g., urban encroachment, changes in TES species populations) and coastal hazards (e.g., winds, waves, surge). Proactive operation and maintenance relies heavily on this feedback. As such, the final step in the process involves developing a monitoring strategy within an adaptive management context at a systems level that assesses ecosystem response (using performance metrics quantifying ecosystem goods and services production), identifies thresholds or tipping points that indicate success or failure of the solutions, and focuses corrective measures to ensure resilience and sustainability.

A major stimulus for many coastal restoration projects is the sense of loss felt by the local communities as a result of the degradation of these ecosystems (Cairns 2000). Yet, choosing which natural areas to restore and how intensively to restore them remain key challenges when allocating scarce resources. Explicitly evaluating the linkages between restoration actions and quality-of-life outcomes can help guide ecosystem restoration choices and promote projects that maximize social benefits.

One approach to evaluating benefits that is beginning to be used for environmental decision making is framing the restoration goals and beneficial outcomes in terms of ecosystem goods and services. Not all ecosystems can be returned to a completely self-regulated and self-sustaining state (i.e., natural state) given external stressors. Nonetheless, ecosystem goods and services can be derived from relatively pristine ecosystems, restored or managed ecosystems, and the natural components of hybrid projects that incorporate both engineered and natural elements. Maintaining a diversity of landforms may be a more successful approach to maximizing ecosystem goods and services benefits than attempting to recreate or restore the natural condition of a coastal zone (Westoff 1985; Nordstrom et al. 2000).

Because coastal systems are in a setting that is particularly vulnerable to climate change, ecosystem goods and services analysis must evaluate the benefits of restoration under a changing future condition. Rising sea level and potential changes in storm frequency and severity will affect the expected benefits in two competing ways. First, the ability of ecosystems to provide a stream of services into the future is potentially reduced by coastal development, sea level rise, coastal subsidence, and loss of environmental features, such as dunes, seagrasses, and wetlands. Conversely, increasing risk to property and loss of natural areas will enhance the value of ecosystems that remain, particularly if they are able to reduce hazard risk and enhance coastal resilience.

Given the scale and rate of coastal ecosystem loss and degradation, assessing and valuing the ecological services of these ecosystems is critically important for improving their management and for designing better policies (Barbier et al. 2011). In a management context, ecosystem goods and services can be used to formulate project plans to maximize benefits, compare benefits of alternative actions, and demonstrate benefits of given management activities (Wainger et al., forthcoming). However, since few ecosystem goods and services are traded in the markets, it can be difficult to establish monetary values. Techniques for monetizing non-market goods and services are available, but are applicable to a subset of services, referred to as use services. Use services are those that result from direct use (e.g., bird-watching or hunting on site) or indirect use (e.g., flood risk mitigation from proximal wetlands) of ecosystem elements. The so-called non-use or passive-use ecosystem goods and services have been defined as the structures and processes that are protected because 1) “we might need it”; 2) “we like it”; and 3) “we think we ought to” (NRC 1999).

Thus, a fruitful approach for capturing a broad range of ecosystem goods and services is to apply traditional economic guidance to monetize what can be monetized, quantify outcomes that cannot be monetized—using metrics closely aligned with human concerns—and describe the remaining benefits (U.S. Office of Management and Budget 2003). Although difficult to combine, a variety of metrics are typically needed to provide a full picture of the ecosystem goods and services benefits.

In this study, the goal was to test the ability to explicitly link coastal restoration outcomes with resulting social benefits using available data and knowledge. Two case studies were evaluated to address these questions: 1) Which ecosystem services can we measure? 2) Are they the services we should measure? 3) How robustly can we measure outcomes and benefits with available data? A framework currently under development for USACE was applied (Wainger et al., forthcoming; Murray et al. 2013), which reflects ecosystems services targeted as a part of USACE mission goals and eco-systems services co-benefits. Both project areas were affected by Hurricane Sandy, which provided an opportunity to demonstrate performance, in terms of delivery of ecosystem goods and services, during an extreme event.

For this analysis, there was developed a streamlined approach in order to analyze a range of potential benefits in the available time frame. The technical aspects of benefits assessment generally follow the same guide-lines as other USACE analyses (USACE 2000). For example, beneficial outcomes are measured relative to a future without project scenario. Tasks in the streamlined analysis approach include the following:

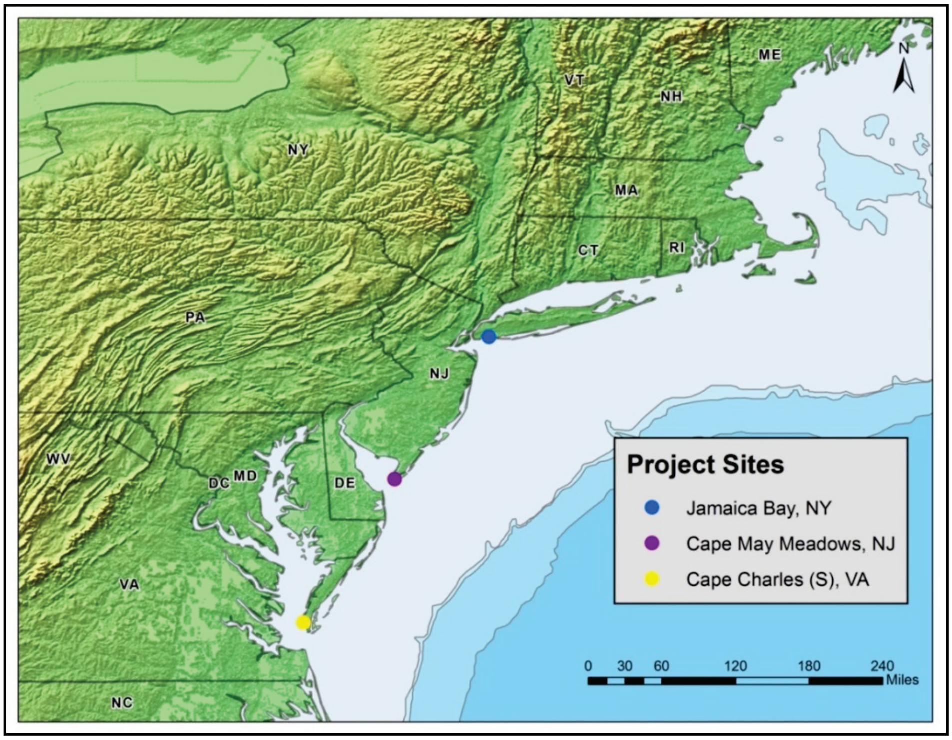
1. Identify ecosystem goods and services of potential interest.
2. Choose the best benefit metrics for a given service from among monetary values, quantitative benefit indicators, and qualitative descriptors of benefits.
3. Develop data on the natural and built environment needed to demonstrate biophysical changes in structures or processes required for ecosystem goods and services outcomes.
4. Develop data on a per-unit value of changes for use services (e.g., value of a recreation day per user) for use services.
5. Develop data on the market size—the number of users or beneficiaries influenced by the project for use services.
6. Develop quantitative data on ecosystem goods and services importance for non-use services related to ecosystem sustainability.
7. Evaluate change in benefit metrics due to restoration relative to the future without project baseline.

Details of the methods employed can be found in Wainger et al. 2013b.

### Case study: Restoration site descriptions

Sites used in analysis are located on the coasts of New York, New Jersey and Virginia (Figure 41).

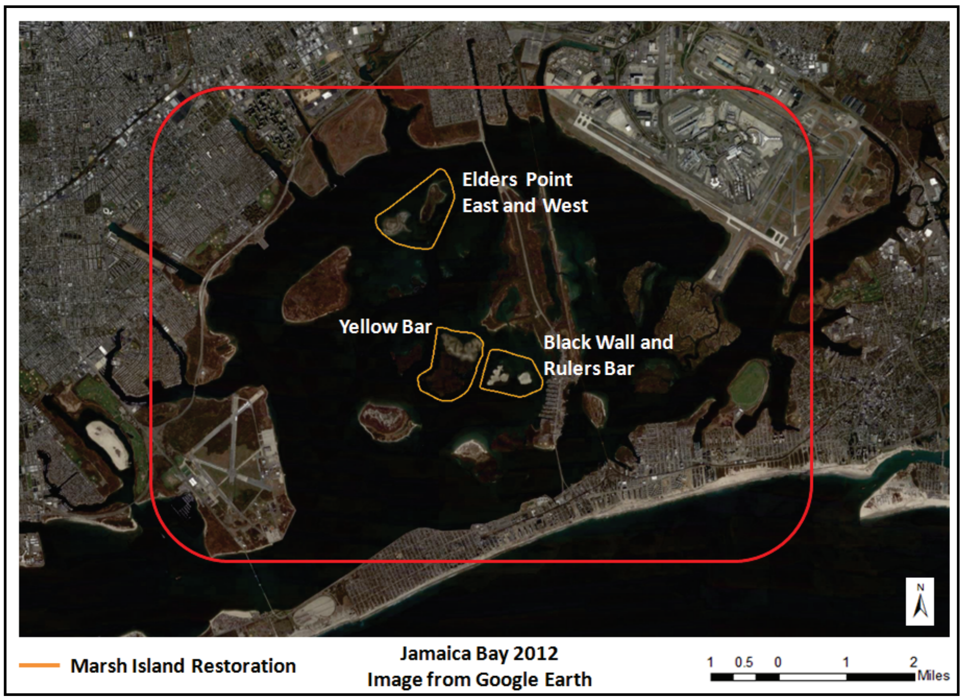
Figure 41. Case study locations.




*Jamaica Bay, NY*

Jamaica Bay (40° 36′ N, 73° 50′ W) is part of the complex urban ecosystem situated within the Boroughs of Brooklyn and Queens, New York City (Figure 42). One of the largest coastal ecosystems in the State of New York, Jamaica Bay is approximately 13 km long by 6.5 km wide, and opens into the Atlantic Ocean via the Rockaway Inlet. The Jamaica Bay Wildlife Refuge, protected since 1972 as part of the Gateway National Recreation Area (GNRA), contains salt marsh islands, mudflats, tidal creeks, and open water. Over the past century, these ecosystems have been degraded through human encroachment and increased urbanization. From1924 to 1974, approximately 205 ha (25%) of tidal salt marsh were lost from the marsh islands at the rate of 4.1 ha/yr. From 1974 to 1999, the system wide rate of loss increased to 12.1 ha/yr; an additional 304 ha of habitat was lost from the marsh islands (calculated from Hartig et al. 2002). If these rates continue, all remaining island marsh habitat within Jamaica Bay could be lost within the next two decades (Messaros et al. 2011). The degradation and loss of coastal habitats in New York has led to an intense interest in the restoration of tidal marsh habitat through beneficial uses of dredged material (Yozzo et al. 2004). In this study, the ecosystem goods and services associated with three island restoration projects were analyzed: 1) Elder Point East and West, 2) Yellow Bar, and 3) Black Wall and Rulers Bar. The Elders East and West project included restoring approximately 32.4 ha of marsh by placing dredged material up to an elevation suitable for low marsh growth. Approximately 27 ha of new marsh island, including 18 ha of low and high marshes, were created at Yellow Bar (Baron 2013). Approximately 8 ha of marsh islands were created at Black Wall and approximately 4 ha at Rulers Bar through sand placement (Baron 2013).

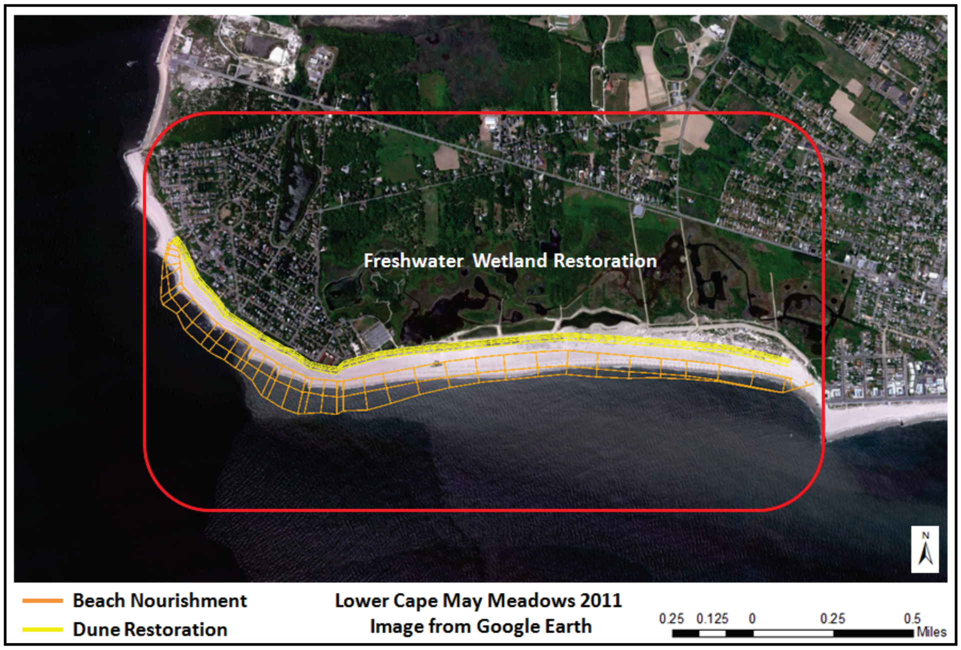
Figure 42. Jamaica Bay site map from 2012.




*Cape May, NJ*

The Cape May Meadows restoration site is located on the southern Atlantic coast of New Jersey (38° 56′ 4.74″N, 74°56´023.24″W (Figure 43). The area consists of beach and coastal wetland, residential land use, and includes Cape May Point State Park and Cape May Migratory Bird Refuge. The primary purpose of the restoration was to protect the freshwater wetland ecosystems existing just behind the dune system; however, the project also plays a role in storm damage reduction for the area. At the time of the restoration, erosion to the dune and beach system had progressed to a point where saltwater inundation had led to the loss of over 50 ha of wetlands (since 1955) and degradation of additional acres. The invasive reed Phragmites australis dominated the freshwater ecosystem (USACE 1998).

Figure 43. Cape May site map from 2011.




The initial construction of the beach and dune was completed in 2005, and the ecosystem restoration components were completed by 2007. The project consisted of the construction of a dune/berm 6 m wide, 5.5 m in elevation, and 3 km in length and the restoration of 14 ha of previously eroded wetland. Additional ecosystem restoration features including the creation of a channel, four dikes, four weir flow control structures, and five impoundments (for bird feeding and resting areas). Periodic nourishment of the dunes and beach is scheduled at 4 yr intervals, and was last renourished in November 2012. The project also included herbicide treatment (by marsh master) of 38.5 ha of Phragmites australis to reclaim the freshwater habitat (USACE 1998; pers. comm. Sarah Murdock, TNC April 2014).

The site is along the Atlantic flyway and thus has the potential to support both migratory and resident bird species. The restored site has been documented to provide valuable breeding habitat for a federally listed bird species, the Piping Plovers (Maslo et al. 2012). The study concludes that the artificial tidal ponds at the restoration site may be superior foraging habitats for both adults and chicks and contributes to reproductive success

(Maslo et al. 2012). Occurrences of rare plant species and reappearance of water plantain and arrowhead have been documented in the area (USACE, n.d.). Park staff have noted an increase in plant diversity, native flowers and butterflies (USACE, n.d.).

*Cape Charles South—Bay Creek, VA*

This site is located along the western shore of Northampton County, VA, in the Chesapeake Bay (Figure 44 and Figure 45).

The project restoration consisted of eight offshore breakwaters and beach nourishment designed to prevent beach and land erosion. Prior to the project, the site included a thin stretch of beach that was eroding and a wider stretch of beach that was known to provide habitat for the endangered tiger beetle (Cicindela dorsalis dorsalis) (Knisley 1999). In 2005, workers installed five breakwaters and added dredged material to regenerate the beach south of the habitat area. In 2006, the landowners received permission from USFWS to build an additional three breakwaters to address erosion north of the original project. Work was completed in 2006. After the project, USFWS personnel noted the recovery of the tiger beetle within the new beach area created by the restoration and habitat for larval beetles. However, the number of adult beetles and larvae dropped in the section of the beach that had provided the best habitat (outside the project), and the amount of habitat has declined (Knisley 2009).

**Figure 44. South Cape Charles–Bay Creek before restoration (1994). The red box indicates the natural tiger beetle habitat north of the restoration site.**

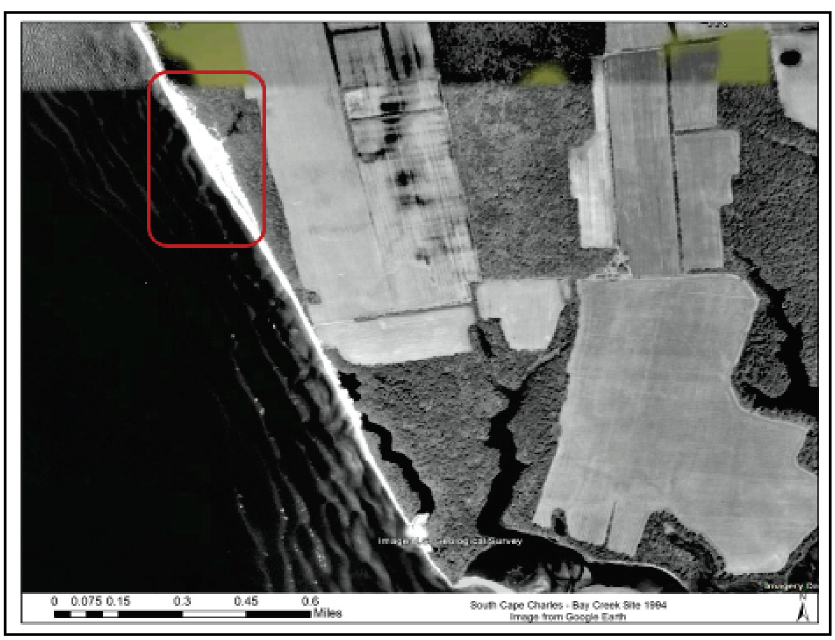


Figure 45. Post project showing eight breakwaters at Cape Charles South.


There is very little observational data before, during, or after construction. Aerial imagery available from Google Earth was used to construct a timeline of shoreline changes. Images are available from before the project (1994), during the project (2005), and after the project (2006). In addition, imagery is available from the period before Hurricane Sandy (2011) but not afterwards. Additional information was obtained by interviewing Mike Drummond, an endangered-species biologist with the USFWS, who has been involved in overseeing the project.

### Measuring economic values or social benefits

The goal with ecosystem goods and services analysis is to communicate biophysical changes in terms of the value that people place on those outcomes. When measuring social benefits, a recommended approach is to monetize what can be monetized, quantify what can be quantified, and describe everything else (U.S. Office of Management and Budget 2003). This approach was used here. All monetization was done with the benefit transfer technique that uses existing studies to suggest the value of improvements elsewhere (see Wainger et al. 2013b for details on these methods).

Ecosystem goods and services benefit assessment measures the net improvements made at the site relative to a without project baseline. This approach is standard for all economic value assessments and is consistent with USACE guidance for benefits assessment (USACE 2000). If benefits are being measured as nonmonetary metrics, they should follow the same approach of characterizing changes relative to a baseline, an approach analogous to the concept of environmental lift, as used by USACE.

*Relationship between significance and economic value*

The difficulty of measuring economic values for changes in non-use ecosystem services is well established. The only economic valuation techniques available for measuring values of non-use services are stated preference approaches in which various forms of surveys are used to elicit willingness-to-pay for ecosystem services derived from species and ecosystem restoration or preservation. These studies have historically been done to examine values associated with charismatic species or ecosystems (Richardson and Loomis 2009) and therefore may not be available to represent all types of ecosystem improvements. The stated preference approach is invaluable for cost-benefit analysis, but the ability to apply this technique accurately has been questioned (Hausman 2012), and the time and expense of applying this technique has limited its use. It is also highly controversial for philosophical and ethical reasons (Ackerman and Heinzerling 2002; McLeod and Leslie 2009; Hernández-Morcillo et al. 2013).

Because of the limitations of economic valuation for representing all facets of non-use ecosystem services, an approach for characterizing their relative importance by location is used. Ample evidence is available to suggest that people value environmental stewardship. Measuring environmental stewardship requires that it be defined in ways that are amenable to quantification. For this, there is an application of evidence that biodiversity contributes to sustaining species and ecosystems (Hooper et al. 2005). Biodiversity also contributes to use services and option values that are poorly quantified, such as the desire to maintain genetic diversity for potential future use. Therefore, some preferences can be captured for both use and non-use services related to ecosystems by examining how well a site contributes to species, ecosystem, or process biodiversity.

Value of non-use services may come from knowing a species exists now or from knowing something will be sustained into the future. Focus is on the latter—sustaining species or ecosystems—since it encompasses both types of value. Thus sought is the identification of where a change results in or contributes to a substantial improvement in the future stream of services.

Substantial improvements are based on two components: 1) opportunities to enhance the sustainability of the future stream of non-use services by moving an ecosystem away from a threshold or zone of increased risk; 2) opportunities where the restoration is most likely to be most successful.

*Benefit transfer*

Benefit transfer, the most commonly applied valuation technique, is founded on the idea that if someone has already invested the necessary resources to value a benefit somewhere, that value can be used to say something about the value of the same benefit elsewhere (Ready and Navrud 2005; Wilson and Hoehn 2006; Johnston and Rosenberger 2010). The accuracy of benefit transfer is a function of the availability and quality of existing studies and the time invested in tailoring the value to the site. Those applying benefit transfer should be aware of the significant errors that can result, particularly when using unit value transfers across dissimilar contexts. The literature generally finds that more sophisticated benefit function transfers outperform unit value transfers, although unit value transfers can perform satisfactorily if the study and policy contexts e.g., social factors, geographic and time scales, degree of resource scarcity) are very similar (see Wainger et al. 2013a for further explanation).

## Analysis

### Steps 1 and 2: Identify ecosystem goods and services of interest and choose benefit indicators

Project reports were reviewed and key personnel were interviewed to identify four major ecosystem goods and services for analysis: 1) property protection and enhancement, 2) recreation, 3) ecosystem sustainability, and 4) climate regulation. Under each major ecosystem goods and services category, one or more specific, measurable services were identified for which benefit metrics were created. Table 47 lists each specific service identified and the components that were intended to use to assess benefits. During analysis, data limitations prevented evaluation of some of these metrics at one or more sites.

Table 47. Ecosystem goods and services analyzed and metrics intended for use in the analysis.

| Service | Biophysical changes | Unit value | Market size | Final Metric(s) |
|---|---|---|---|---|
| **Property Protection and Enhancement** | | | | |
| Private property protection from flooding and storm surges | • Protection to private property including agriculture, land, and built structures (estimated physical damage avoided) | • Value of built structures at risk (% of total value)<br>• Value of land not eroded | • All private structures and land in protected zone | • Value of property and land protected<br>• Number of residents protected |
| Public property protection and economic disruption | • Protection of public infrastructure (estimated physical damage avoided) | • Critical infrastructure (e.g., major roads, hospital, school, police dept, central business district, power grid)<br>• Extra commute time per commuter | • Infrastructure and property in public ownership<br>• Commuters<br>• Days to reopen bridge | • Critical infrastructure protected<br>• Commuting time saved and number of commuters not inconvenienced |
| Property value enhancement from wetlands/beaches/natural amenities | • Natural area retained (by land cover type: wetland, beach) | • Percent value of parcels attributable to ecosystem goods and services | • Private property within 0.5 mile of amenity | • Total enhancement value<br>• Number of homes with enhanced value |
| **Recreation** | | | | |
| Recreation – beach use | • Area of beach retained<br>• Days that the beach was unusable (e.g., due to flooding, debris) | • Percent consumer surplus per beach user day attributable to project | • Total user days for this beach (derived from NSRE++ saltwater beach use module)<br>• (Participation rate * Pop within average user distance * days/participant)<br>• Area of non-users (e.g., county) | • Value of beach user days saved |
| Recreation – bird or wildlife watching | • Bird habitat retained<br>• Bird watching areas retained<br>• Days that sites / boardwalks were unavailable for birding (e.g., due to flooding, road closure) | • Percent consumer surplus per user day attributable to project | • Total user days | • Value of birding days saved |

| Service | Biophysical changes | Unit value | Market size | Final Metric(s) |
|---|---|---|---|---|
| **Ecosystem Sustainability** | | | | |
| Ecosystem diversity+ | • Area of rare terrestrial ecosystems create/enhanced/ protected | | | • percent of rare habitat area that is created/enhanced/protected |
| Terrestrial and aquatic species biodiversity+ | • Species of concern associated with habitat created/enhanced/ protected | | | • Number of Federal RTE+++ species that benefit (aquatic-terrestrial)<br>percent of species of concern that benefit |
| NE Beach tiger beetle (TB)+<br>(Cicindela dorsalis dorsalis)<br>Federal threatened species; globally imperiled<br>(similar subspecies Cicindela dorsalis media is not threatened) | • Likely distribution in and near the study sites | n/a | n/a | • Area of TB habitat retained<br>• percent total TB habitat retained |
| Aquatic species of concern (horseshoe crabs) + | • Area of suitable habitat retained | | | • Habitat area retained<br>• percent total horseshoe crab habitat area retained |
| Red knot | • Area of suitable habitat retained | | | • Habitat area retained |
| **Climate Regulation and Risk Reduction** | | | | |
| Carbon sequestration | Net annual sequestration as a function of wetland type and salinity regime (low salinity–net sequestration not assured) | Social cost of carbon (interagency report) | n/a | Tons of net $CO_2$e sequestered annually<br>Social value of $CO_2$e (annual) |

+ Service is a proxy for the non-use services derived from maintaining species or ecosystem biodiversity.

++National Survey on Recreation and the Environment

+++Rare, threatened, and endangered

The second column of Table 47, Biophysical changes, shows the ecological, physical, or built infrastructure change that was sought to measure to identify the effectiveness of the restoration for improving that service. The next column, Unit value, lists the monetary values and nonmonetary benefit indicators that were measured on a per-person or per-acre basis to assess benefits per person. Not all services have these values since they were not appropriate in all cases. The next column, Market size, lists the methods used to assess the total number of users of a service. This is only measured for use services and not non-use services. The Final metric column lists either the product of the previous two columns (e.g., change in recreational value per person * number of recreators) or lists an alternative metric used to suggest the relative importance or benefit of a given service.

### Step 3. Quantifying biophysical changes

All benefits are measured relative to the without project baseline. In this section there is a presentation of information regarding the amount and type of natural systems created by the project and the expected future without project condition.

*Jamaica Bay*

The without project baseline for Jamaica Bay estimates that the unrestored islands would be completely eroded by 2025 (Baron 2013). Thus, all marsh within the restored islands can be considered to be part of the ecological benefits over the long term. Five island sites were considered, which created 161.4 acres of new ecosystem area.

*Cape May Meadows*

The without project baseline for Cape May Meadows includes continued erosion of beach, dunes and wetlands and damage to property. The project team projected a 15 ft/yr per year erosion rate (USACE 2005), which translates to 173 acres not eroded and 170 acres not inundated with seawater due to the project (USACE, n.d.).

The Lower Cape May project has been in place for over 5 yr, and available data was analyzed to estimate project effectiveness. To estimate without project conditions, recent Google Earth imagery was used. Twenty-two markers were placed along the 1991 preproject shoreline in Cape May, NJ, using graphic information system (GIS) tools. Beach movement relative to these markers within and outside of the project area was tracked using Google Earth images available from 2002 (preproject), 2006 (during project), 2008, 2010, and 2011 (post project). Beach width for each image and the position of the shoreline edge relative to each marker (along a line perpendicular to the shoreline) for each available date was measured. The latter measurement is referred to as beach movement. Positive beach movement values indicate shoreline accretion, and negative values indicate erosion. It was not possible to correct for tide height because images were not time-stamped, thereby reducing the precision of these estimates.

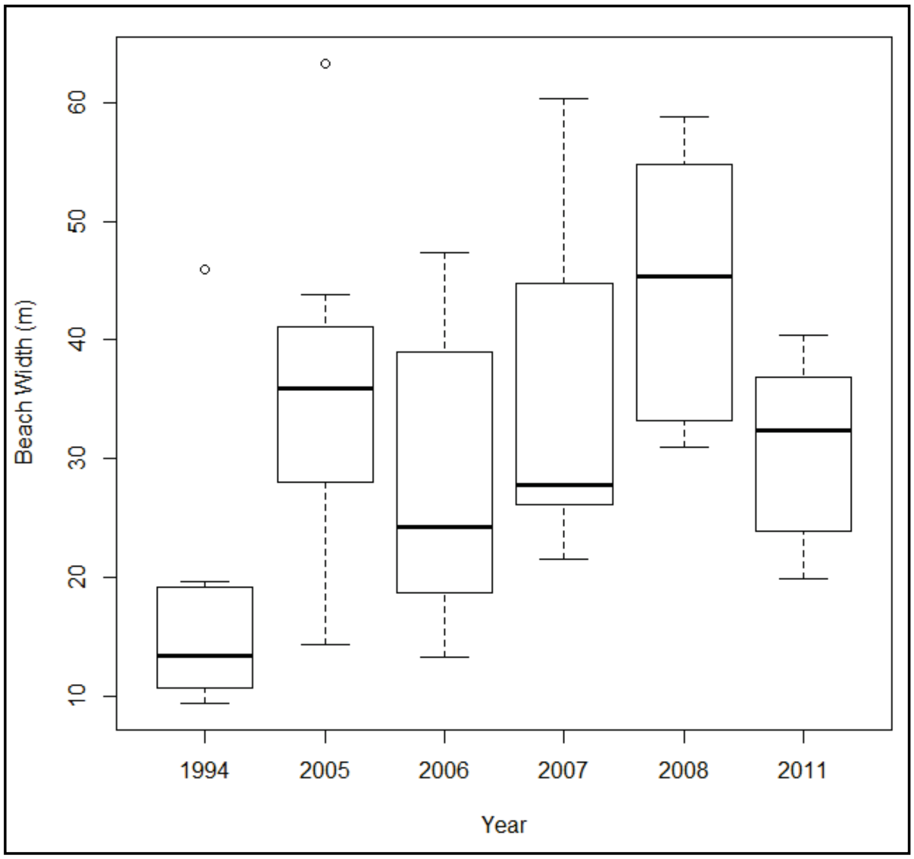
The median accretion of all markers after the project was much higher at the project site than the control site, and the average of this median value over all observations is approximately four times higher at the project site (90.8 m vs. 22.8 m). This entire difference cannot be attributed to the project; however, the data suggest that the project has been effective at preventing erosion over this time frame and possibly more effective than the beach nourishment conducted by the local government. The net accretion at the project site translates into an additional 15 ft of beach width (3 m) due to the project, including beach renourishment.

*Cape Charles South*

A Without Project baseline was not available for the Cape Charles South. To fill this gap, with and without project conditions using the same type of analysis as for Cape May Meadows were evaluated. A total of 14 markers were placed along the 1994 preproject shoreline using GIS tools and Google Earth imagery. Only one image was available prior to project installation. Beach movement relative to these markers within and outside of the project area using images available from 2005–2008 and 2011 (one per year) was tracked.

Outside the project, the median for each year is less than zero, indicating net erosion from the 1994 shoreline at the control points. The median beach erosion for all markers outside the project, averaged over all years is 5.1 m total or approximately 0.5 m/yr between 1994 and 2011. In comparison to the control sites outside the project, the markers within the project showed an average median accretion of 0.8 m total relative to the preproject condition. Measurements were highly variable. As a result, the average annual movement in this time frame is –0.03 m, suggesting a relatively stable shoreline over the postproject period analyzed. When compared to the without project baseline of 0.5 m/yr erosion, the net effect of the project is estimated to be 0.47 m of erosion prevention. The accretion also translates into an average beach width of 34.88 m post project (Figure 46). When compared with the 1994 condition, this represents an additional 17 m of beach width attributable to the project, or an additional 0.8 ha (2 acres) of beach added. The 1994 mean beach width was statistically smaller than the means for the years 2005 and 2008 (based on one-way analysis of variance (ANOVA)), but the difference was not significant for the other years.

Figure 46. Cape Charles South Beach width within the project area over time. Values represent the distance that shoreline edge has moved relative to the 1994 shoreline. Boxes show the 25th and 75th percentiles of beach movement for a given year. The bold horizontal line shows the median value.




### Steps 4 and 5: Unit value changes and market size analyses

*Property protection*

The intention was to use data from Hurricane Sandy to demonstrate the effectiveness of ecological restoration projects in protecting private property during extreme storm events. Anecdotal evidence suggested that wetlands and sand dunes had been effective at reducing the extent and or depth of the storm surge. However, data that were available were not sufficient to estimate the magnitude of damage reduction. For example, the storm surge data for Cape Charles South shows extensive flooding behind the project (Figure 47). Therefore, it was not possible to improve upon the damage-costs-avoided modeling conducted for the project planning and thus that analysis is omitted from this report. Other services such as property value enhancement and ecosystem sustainability were able to capture some of the erosion control benefits of the project.

Figure 47. Hurricane Sandy storm surge at Cape Charles South.


*Critical infrastructure protection*

In addition to private property damages avoided, it can be useful to consider the level of economic disruption that can result from a storm and the potential for ecological restoration to prevent or mitigate such disruption. A key factor in the level of economic disruption is whether critical infrastructure is damaged or destroyed by storms. Critical infrastructure can include roads and bridges; water, sewer, power and communication lines; shipping channels; central business district (centers of commerce); schools; hospitals; and police stations. The potential for critical infrastructure harm for all sites was evaluated, and a choice was made to conduct an analysis for Jamaica Bay.

The Cross Bay Bridge, through Jamaica Bay, connects the Rockaways and Long Island into Brooklyn and Queens in New York. This high-traffic commuter route is located within the National Park Service's (NPS) Gateway National Recreation Area (NRA). Due to Hurricane Sandy, the Cross Bay Bridge was closed on 29 October 2012. It was not washed out during the storm and was mostly open again by 6 November 2012, with toll collection suspended through the end of November (New York Times 2012). In contrast, the railroad bridges to the east suffered substantial damage, and the rail line was closed until 30 May 2013.

Stakeholders in the Jamaica Bay project have suggested that the restored marshes dispersed wave energy thus mitigating the impact of the storm surge flooding on the Cross Bay Bridge. The complex geophysical modeling required to substantiate such a hypothesis is beyond the scope of this project. However, an evaluation was made regarding the potential for this effect by considering the degree to which the projects might reduce horizontal fetch at a critical bridge support point.

Information necessary to evaluate whether the change in fetch would be enough to prevent structural damage was not available, but considered was a scenario in which the bridge needed to be closed for repairs to evaluate potential benefits of these changes

**Unit value.** An analysis was made as to how much additional commuting time might be required if the Cross Bay Bridge were closed. The direct path over the bridge from the Rockaway Freeway to the Belt Parkway is a distance of 5.7 miles with a car travel time of approximately 10 minutes (min) in low traffic (12 min in rush hour). When the road is closed, the travel distance becomes 13 miles with a traffic-free car travel time of 33 min (45 min during rush hour). It was assumed likely that a commuter would be traveling across the bridge to reach a central business district.

An evaluation was made of the change in commute time from Rockaway Beach near the southern end of the bridge to Midtown Manhattan. Assuming the traveler takes an alternative route to the east, this route adds an additional 6.2 miles and an additional 9 min in low traffic conditions, according to Google Maps. The alternative route to the west results in similar differences in miles traveled. During rush hour, the additional time was estimated to double to 18 min extra commuting time.

**Market size analysis.** The NPS collects statistics on visitation to multiple sites within the Gateway NRA, both in New York and New Jersey. The car-count data over the Cross Bay Bridge was downloaded from the NPS Visitor Use Statistics website for the last decade (2000–2013) (NPS 2013). The monthly average car count over the Cross Bay Bridge was 597,064 in 2011. This value rose slightly in 2012 to 622,895 despite the closures due to Hurricane Sandy. However, the monthly totals for October and November of 2012 are lower at 599,383 and 573,407, respectively. Using the 2012 average monthly car count divided by 31 days, an average daily car count of 20,093 can be calculated. It was assumed that one-third of bridge users traveled during rush hour, to estimate commuting time saved.

*Private property value enhancement*

Private property values can be enhanced by the positive attributes provided by nearby natural lands and other types of open space. These enhancements include aesthetic enhancements, erosion control, and recreational opportunities. Therefore, the ecosystem goods and services benefits provided by natural lands are partially captured in property values and the property value premium, or the extra value due to the availability of ecosystem goods and services. This premium can be estimated based on statistical (hedonic) analysis (Bockstael and McConnell 2007). The size of the property premium depends on many characteristics of the natural lands, the enclosing landscape, and the real estate market. For example, adjacent wetlands may greatly enhance value in a densely developed landscape (Boyer and Polasky 2004) but may have little effect, or even a negative effect, where wetlands are abundant in the landscape (Bin and Polasky 2005). Similarly, the value of many types of open space appears to increase with its scarcity (Geoghegan et al. 1997; McConnell and Walls 2005).

At the case study sites, beaches and wetlands are expected to enhance nearby property values. Furthermore, the degree of value enhancement is expected to vary with beach width and the associated degree of erosion control (Kriesel et al. 1993, 2005; Pompe and Rinehart 1995; Whitehead et al. 2008; Gopalakrishnan et al. 2011). To analyze the partial value of these ecosystem goods and services, an estimation was made of the value of their contribution to existing property values in the region using GIS analysis and benefit transfer. Due to the lack of an existing transfer function for beach property premiums, a unit value transfer was used. The unit value through a literature review was developed. It appears that a functional benefit transfer analysis may not be possible given the limited number of available economic studies that considered effects of beach width.

*Property premium unit value (percent enhancement to property values)*

A consideration was made of the effect of additional beach width and wetlands on property values at the case study sites. Two sites added beach width relative to the preproject condition, Cape May and Cape Charles South. In addition, the Cape May restoration includes vegetated dunes and marsh enhancement. The improvement of the marsh condition at Cape May is also likely to positively influence property values, but the effect of wetland improvements on property values (as opposed to wetland creation or loss) is not well studied in these types of settings, so it is difficult to assess. The data on effects of dunes on property values are sparse, but some evidence suggests that vegetated dunes increase property value (Gopalakrishnan et al. 2011) although home owners are known to object to dunes that block water views.

A study of South Carolina beaches found that property values for homes adjacent to beaches increased 0.6% for a 1 ft increase in beach (79–80 ft) and 0.3% for homes 0.5 mile away from the beach. It was found that effects diminished with wider beaches (Pompe and Rinehart 1995). The beaches in the study are narrower than the examples, but lacking other information, the 0.3% increase per foot of beach for all homes within a 0.5 mile buffer was used (Pompe and Rinehart 1995).

*Market size (affected zone and property values)*

The properties that would be most strongly affected by enhancements to beaches and wetlands are those in relatively close proximity to the natural areas that can benefit from the erosion control, aesthetics, and recreational opportunities. The literature suggests that those adjacent to the amenity have the highest property premium but that the effect of the amenity on property value can extend well beyond the adjacent properties (Pompe and Rinehart 1995), particularly when the amenity includes public access, which is the case for the beach study sites. For this study, results of Pompe and Rinehart were used to consider the effect of extended beach width on all private property within 0.5 mile of the beaches and the effect of vegetated dunes and wetlands.

For all sites analyzed, a distance of 0.5 mile from the beach or adjacent wetland was used to establish which parcels were in a zone affected by beach and marsh condition following findings in Pompe and Rinehart (1995).

**Jamaica Bay.** The closest residences were outside of the 0.5 mile buffer of the project, so this service was not analyzed for this case study site. It is possible that views of the marshes and any erosion control benefits/harms may affect value of property on or near the shoreline. However, there was insufficient information to evaluate these effects.

**Cape May.** Cadastral tax assessment data were used in this analysis to assess the value of affected properties (State of New Jersey Office of Information Technology 2005). Properties under the influence of the project were selected and then parcels owned by government agencies and The Nature Conservancy were removed to generate a set of private properties. The total improvement value of the beach-affected parcels is $574,554,000 and $260,298,400 of the wetland-affected parcels.

**Cape Charles South.** A similar study was conducted at Cape Charles South and revealed that the total value of properties within 0.5 mile of the beach was $89,248,000.

#### Recreational bird and wildlife watching

*Unit value of a recreational birding day*

The value of a user day for recreational wildlife watching was developed by using a database of economic valuation studies, the Recreational Use Values database, and associated documentation that were created for conducting benefit transfer of environmental benefits (Loomis et al. 2007; Loomis and Richardson 2008; Rosenberger 2013). A choice was made to conduct a unit value transfer because the database developers had been unable to estimate a significant statistical model to use in functional transfer (Loomis and Richardson 2008). To create a unit value to use in estimating the benefits of wildlife viewing at Jamaica Bay, values for wildlife viewing were selected that have been estimated in sites with similar geographic and ecological characteristics.

A comparison was made of two approaches to generate a value for user days in Jamaica Bay. One approach was to find the study that was most similar to the situation in the site being valued. The second approach was to use a large set of similar studies to generate a value with a strong central tendency. Two studies were found that were conducted in an estuarine setting and were markedly similar to Jamaica Bay. One study was for the Peconic Estuary in New York State, and the researchers estimated an average consumer surplus, in 2010 dollars, of $71.29 (Johnston et al. 2002). The other study was for Delaware Bay, and researchers estimated an average consumer surplus of $90.87 (Eubanks et al. 2000). These values were compared to the average of 60 relevant studies that were selected from the full database, which was $50.70. The Johnston et al. (2002) value of $71.29 was selected because of its close correspondence to the case study in terms of resources valued and user demographics. The final step before using the value was to convert 2010 dollars to 2013 dollars using the consumer price index (CPI) (Bureau of Labor Statistics (BLS) 2013), for a final value of $76.34/user day for bird-watching in a coastal wetland setting.

*Effect of restoration on recreational value*

One of the projects (Jamaica Bay) is creating additional marsh in an area of existing marshes, and the other (Cape May) is enhancing the quality of an existing marsh. These particular changes in wetlands are difficult to value directly, although they are likely to enhance multiple recreational ecosystem goods and services that are relatively easy to quantify.

A well-known economic meta-analysis suggests that there is no clear relationship between wetland size and value for recreation or other ecosystem goods and services (Woodward and Wui 2001). Yet, the landscape ecology literature suggests that it is a reasonable assumption that larger habitat will support a greater diversity of species. Studies in wetlands confirm this is the case (Findlay and Houlahan 1997). Therefore, to assess the change in value due to wetland restoration at Jamaica Bay and Cape May Meadows, it is assumed that additional acres of marsh provide a higher likelihood of observing more species and more types of wildlife based on increases in size and habitat quality. Studies that quantify the value of greater species diversity to recreators are sparse; however, greater species diversity has been associated with higher willingness to pay for non-use services (Morrison et al. 1999). Here it is assumed that increases in non-use values from enhancing species diversity are similar to increases in value to wildlife watchers. For lack of a better value to represent recreational enhancement, use was made of the Morrison et al. result of a willingness to pay of 7% of consumer surplus for the addition of an endangered species. The 7% value is a conservative estimate since the study found that households assigned a value of 44% of consumer surplus for an increase in a breeding pair of waterbird species. Further analysis of the effect of the marsh area change on species diversity (e.g., through a species-area relationship), and economic studies of the value of increasing diversity of species would allow a better constraint of this figure.

*Establishing market size and user days*

The **Jamaica Bay** Project site is a premiere bird-watching site. Its location along the Atlantic Flyway and priority salt marsh habitat make it a stopping point for many migratory bird species throughout the year. The project can increase the value of recreational bird-watching by increasing the number of user days or enhancing the value, per day, by attracting additional species or other effects. Hurricane Sandy forced the closure of the visitors' center for 26 days along with the bridge that provides one type of access to areas near the marsh islands. If the project is able to prevent damage to visitors' centers or reduce the duration of closures, then these would enhance the project-derived benefits to bird-watchers. Due to data limitations, a focus was made on the effect on value per user day.

There was developed a GIS analysis to estimate the number of bird-watchers who would be likely to use the site. The method establishes the residences that are within the average driving distance associated with this type of recreator in this region of the country and the average participation rate, in order to estimate total potential users. The method was calibrated with visitor statistics at this site to generate a total of 43,000 visitors per year (see Wainger et al. 2013b for details). Visitation statistics were not used to estimate user days because they were not available at all sites, and a consistent method for comparing sites was desired.

**Cape May Meadows** provides a vital resting spot for shorebirds, birds of prey, and songbirds during their seasonal migration as well as providing habitat for residential birds. It is considered by Federal, State and private organizations to be one of the foremost avian viewing areas in North America attracting more than 100,000 birders each year (USACE 1998).

A GIS analysis similar to the one conducted for Jamaica Bay was conducted for Cape May Meadows. That analysis resulted in an estimate of 44,615 bird-watching days per year for the area. This number is substantially less than the USACE estimate, and it is likely the estimate based on the GIS analysis has high error. Both numbers were used to assess benefits because the method of generating expected visitors is comparable across all sites, many of which will not keep visitor statistics.

### Recreational beach use

*Biophysical changes*

The biophysical changes with the potential to impact recreational beach use were quantified using Google Earth imagery to assess with and without project conditions as described above. Also referenced were the future without project plans because the amount of time that has passed since the projects were in place may be insufficient to understand long-term consequences.

*Unit value of a recreational beach day*

The value of a user day for beach visitation was developed by using a database of economic valuation studies, the Recreational Use Values database, and associated documentation that were created for conducting benefit transfer of environmental benefits (Loomis et al. 2007; Loomis and Richardson 2008; Rosenberger 2013). A unit value transfer was used due to a lack of appropriate meta-analysis for a transfer function. Studies were selected based on the primary activity being beach recreation and the region being northeast, mid-Atlantic, or multiregion. It was decided to use the average (mean) value of $45.89 (2010 dollars) converted to $49.14 in 2013 dollars to estimate the total value of a beach day.

*Effect of restoration on recreational value*

The next component of estimating the effect on user value is how consumer surplus changes with beach width. These projects are not creating beach where there was no beach but are creating wider beach, which has been shown to be valued by many beach users. Whitehead et al. (2008) found that the increase in the consumer surplus per trip with a 100 ft increase in beach width (from a current range of 10–100 ft) was approximately $7.00 or 7.8% for visits to North Carolina beaches. This result is consistent with earlier studies that documented similar effects of increased beach width on value of a recreational experience (Pompe and Rinehart 1995). The available studies were insufficient to relate change in value to amount of beach width change. Thus, it was decided to use the 7.8% increase in consumer surplus as representative of the beach changes because it was the best number available. However, this value is subject to error and further analysis would be useful to better constrain this figure.

*Establishing market size and user days*

Two sites provide recreational beach opportunities, Cape May and Cape Charles South. To define potential users of the beach sites, a GIS analysis was developed to identify the area from which the most frequent users would be drawn, which then combined that information with beach recreation participation rates to estimate potential annual use of these sites. The technique used population distribution (dasymetric data) near the site (USEPA 2013), median distance traveled by beach users in the State (NSRE 2000), and state-wide beach recreation participation rates (NSRE 2000).

The NSRE is a multiagency effort to assess participation rates for all types of outdoor recreation (NSRE 2000). The total calculated annual saltwater beach recreation days demanded is approximately 3 million for Cape May Meadows and 58,000 for Cape Charles South. Using the factor of 10 correction based on the bird-watching results for Jamaica Bay, the result is an estimate of 300,000 annual beach-user days for Cape May Meadows and 6,000 days for the South Cape Charles-Bay Creek site. This approach is a quick method for estimating likely beach users when direct visitation data are not available; however, the degree of error is unknown. A more thorough approach would be to measure likely visitation as a distance decay function to reflect user behavior and to consider availability of substitute sites in order to better assess the proportion of total annual visitation likely to occur at a given site. In addition, it is common to use a market segment approach in which participation by demographic group (combinations of age, race, sex, income, and education that influence participation) is considered to better reflect demographic characteristics near the site.

**Ecosystem sustainability**

Each of these sites has been deemed nationally significant. Here, the aim is to quantify the relative conservation interest at each site and the importance of the project for protecting or enhancing ecosystem sustainability. What is able to be quantified with available data will never fully capture the benefits of retaining all aspects of natural function in systems. However, the aim was to produce quantitative metrics that will serve as useful comparisons among sites. To that end, there was a development of multiple metrics using readily available data to capture site qualities.

It is considered that a project contributes to an important or significant ecosystem sustainability outcome when it enhances species, ecosystem, or landscape process diversity. Diversity represents both the number of species/ecosystems/processes (e.g., species richness) and the abundance of the species/ecosystems/processes. The geographic range used for assessing diversity or abundance will have a strong influence on the metrics. For abundance measurements to reflect national significance, they need to be conducted over an ecologically relevant range rather than a geo-political boundary, such as a state.

Several data sources were used to assess ecosystem and species biodiversity at the sites and because data were not consistent across all sites; some metrics are calculated for only one site. No attempt was made to address process diversity, although with future work, it would be considered whether the islands created in Jamaica Bay or the marshes preserved at Cape May meadows were critical to maintaining bird migratory routes or other landscape functions. It is likely that process diversity will often be reflected in a thorough analysis of species and ecosystem concerns, but this category alerts the analyst to the need to consider landscape processes beyond the site scale.

*Ecosystem diversity*

To evaluate ecosystem rarity, an estimation was made of the area classified as rare ecosystem using a metric available from the U.S. Environmental Protection Agency (USEPA) EnviroAtlas (USEPA 2013). The EnviroAtlas offers four metrics of ecosystem rarity. A choice was made to choose to use the Macroform Relative Rarity metric, which defines rarity as an ecosystem with an extent that falls within the lowest quartile of all ecosystems within a macroform group. A macroform group is defined by the level of ecosystem aggregation and the spatial pattern type. The ecosystem classification is the USGS Gap Analysis Program (GAP) (v2) (USGS 2011) ecosystems aggregated to the macrogroups of the National Vegetation Classification (NVC). This represents an intermediate level in the hierarchical classification of ecosystems. Four spatial patch classifications are used: large patch (50–5000 acres), linear (tend to be ecotonal between terrestrial and aquatic areas), matrix (5000–1,000,000 acres), and small patch (< 50 acres). Thus, the spatial extent of an ecosystem is only compared to other ecosystems that tend to form similar-size patches. Within the EnviroAtlas, the metric is summarized by 12-digit hydrologic unit code (HUC) as the total area of rare ecosystems or provided as a raster data set (pixel-based map) showing the location of the rare ecosystems.

Using EnviroAtlas data, both Jamaica Bay and Cape May Meadows sites had rare ecosystems in the project-affected area (the bay and 1 km buffer around the shoreline). A single rare large patch ecosystem was identified as occurring within Jamaica Bay called North Atlantic Coastal Plain Dune and Swale. While the rare ecosystem is present on some of the Jamaica Bay Islands, it is not present on the restored islands. Similarly, the identified rare ecosystem at the Cape May Meadows site, the Atlantic Coastal Plain Southern Dune and Maritime Grassland, is also just outside the project area. Cape Charles also had a single rare ecosystem, Atlantic Coastal Plain Northern Fresh and Oligohaline Tidal Marsh, adjacent to the project. These results highlight the fact that created features are unlikely to show up in databases of existing ecosystem condition. The presence of rare ecosystems close to the restoration activity suggests that the project has the possibility to enhance existing systems through buffering and to expand those ecosystems if the restored sites are expected to develop into similar ecosystems. At the Cape Charles South restoration site, the single rare large patch is classified as an herbaceous wetland system dominated by tidal vegetation. At the Cape Charles South restoration site, a rare ecosystem was identified (Atlantic Coastal Plain Northern Fresh and Oligohaline Tidal Marsh) and five natural land cover classes were identified. The site falls within the The Nature Conservancy's (TNC) Chesapeake Bay Lowlands terrestrial ecoregions.

*Species diversity*

**Total TES species by watershed.** The EnviroAtlas provides summaries of the distribution of TES species as modeled by the USGS GAP (USGS 2011) and the Southwest Regional Gap Analysis Project (SWReGAP) for the Southwest U.S. Over 800 species models are included in these databases to represent their potential distribution. In the data provided by the EnviroAtlas, species are grouped together into guilds of interest such as vertebrates and summarized as the mean, maximum, or normalized index of potential species richness within a 12-digit HUC watershed. Using the maximum potential species richness data, it was documented that all study sites have TES species in the enclosing and/or adjacent watersheds. However, because the data are highly aggregated by species and over large areas, it was not possible to use these data to suggest the relative importance of the restoration.

**Species of concern occurrences in Jamaica Bay.** Using the Jamaica Bay site, testing ensued on the utility of a new online mapping database entitled Biodiversity Information Serving Our Nation (BISON) (USGS 2013) that documents species occurrences throughout the U.S. The output is a downloadable GIS file with species occurrence location and date. The database integrates museum records as well as publications and other sources. Not all points are georeferenced, and some date back into the 1800s. A search by location yielded a large number of species for the sites, many of which were common species. Therefore, elected choice was made to search for species of concern identified within the New York State Wildlife Action Plan (SWAP). Attention was focused on the species most likely to use the restored salt marshes in Jamaica Bay, including 28 bird species and the horseshoe crab. Each of the 29 species identified from the SWAP were input into the BISON database for the Jamaica Bay project site. No records were found in the database for four of these species: Cory's shearwater, long-tailed duck, red-necked phalarope, and the short-billed dowitcher. All of the remaining 25 were found within the BISON database located within Jamaica Bay.

Using the BISON data, it was possible to show the percentage of species of concern that are under the influence of the restoration site. Species of concern are designated for a variety of reasons including being listed as a threatened or endangered species or because they show declining populations or other signs of stress. Among the species of concern that were evaluated, the roseate tern, the piping plover, and the least tern (interior population) are all federally endangered. The common tern is listed as endangered by several states. The red knot is currently listed as a candidate endangered species and has been documented to be in steep decline for the last decade. The prevailing hypothesis is that the decline in the red knot is tied to a similar decline in the horseshoe crab, on whose eggs they feed. The horseshoe crab is also not currently listed as an endangered species but has had declining populations for the last 40 yr.

*Conservation Priority*

An increasing number of data sets are available to assess conservation importance by location (Landscope America 2013). One dataset was selected to demonstrate the type of metrics that can be derived from such data.

The Cape Charles site falls within the highest ranked zone of the Coastal Virginia Ecological Value Assessment (VEVA) dataset (Virginia Dept. of

Environmental Quality 2011), which is one of the inputs to the Chesapeake Landscape database. The VEVA dataset combines scientific data and best professional judgment to rank terrestrial and aquatic areas on a 1-to-5 scale of ecological value, with 5 representing the highest conservation priority. A GIS analysis of a conservation priority dataset with a broad regional focus revealed that approximately one-fourth of the new beach is considered to be of “high opportunity” or Rank 3. The Priority Wildlife Diversity Conservation Areas (PWDCA) dataset was created by the Virginia Department of Game and Inland Fisheries (VDGIF) to identify areas important to conservation of nongame wildlife. Because the beach has a long linear shape, the project’s erosion control of the beach offers protection to a long stretch of adjacent inland area, the majority of which (44 acres) is classified as Rank 4 or “very high opportunity.”

#### Climate regulation

Coastal wetland ecosystems have a large capacity to store carbon in organic-rich saline soils. Three systems can be quantified as carbon sinks, including salt marsh, mangroves, and seagrasses (Pendleton et al. 2012). None of the three sites include mangroves or seagrasses. The Jamaica Bay project includes salt marsh restoration and warrants greater attention with regards to carbon sequestration.

For these sites, it is assumed that the annual carbon accretion rate in salt marsh systems is related solely to soil accretion and the carbon content of the accreted soils. In other words, the carbon in above-ground biomass that goes into long-term storage is assumed to be collected in accreting soil. Salt marsh sediment accretion rates are linked with sea level rise, and soil volume is roughly equivalent with marsh elevation (Kirwan and Mudd 2012). Multiple studies suggest that sediment accretion rates will likely increase and keep pace with sea level rise, as long as the rise occurs at a moderate level (Kirwan and Mudd 2012). However, large changes in relative sea level (i.e., from the combination of eustatic sea level rise and marsh subsidence) can result in marsh die-off and peat collapse (DeLaune and White 2011), thus lowering the rate of carbon sequestration. In addition, a warmer climate may result in higher rates of decay leading to lower rates of carbon export to marsh sediments (Kirwan and Blum 2011; Kirwan and Mudd 2012).

Chmura et al. (2003) conducted the first review of all available literature relating to carbon storage in tidal saline wetlands. An updated review was completed in 2011 and is available online (Sifleet et al. 2011). The analysis uses an updated data set that was provided in December 2012 to the Commission for Environmental Cooperation and that focused only on North America (Sifleet 2013[1]). When data were limited to sites along the U.S. Atlantic Coast and north of Florida, the database included 42 observations of annual net carbon sequestration rates. The values range from 0.3 to 5.9 tons of $CO_2$e/acre/yr. The mean value of 1.78 was used to approximate the carbon sequestration rate of the Jamaica Bay restored salt marshes. Area values were collected from the Jamaica Bay Restoration Project Fact Sheet from USACE.

### Value of $CO_2$ sequestration

An estimate was made of the amount of Carbon Sequestration Rates at the Jamaica Bay Project Sites based on a total area of 161 acres and an average annual carbon sequestration of 287 tons $CO_2$e/yr-1. To express greenhouse gases (GHG) and carbon-related ecosystem goods and services in monetary terms, consideration was made of a range of values based on estimates of the marginal social cost of carbon sequestered. An amount of $47/metric ton of carbon (2012 dollars) was used as a central value based on published results (Tol 2005, 2008; IPCC 2006). Following methods in Wainger et al. (2013), sensitivity of the results was considered by applying a low-end estimate of $27/metric ton of carbon and a high estimate of $97/metric ton—that corresponded broadly with the range of recommended values by the Interagency Working Group on Social Cost of Carbon (2010). By applying the unit dollar values to the net sequestration estimates, there was derived an estimate of average annual total value for the carbon sequestered at Jamaica Bay of $13,503 (2013 dollars).

## Results

Table 48 through Table 50 document the results for Jamaica Bay, Cape May Meadows, and Cape Charles South (respectively). As described earlier, these results are preliminary and based on incomplete datasets and knowledge for some services. The values were meant to demonstrate approaches and quality of available data while revealing gaps in data and knowledge that should be pursued in future efforts to quantify and value ecosystem goods and services in the region.

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[1] Personal Communication. S. D. Sifleet, Policy Research Associate, Nicholas Institute for Environmental Policy Solutions, Duke University, July 2013.

Table 48. Results for Jamaica Bay. [1]

| Ecosystem Service | Biophysical Change Due to Project | Per-Unit Value | Market Size | Benefit Metric |
|---|---|---|---|---|
| Property protection | Was not measurable from available data | | | Total value of property protection as estimated in project planning |
| Critical infrastructure | 161.4 acres of islands added. Horizontal fetch to the bridge reduced 54% and 64% when wind comes from the W or SW | 6.2 miles additional travel distance (if bridge damaged); 9 min of additional travel time / commuter (nonrush) and 18 min (rush) | Travelers using Cross Bay Bridge = 20,093 travelers per day | 4,000 hr total commuting time saved[2]/day of bridge closure avoided |
| Property value enhancement | n/a | | | |
| Recreational beach use | n/a | | | |
| Recreational bird watching and wildlife watching | 161.4 additional marsh acres | Change in consumer surplus due to increased marsh area $76.34 * 7% = $5.34/user day | 43,000 user days annually | $229,620 annual consumer surplus from wildlife watching |
| Ecosystem diversity | 124 acres of Northern Atlantic Coastal Plain Dune and Swale added | | | 124 acres area of rare ecosystem added; 0.19% of ecoregion represented in project |
| Terrestrial species diversity | | | | 25 species of concern present near site; 86% of species of concern represented |
| Conservation priority | n/a | | | |
| Climate regulation and risk reduction | 287 metric tons $CO_2e$ sequestered per year (1.78 metric tons $CO_2e$/acre salt marsh) | $27–$97/metric ton (2012 dollars) | | $7,800–$27,900 total annual value of carbon sequestered |

[1] Benefits were derived on an annual basis.

[2] Commuting time can be converted to a monetary value by using average wage rate for the area. Commuting time is typically valued at 100% or 33% of average wage rates.

Table 49. Results for Cape May Meadows. [1]

| Ecosystem Service | Biophysical Change Due to Project | Per-Unit Value | Market Size | Benefit Metric |
|---|---|---|---|---|
| Property protection | Was not measurable from available data | | | |
| Critical infrastructure | n/a | | | |
| Property value enhancement | Beach width enhancement = 15 ft | 0.3% of home value | Property within 0.5 mile of beach<br>$574,554,000 | $1,723,662 property value enhancement due to project |
| Recreational bird watching | | Change in consumer surplus due to increased marsh area $76.34 * 7% = $5.34 | 45,000 annual user days (GIS analysis) or<br>100,000 annual visits (USACE estimate) | $240,300–$534,000 annual consumer surplus increase |
| Recreational beach use | 15 ft/yr protected | Change in consumer surplus due to increased beach width:<br>($49.14 * 0.078) = $3.83/user day | 300,000 user days annually | $1,149,000 annual consumer surplus increase due to project |
| Ecosystem diversity | 1.33 acres of Atlantic Coastal Plain Southern Dune and Maritime Grassland | | | 1.33 acres of rare ecosystem added |
| Terrestrial species diversity | n/a | | | |
| Conservation priority | n/a | | | |
| Climate regulation and risk reduction | n/a | | | |

[1] Benefits were derived on an annual basis.

Table 50. Results for Cape Charles South. [1]

| Ecosystem Service | Biophysical Change Due to Project | Per-Unit Value | Market Size | Benefit Metric |
|---|---|---|---|---|
| Property protection | Was not measurable from available data | | | |
| Critical infrastructure | n/a | | | |
| Property value enhancement | 17 ft of beach width added | 0.3% of home value | Property adjacent<br>Property within 0.5 mile of beach.<br>Cape Charles = $89,248,000 | $2,677,440 property value enhancement due to project |
| Recreational bird watching | n/a | | | |
| Recreational beach use | 17 ft of beach width added | Change in consumer surplus due to increased beach width:<br>($49.14 * 0.078) = $3.83/user day | 6,000 annual user days | $22,980 annual increase in consumer surplus |
| Ecosystem diversity | 1.78 acres of Atlantic Coastal Plain Northern Fresh and Oligohaline Tidal Marsh protected by project | | | 1.78 acres of rare ecosystem protected |
| Terrestrial species diversity | 2 acres of beach added relative to preproject condition | | | 0.5-acre increase in “High Opportunity” (medium priority) wildlife conservation area;<br>2 acres of endangered species habitat added |
| Conservation priority | 2 acres of beach added relative to preproject condition—habitat area for federally endangered tiger beetle | | | 44 acres of high conservation priorities protected (Landscape);<br>2-acre increase in area of highest priority for Chesapeake Bay Restoration (VEVA) |
| Climate regulation and risk reduction | n/a | | | |

[1] Benefits were derived on an annual basis.

## Conclusions and recommendations

The results of this postproject analysis demonstrate that a variety of ecosystem service changes at USACE project sites involving the creation or enhancement of ecosystem features can be reasonably well quantified and/or monetized, with current data and understanding. Property value enhancements and recreational benefits are among the easiest benefits to monetize. However, some of the services that are of greatest relevance to USACE mission goals are not easy to monetize, particularly since available economic literature is dominated by efforts to value effects on charismatic endangered species. Ecological research suggests that sustainability goals are not fully encompassed by protecting rare species. Therefore, to provide a broader assessment of services under the Ecosystem Sustainability category, a quantitative metrics was developed using a variety of new georeferenced databases that capture occurrences of a broad range of species of concern, assess rarity by ecosystem, and represent conservation priorities from the perspective of international NGO or local constituencies.

Among the services that could be monetized, the highest values were estimated for property value enhancement due to beach width enhancement, where this service was present. Recreational visitation for wildlife watching had the next highest value, followed by carbon sequestration, which is a proxy measure of the value of reducing risks of climate change. Some additional services, such as protection of critical infrastructure, could be monetized with further analysis but were represented as quantitative metrics that suggested benefits (e.g., hours of commuting time saved).

For the nonmonetary metrics, there were found many useful datasets to inform the analysis, but it was also found difficult to develop consistent ecosystem sustainability metrics across all sites because data availability and qualities varied. The BISON dataset proved time consuming to use but with more time could be used to represent occurrences of species of concern at all sites. The national georeferenced databases worked particularly well at Jamaica Bay because the project was restoring the types of ecosystems that support the majority of State species of concern (86%) and because it added substantial acreage (124 acres) of rare ecosystems. The added acres represented a 0.19% increase in acreage within the ecoregion, which is a notable increase given the large area of the ecoregion. The project at Cape May meadows also restored ecosystems considered rare by the USEPA EnviroAtlas database, but more work could be done to capture the value of restoring 1.33 acres of rare habitat in this developed landscape. For the Cape Charles South site, advantage was taken of the two recently released datasets that mapped conservation priorities in Virginia or the Chesapeake Region to reveal the relatively high importance this site has to local and national stakeholders.

Some important caveats to these results are that some values shown in Tables 48 to 50 are based on assumptions or data that would require refinement if used in project planning or similar decision contexts. For this effort, an estimate was made of relationships necessary to value some services based on limited data, but only when more accurate numbers appeared within reach. In other words, if the research team felt that further research could generate a supportable number, a placeholder value to show the potential for the service to be quantified or valued was used. Further, it is clear that the emerging national databases have great value for consistently comparing different project sites. However, it is also clear that the amount of data in these national databases varies by state or region and that the coarse data scales can miss important site details. Therefore, local data will be better able to inform specific conditions in or near sites, and assessments based on national data should be used with these limitations in mind.

Ecosystem goods and services analyses to assess the performance of NNBF projects could be improved in two main ways. First, for postproject analysis, better data are needed for comparing conditions with and without the project and for assessing performance before and after extreme events such as Hurricane Sandy. Although much additional data were collected to document effects of Hurricane Sandy, the data were not ideal for conducting the ecosystem goods and services assessment. A simple example is that some satellite imagery taken to represent the after conditions at Jamaica Bay restored islands were taken while the sites were still under water. Generally, capturing outcomes in dynamic ecosystems requires multiple observations in time and space. Google Earth imagery was used to meet some of this need for long-term, spatially detailed data, but data shortfalls remained.

The second area of improvement is the need for additional studies on the effectiveness of restoration approaches and their economic effects. It was found that some high-quality studies met these needs, but additional studies are needed to be able to build general understanding or models of how magnitude of responses vary by location. For example, more economic studies of the value of beach width enhancement would allow a creation of a benefit transfer function that would capture how value varies by demographic characteristics, location variables, and beach width. While additional studies are a long-term goal, much can be done in the short term to organize existing information to enhance its accessibility to USACE analysts and research partners. Examples include building web portals to existing databases, creating GIS tools to simplify analyses, and creating databases of relevant economic studies.

Ecosystem restoration projects regularly employ NNBF to meet their goals and objectives. Long-term sustainability is dependent on monitoring and adaptive management to ensure coastal resilience and system-wide coastal protection from flooding. These case studies demonstrate that the tools are available to quantify a broad suite of benefits generated by these types of projects for monitoring purposes. Making clear linkages between restoration and quality of life outcomes promotes the social and political commitments necessary for successful restoration that addresses community needs and concerns (Cairns 2000).

# 8 NNBF Policy Challenges and Opportunities

## Introduction

Following Hurricane Sandy striking the northeast region of the United States in 2012, the USACE was authorized to conduct the NACCS under Public Law 113-2. Public Law 113-2 required USACE to identify institutional and other barriers to reducing coastal risks. The NACCS main report presents a general overview of the policy and institutional barriers across the North Atlantic region (USACE 2015). In this chapter, there is an exploration of the policy and institutional barriers associated with the use of NNBF to reduce risk and increase coastal resilience. NNBF may include dunes and beaches, vegetated features, oysters and coral reefs, barrier islands, and maritime forests/shrub communities. These features are sometimes referred to as green infrastructure.

To achieve robust implementation of NNBF, there are many policy challenges and institutional barriers that need to be addressed. These needs were also recognized in Public Law 113-2 and in policy issues, and barriers that could hinder the ability to provide coastal storm risk management and increased community resilience are further discussed. Many government agencies and other organizations have differing, sometimes conflicting, roles and authorities along the coastline and related to NNBF. For NNBF to be employed as a major component of a resilient coastal strategy, these differences need to be explored.

The section that follows provides further detail on the challenges and potential opportunities related to NNBF discerned from a November 2013 meeting. Through workshops, webinars, and other means of coordination, the USACE NNBF team will continue to coordinate with Federal, State, local, and nongovernmental stakeholders to identify NNBF-related policy challenges and opportunities to pursue.

## Approach

To inform the efforts of the USACE NNBF team and to provide feedback to the NACCS, a workshop was planned entitled Policy Challenges to Using Nature-Based & Green Coastal Features for Risk Reduction and

Resiliency. It was held on 20 November 2013 at the USACE Institute for Water Resources in Alexandria, VA. The information presented in this chapter is derived from this workshop. A thorough policy analysis is presented in the NACCS main report (USACE 2015).

The purpose of this workshop was to assess the policy challenges that exist that may impair the implementation and use of NNBF to create coastal resilience and reduce coastal risk. Specifically, there was sought the identification of the policy challenges that exist within and among Federal agencies that have a role in the implementation of these features. Thirty-four individuals from the Bureau of Ocean Energy Management, CDM Smith, the Department of Homeland Security, the U.S. Army Corps of Engineers, the U.S. Environmental Protection Agency, the U.S. Fish and Wildlife Service, the U.S. Forest Service, the U.S. Geological Survey, HR Wallingford, the National Park Service, the National Ocean and Atmospheric Administration, the National Wildlife Federation, and the Water Institute of the Gulf were present.

Workshop attendees were divided into four breakout groups with approximately nine people in each group. Group assignments were created to ensure a diverse organizational representation in each breakout group. Group participants were asked to record their thoughts on the following four questions onto sheets of paper. These sheets were collected at the end of the day.

- **Question #1:** What do you believe are the most significant policy challenges related to the implementation of NNBF? What changes in existing policy would have the greatest positive influence on the implementation of NNBF?
- **Question #2:** What actions could be taken to improve the coordination needed among Federal, State, and local agencies in order to implement NNBF? What actions could be taken within your own organization to expand opportunities for the implementation of NNBF?
- **Question #3:** What uncertainties or information gaps impede decision-making for NNBF projects? How can progress be made on implementing NNBF in view of these uncertainties? How do existing policies support or impede the application of adaptive management to NNBF projects?

- **Question #4:** How can communication across the organizations interested in NNBF (including governmental and nongovernmental organizations) be improved?

After participants had time to silently record their answers, breakout session leaders held facilitated discussions with participants. Each breakout group presented its thoughts and key findings from this discussion in the afternoon plenary session. A facilitated discussion was then had with all attendees. Following the completion of the workshop, participants' breakout session sheets and presentations were analyzed, and key findings were summarized. These findings are listed in the following. It is important to emphasize that many of the findings are opinions of many field practitioners, and as such, may not be true.

## Outcomes

### Theme 1: Science, engineering, and technology

Policy Challenges: Knowledge and data deficiencies pose significant challenges for the development of guidance and policies for the evaluation and implementation of NNBF. For instance, there are numerous uncertainties regarding the performance, timing, and scale of NNBF needed to provide flood risk reduction and decrease storm damages. NNBF are typically more responsive to storms, and the risk reduction services provided often depend on local conditions. More information is needed on this variation in NNBF performance to effectively compare and integrate NNBF with structural and nonstructural measures. The lifecycle costs needed to operate and maintain NNBF are also uncertain. Finally, many threats including sea level rise and climate change also have unknown effects on the performance of NNBF.

Although it is known that NNBF can provide a wide range of ecosystem goods and services. The kinds of ecosystem goods and services and the extent of these goods and services provided by different NNBF are generally poorly understood. Meeting participants stated that the most important change that needed to occur to increase the use of NNBF in the future was the need to quantify ecosystem goods and services. It is also difficult to describe and properly quantify the secondary and tertiary benefits of NNBF. There are perceptions that benefits that are more difficult to monetize are less reliable in their performance or in decision criteria. The means to perform full valuations of the complete range of ecosystem goods and services provided by NNBF are needed. Policies to inform cost-benefit valuations of the ecosystem goods and services provided by NNBF are also needed for project prioritization and agency budgeting. There is a need for policies regarding the use of nonmonetized benefits, as well as direction on how to monetize benefits provided by NNBF.

There are a number of data needs to address uncertainties associated with NNBF. Baseline condition data are often lacking as are basic production functions for linking ecosystems to goods and services outputs. The most pressing need is for improved process modeling and engineering tools that are informed by data collection and experimental studies. There is also a need for improved risk communication methods and visualization tools to better communicate data and information to stakeholders and the public. Enhanced sea level rise and storm models are necessary to improve the project design of NNBF.

Conducting adaptive management on existing and future NNBF remains an ongoing problem as well. Adaptive management can improve knowledge about NNBF and the performance of these features over time, as well as improve their use. Obtaining funding for adaptive management is an ongoing challenge for Federal agencies. Further, while the National Environmental Protection Act (NEPA) is an opportunity to improve project design and gather stakeholder input, it frequently poses a challenge to implementing timely adaptive strategies. Adaptive management can be accommodated through NEPA with a tiered or programmatic approach. However, many interviewees indicated that this approach is not always taken, and as such, meeting NEPA requirements can pose challenges to implementing adaptive management. In municipalities, existing policies hamper the application of adaptive management as municipalities may be penalized for reporting results that are below expectations.

**Opportunities for Action:** NNBF demonstration projects are needed to provide opportunities for experimentation and to learn the best practices and uses of NNBF and resolve some of the uncertainties. The lack of successful examples of NNBF was the chief barrier identified to integrating NNBF with nonstructural and structural measures to reduce risk and increase resilience. As implementation and monitoring funds for these types of projects are typically lacking, it will likely be necessary to develop innovative policies and procedures to share resources among organizations and agencies. The funds and ability to conduct long-term project monitoring is another extremely critical, and most of the time, unmet need.

Development of case studies, best practices, and guidance documents are needed to demonstrate what types of ecosystem goods and services can be expected from NNBF and to quantify their value. Federal agencies, NGO, and academia are working to address this information gap and explore how ecosystem goods and services can be used in project planning. Additionally, it is important to create risk and resilience performance metrics for NNBF to consider processes and outputs across a range of scales, including at the scale of the overall system. The development and use of a consistent set of metrics could also facilitate efforts to effectively monetize ecosystem goods and services and incorporate consideration of them into project cost-benefit analyses.

There is also the need and opportunity to more effectively and transparently share information between the government, stakeholders, and general public about NNBF. This could be helped with a wiki-type repository of knowledge adjacent to a data portal that could include contact information of people involved in NNBF efforts in different organizations and agencies.

#### Theme 2: Communication and outreach

**Policy Challenges:** There is a need for better communication and information sharing on NNBF. NNBF remain a nebulous concept for many, including decision makers and others with the responsibility to implement coastal projects. Common definitions for NNBF would enable interested parties to communicate more effectively about these features. A greater understanding of the costs and benefits of NNBF is needed, particularly, in terms of how these features can increase the resilience of a community, ecosystem, or local economy. Clear and concise language about the benefits of NNBF is needed to be able to compare these features to the more traditional structural methods that have been implemented in the past.

Communication needs to be improved at multiple levels including among and within Federal, State, and local levels of government. Outreach and communication should also target private interests and homeowners who determine the type of project to implement on their land.

**Opportunities for Action:** It would be helpful to develop a policy digest or similar document that would include relevant definitions of NNBF, as well as the authorities, roles and responsibilities of Federal, State, and local agencies that have jurisdiction or interest in the implementation of NNBF. This guidance should include direction on programs that have authorities or initiatives that relate to NNBF. This guidance could then improve decision-making by decision-makers.

Guidance documents and tools providing information on the use, implementation, and performance of NNBF could better inform private interests and landowners about NNBF options. These tools would have to answer practical questions such as the cost and maintenance requirements of NNBF solutions. Guidance for agencies with standard procedures for developing NNBF could also be helpful in increasing the implementation of these features. There is a need for greater information sharing on NNBF, and this gap could be addressed by webinars, conferences, public forums, and the development of an NNBF community-of-practice. Existing groups and meetings with similar interests should also be leveraged to learn more about NNBF and share knowledge on these features. A list of all the working groups which focus on NNBF-related issues should be created and their activities shared among the groups so that they can work together on common needs and share resources.

### Theme 3: Leadership and institutional coordination

**Policy Challenges:** Improved coordination among government agencies, academia, NGO, and others is needed to determine where NNBF could best be used to reduce risk throughout an entire region. NNBF are not practical in all instances, but a broad understanding and characterization of the landscape can facilitate their use. Land-use planning and zoning policies often do not encourage, and in some cases, limit, the use of NNBF. Informing local governments about the benefits of NNBF and working with them to institute policies that allow for NNBF while promoting resilient communities could alleviate this problem. The promotion of a holistic or integrated community strategy and decision-making framework would facilitate collaboration among communities on how to achieve resilience through measures that include NNBF.

As a matter of Federal policy, all USACE flood and coastal storm damage reduction projects require a cost-sharing partner, but aligning budgets and schedules for cost-sharing partnerships is an ongoing challenge. The use of

NNBF is heavily influenced by regulatory decisions; most projects that incorporate NNBF into project plans require decisions made by a variety of Federal and State regulatory agencies. Local agency planning often occurs without coordination with State and Federal regulatory agencies. Integration and coordination of planning and regulatory processes within and among local, State, and Federal agencies is an incredibly important need that would help inform planning and regulatory activities before all decisions and investments are finalized. Projects are often authorized and regulated on a case-by-case basis that precludes the development of comprehensive programmatic, regional, landscape, or system-focused projects. Additionally, there is a need for policies that support efficient coordination and decision making for NNBF projects that could impact wetlands, TES species, or essential fish habitat. Construction schedule restrictions related to environmental concerns (e.g., dredging windows) remain an ongoing concern and may restrict or preclude the implementation of NNBF solutions.

When a disaster occurs, emergency response and ensuring the safety of a community and its citizens is the top priority. After an emergency or natural disaster, there is an opportunity to reconsider the infrastructure previously established. Aid provided after emergencies should be delivered in a strategic way by implementing updated and more resilient solutions, including NNBF, as opposed to rebuilding to predisaster conditions. There are some authorities that restrict what can be built using emergency funds, and potential changes to these policies should be discussed. A gap in coordination among the emergency response, recovery, and mitigation communities is currently present that could be addressed to encourage the implementation of more resilient solutions following a disaster.

**Opportunities for Action:** Regional coordination is needed to identify the vulnerabilities, flood risk issues, and challenges within a region at a system scale and to come up with innovative solutions to resolve them. Improved coordination will also enable improved information exchange and the transfer of best practices. Regional organizations such as the NOAA Sea Grant State programs, USDA extension offices, and Silver Jackets (which brings together multiple State, Federal, tribal, and local agencies to learn from one another and apply their knowledge to reduce risk within their state) could be leveraged to address coordination issues. Public/private partnerships could also be established and used to decrease redundancies, link opportunities, and serve as a catalyst for comprehensive implementation of NNBF.

Incentivizing the use of NNBF in communities would help foster implementation of their use. FEMA's National Flood Insurance Program's (NFIP) Community Rating System (CRS) program is a voluntary incentive program that recognizes and encourages community floodplain management activities that exceed the minimum NFIP requirements. Flood insurance premium rates are discounted to reflect the reduced flood risk from community actions for which they earn credits. The CRS provides credit for designated open-space corridors, natural shoreline protection, and other areas that support native species, maintain natural ecological processes, and sustain air and water resources, and information on these credits should be shared and pursuit encouraged. NOAA's Coastal and Estuarine Land Conservation Program (CELCP) provides support for State and local governments to purchase coastal and estuarine lands that are important for ecological, recreational, historical, or aesthetic values. This land acquisition for ecological and community benefits could be modified to encourage the use of NNBF. Agencies can also work with municipalities on managed retreat strategies and the use of eminent domain in highly urbanized settings to protect vulnerable regions, reduce life loss, and increase the use of NNBF.

NOAA and other agencies have decision support and communication tools that could be more useful if they better incorporated NNBF. Through the activities of the Federal Interagency Floodplain Management Task Force (FIFM-TF) and those activities spurred from the Sandy Recovery Task Force Report, this need is being addressed. Through these groups and others, partnerships and funding could be leveraged to promote NNBF and resilient communities and to fund research of common interests that demonstrate the effectiveness and cost of NNBF.

There are a number of opportunities to promote the use of NNBF in planning, financing, and regulating projects. Incentives could be offered in the USACE cost sharing ratio if the use of NNBF is prioritized, although this may require congressional action to achieve. There are a number of potential solutions that would improve regulating NNBF. Programmatic regulatory consultation could facilitate the implementation of NNBF. Earlier coordination on timelines and schedules among the resource and planning agencies is especially needed. To achieve this robust coordination, guidance and policies need to be created that facilitate data sharing among agencies. The development of guidance documents and criteria that facilitate science-based decision-making could also assist regulatory agencies.

The emergency management, recovery, and mitigation practitioners have differing authorities and priorities for actions that can be pursued through the FIFM-TF and the Mitigation Framework Leadership Group. Increasing awareness among those who work on mitigation about Presidential Policy Directive Number 8 (particularly the National Response Framework and National Disaster Recovery Framework) would help improve the understanding of when and how NNBF could be implemented during recovery from a disaster. The use of NNBF could also be a major part of community hazard mitigation plans required by FEMA and/or floodplain management plans required by USACE. Development of a guidebook with information on NNBF that could be implemented during the recovery process should be shared with emergency managers and others working on disaster recovery across agencies and governments.

## Summary of opportunities for action

As enumerated previously, there are significant policy challenges for NNBF. These challenges can be addressed in a variety of ways by government agencies, NGO, and academia. The following is a summary of the opportunities to tackle these identified issues.

*Science, engineering, and technology*

1. Create NNBF demonstration projects and develop case studies of existing projects to learn the best practices and uses of NNBF.
2. Generate a compilation of information on the ecosystem goods and services provided by NNBF.
3. Develop risk and resilience performance metrics for NNBF.
4. Initiate a wiki-type repository of knowledge adjacent to a data portal that could include contact information of people involved in NNBF efforts in different organizations and agencies.

*Leadership and institutional coordination*

1. Improve regional coordination through existing mechanisms such as Silver Jackets, NOAA Sea Grant, and USDA extension offices.

2. Utilize public/private partnerships to implement NNBF.
3. Initiate the development of guidance and policies to achieve robust coordination and data sharing among resource and planning agencies.
4. Incorporate NNBF into existing decision support and communication tools.
5. Leverage partnerships and funding to promote NNBF in support of community resilience.
6. Develop a guidebook with information on NNBF that could be implemented during the recovery process following a disaster.

*Communication and outreach*

1. Develop a policy digest with relevant definitions of NNBF, as well as the authorities, roles, and responsibilities of Federal, State, and local agencies that have jurisdiction or interest in the implementation of NNBF.
2. Form an NNBF community-of-practice.
3. Develop guidance and tools for private interests and landowners with information on the use, implementation, and performance of NNBF.

# 9 The Path Forward

Coastal systems provide important social, economic, and ecological benefits to the nation. However, coasts are vulnerable to the influence of a combination of factors, including storms, changing climate, geological processes, and the pressures of ongoing development and urbanization (Woodruff et al. 2013). NNBF can help reduce coastal risks as a part of an integrated approach that draws together the full array of coastal features that contribute to enhancing coastal resilience (Temmerman et al. 2013; USACE 2013). By employing sound science and engineering practices, collaborating organizations will be able to identify timely opportunities, formulate and evaluate robust alternatives, and implement feasible approaches for making use of NNBF to enhance the resilience of the social, economic, and ecological systems along the coasts.

There are three overarching points that warrant consideration with respect to the path forward on NNBF. First, there are many organizations that have important, even necessary, contributions to make in advancing the use of NNBF to reduce flood risks while enhancing coastal resilience. Federal, State, and local government agencies encompass a broad range of authorities and mandates that are germane to implementing NNBF. Private organizations, including NGO which have been building and monitoring NNBF in coastal environments, represent potential partners in such projects as well as sources of innovation in their development. Organizations representing cross sections of the science and engineering community contributing technical knowledge and experience will be important sources of research activity needed to reduce key uncertainties related to the implementation of NNBF.

The second overarching issue is the need to acknowledge that an effort which intends to move, or advance, practice will require people and organizations to make changes in the way they think about problems and pursue solutions to those problems. In respect to NNBF, these changes could take the form of adjustments in policy and law, and cultural and social practices, as well as relevant science and engineering practice. There are different constraints or impediments to change in these various aspects of the NNBF opportunity, as well as different time scales over which the impediments can be overcome.

The third point is that there is a broad interface between the policy and technical aspects of NNBF. For orderly progress to be made, activities focused on policy and technical development should be coordinated so that advancements can be made on both fronts, simultaneously. There are many actions that can be taken that would help advance the use of NNBF. A list of these actions would include

- forming a community-of-practice that would draw from the diversity of organizations interested in contributing to NNBF practices
- developing a policy digest that would include a listing and description of relevant authorities, roles, and responsibilities for Federal, State, and local governments as well as other organizations
- compiling information and data on ecosystem goods and services provided by NNBF
- strategically developing pilot studies to test the design, construction, and adaptive management of NNBF measures
- addressing uncertainties concerning the performance of NNBF over time under a range of appropriate environmental and physical conditions
- developing technical guidance to define good practice in evaluating, designing, constructing, monitoring, and maintaining NNBF.

As progress is made on these and other actions across the many organizations contributing to the use of NNBF, implementation of the full array of measures available will reduce the risks and enhance the resilience of coastal systems.

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# Appendix A: NNBF Mapping of the NACCS Study Area

This appendix provides detailed maps of the NACCS study area, indicating the location and types of existing NNBF across the region. The USACE Baltimore District (CENAB) used pre-processed GIS-based data obtained from the original source organization or the CENAB NACCS server to generate these products (Table 51).

Table 51. GIS source layers and geoprocessing descriptions used to develop the study's NNBF mapping products.

| GIS Feature Name | Source | Geoprocessing protocols |
|---|---|---|
| NHD_Ocean_Bay_1500ft _Buffer | USGS National Hydrography Dataset | Select item FType = 445 (SeaOcean) Or FType = 312 (BayInlet) . The source data did not encompass the shoreline features, so a 1500ft buffer was created in order to capture the shoreline. |
| NACCS_Shoreline_Type | NACCS Shoreline | Selections were made from the original ESI ITEM. |
| CCAP20_Poly | NOAA Coastal Change Analysis Program (CCAP) Land Cover Atlas | The rasters for each state were merged then clipped to the NACCS Study Limits and converted to polygons based on the raster's VALUE item. A value of 20 (Bare Earth) was then extracted to produce this dataset. |
| GAP_Dune | USGS Gap Analysis Program land Cover Data | Reclassified to obtain from Level3 item values of 7503 (Atlantic Coastal Plain Southern Dune and Maritime Grassland) and 7507 (Northern Atlantic Coastal Plain Dune and Swale). The reclassified raster was then converted to polygons. This feature set was used in the Beach Restoration Measure selection. |

The mapping was organized by NACCS planning reach (Figure 48) and generated on a site-by-site basis (Figure 49 through Figure 67).

Figure 48. NACCS planning reaches (USACE 2015).

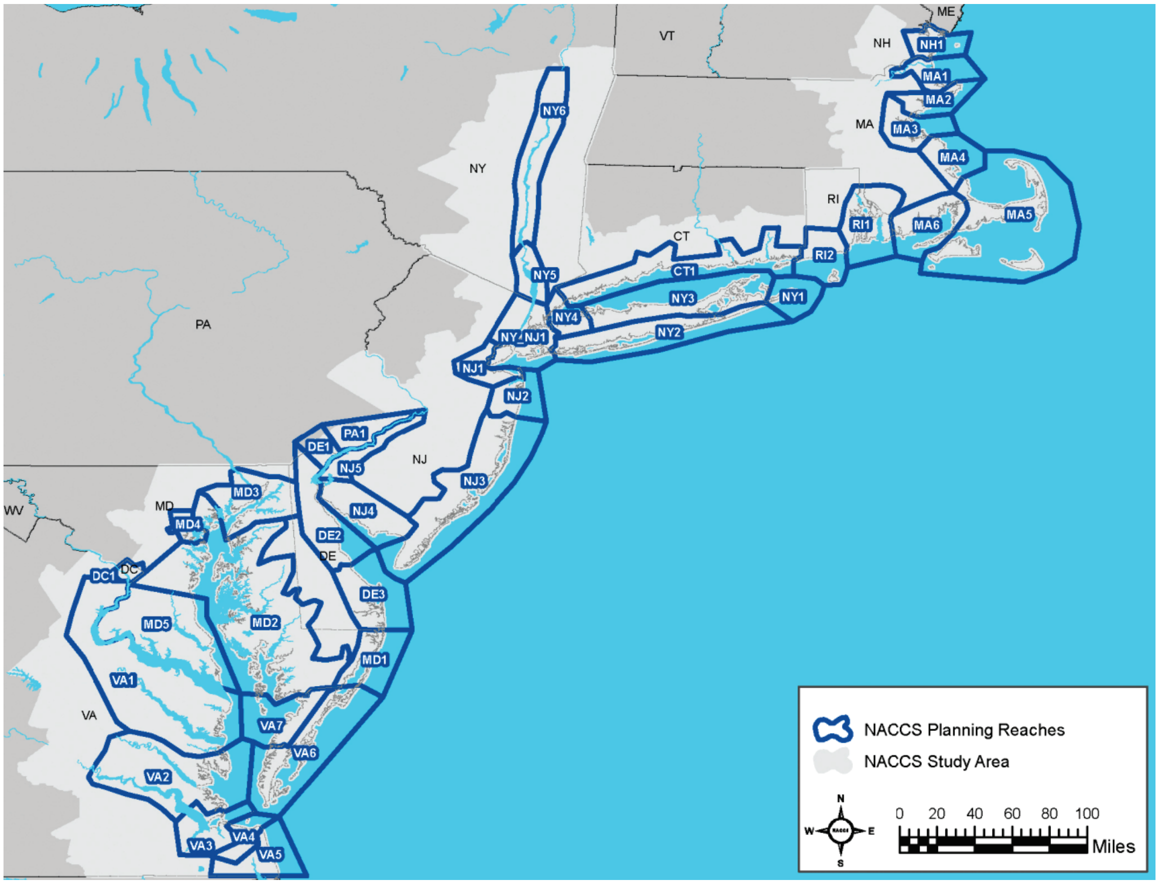


Figure 49. NNBF within NACCS planning reaches NH1 and MA1.

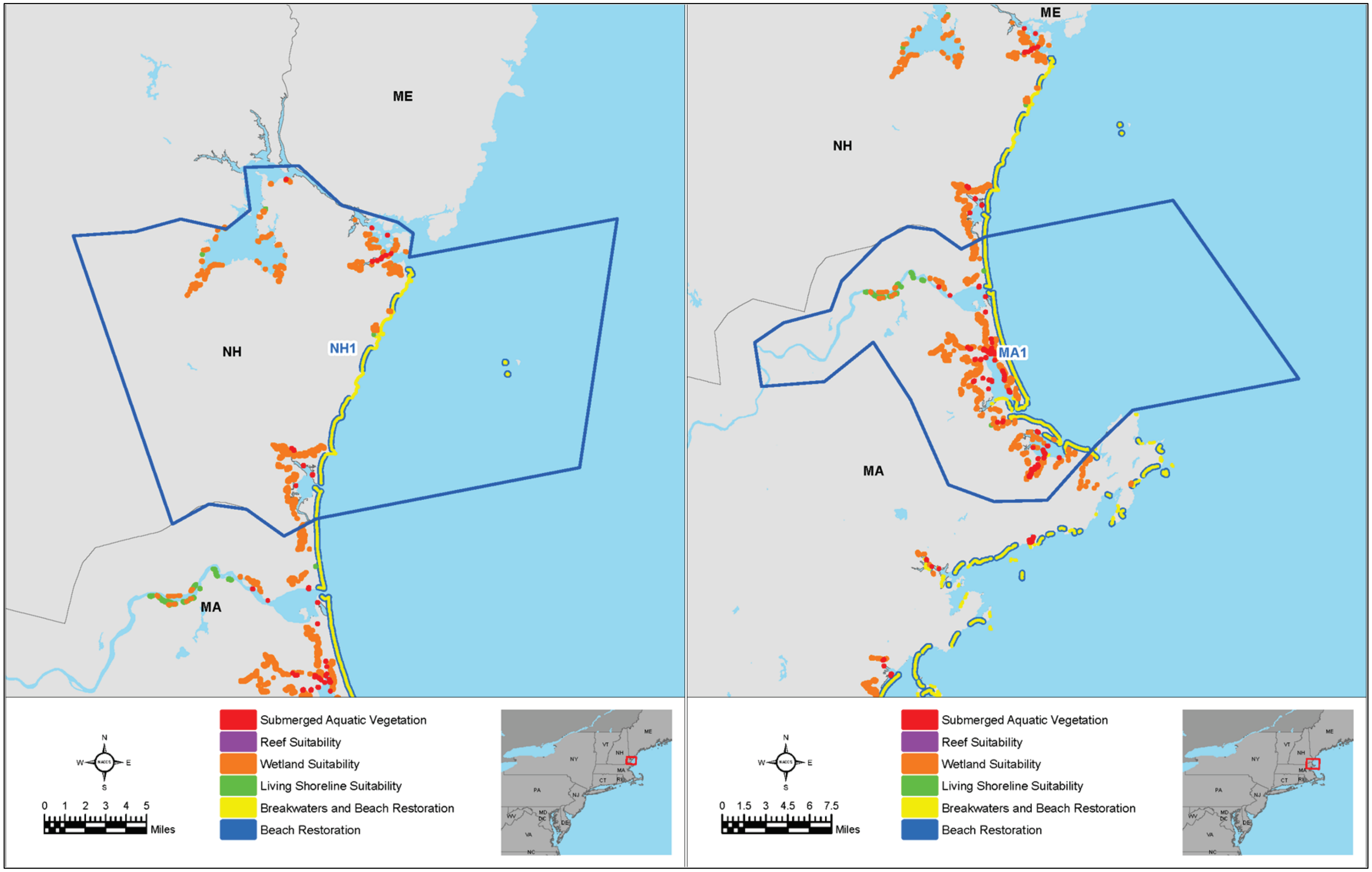


Figure 50. NNBF within NACCS planning reaches MA2 and MA3.

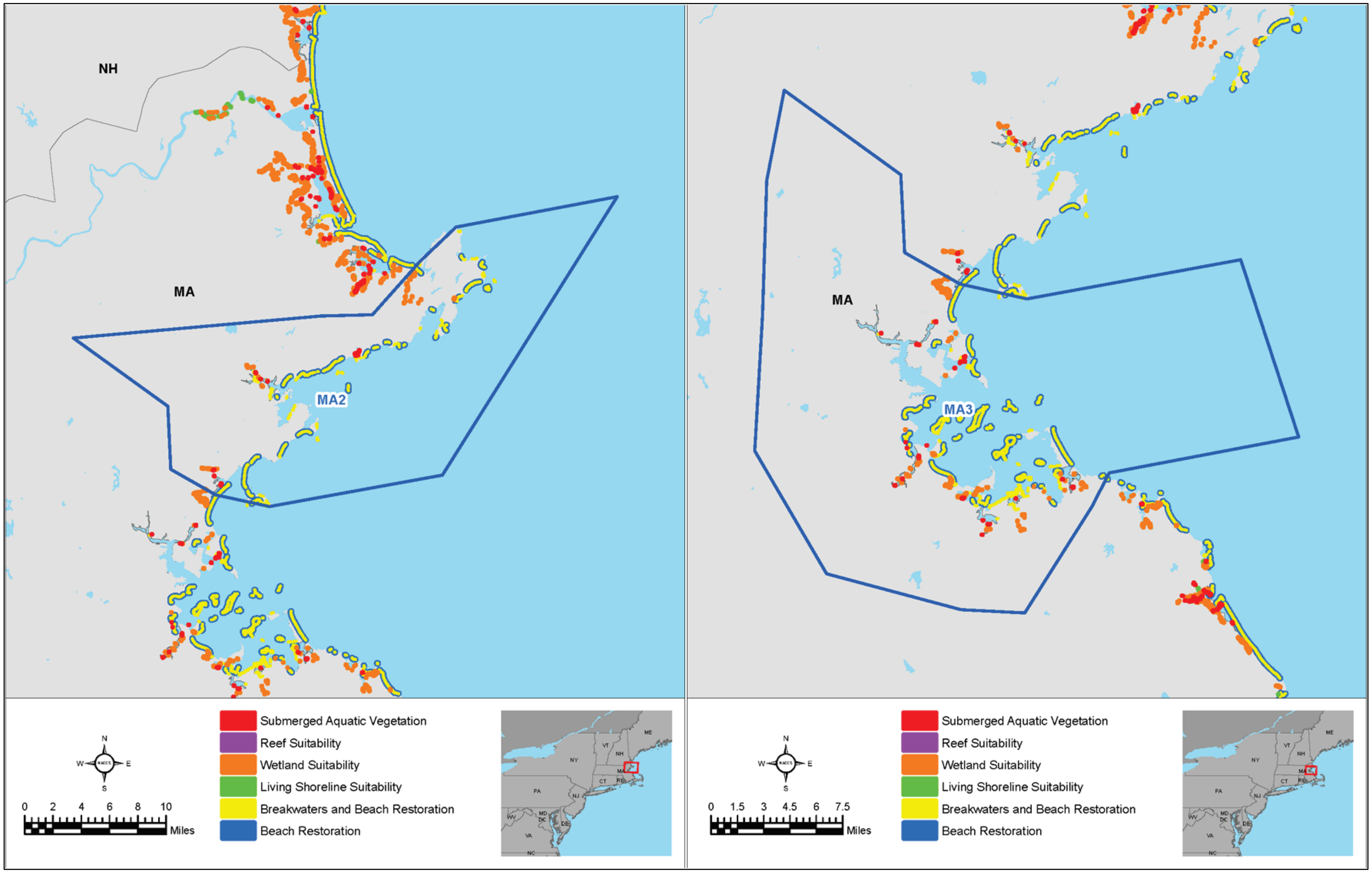


Figure 51. NNBF within NACCS planning reaches MA4 and MA5.

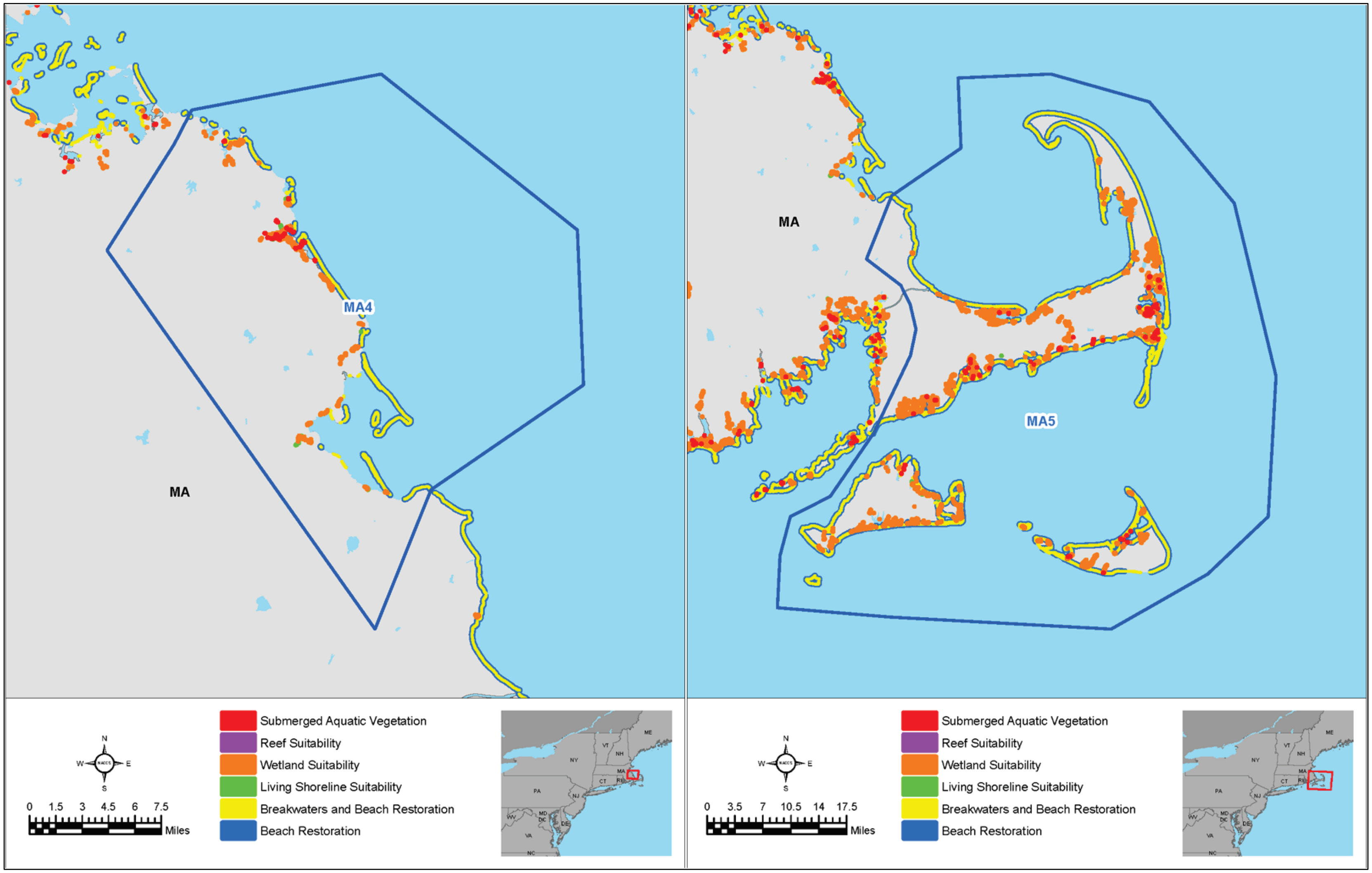


Figure 52. NNBF within NACCS planning reaches MA6 and RI1.

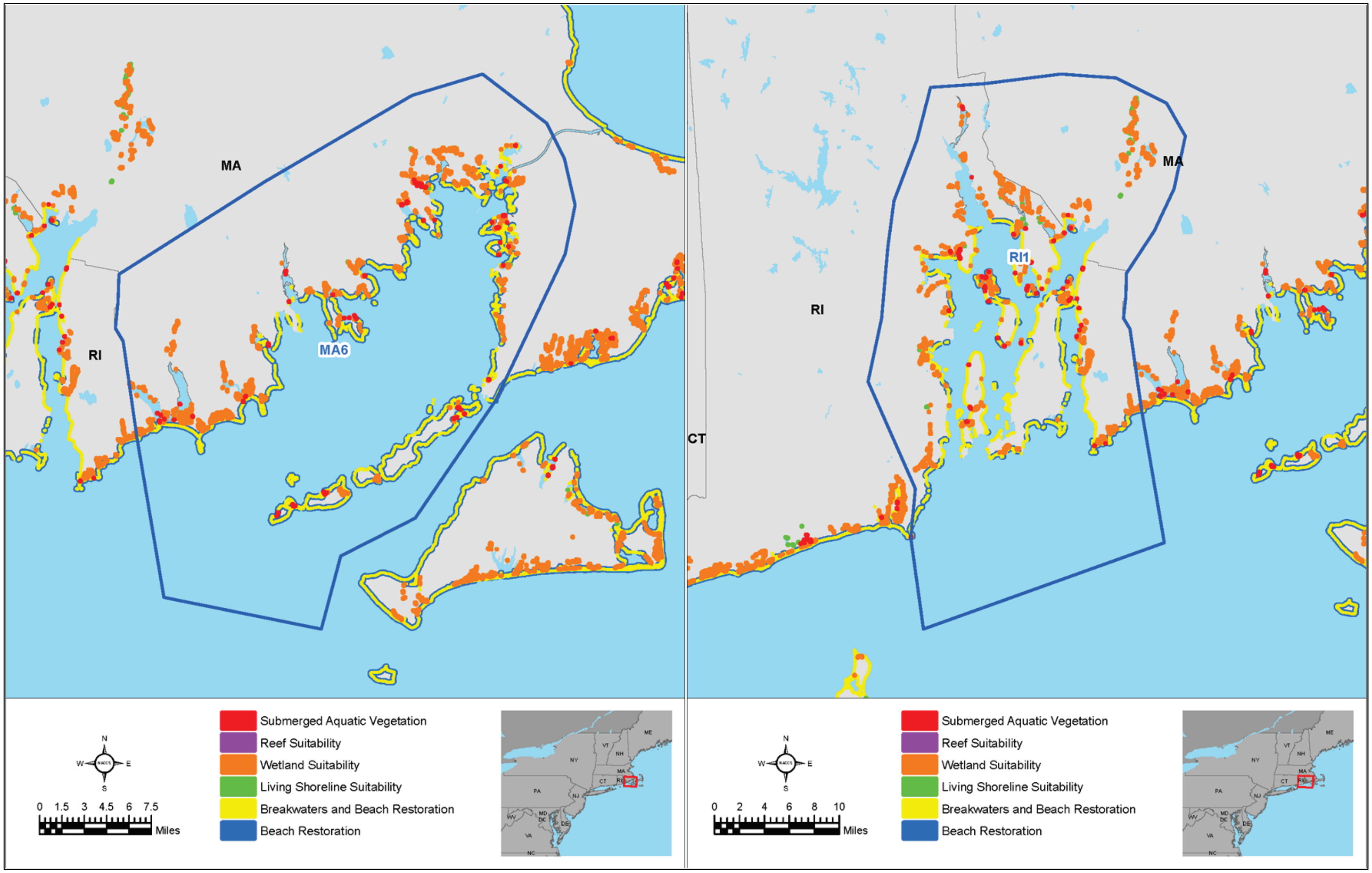


Figure 53. NNBF within NACCS planning reaches RI2 and NY1.

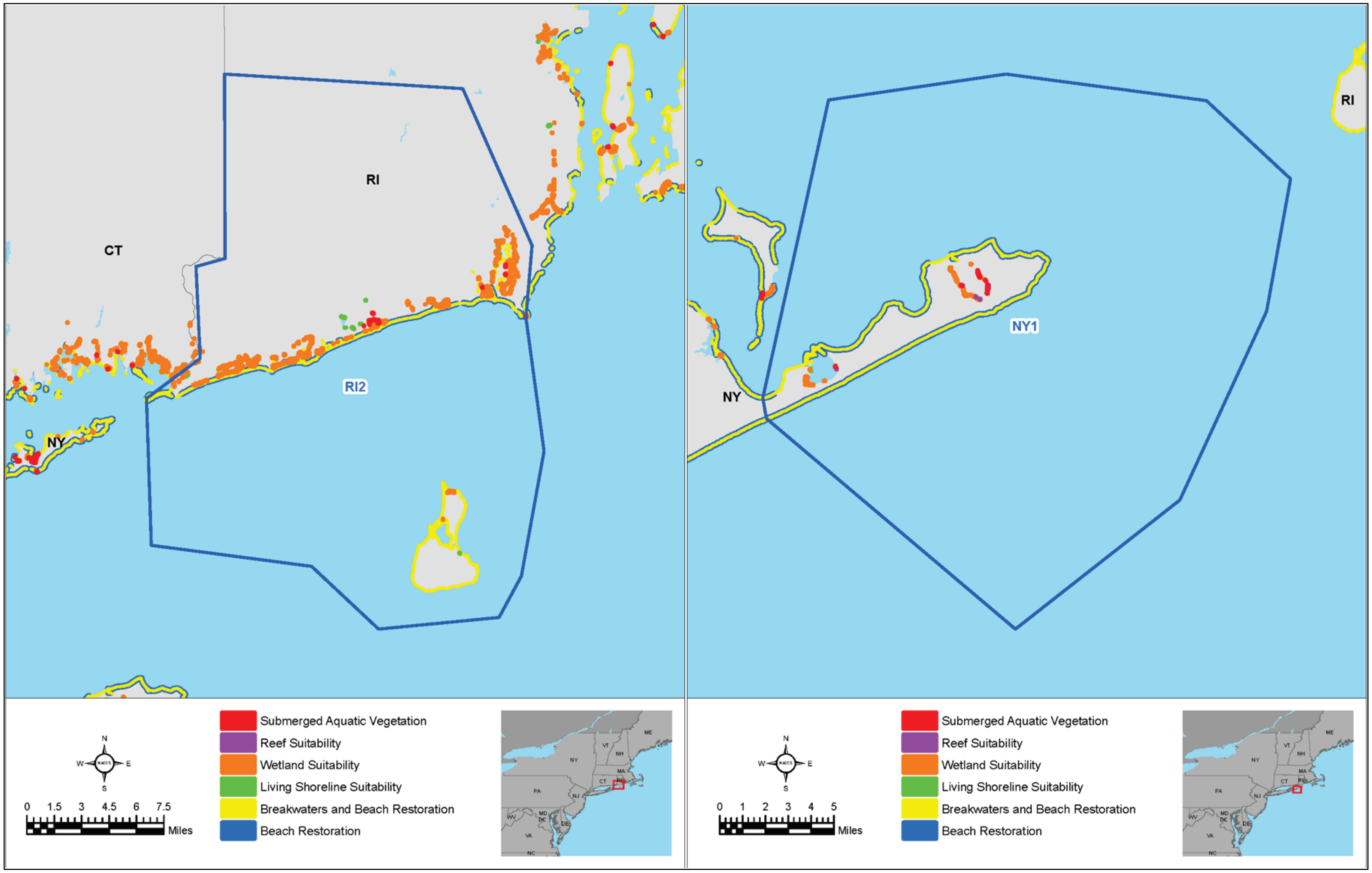


Figure 54. NNBF within NACCS planning reaches NY2 and NY3.

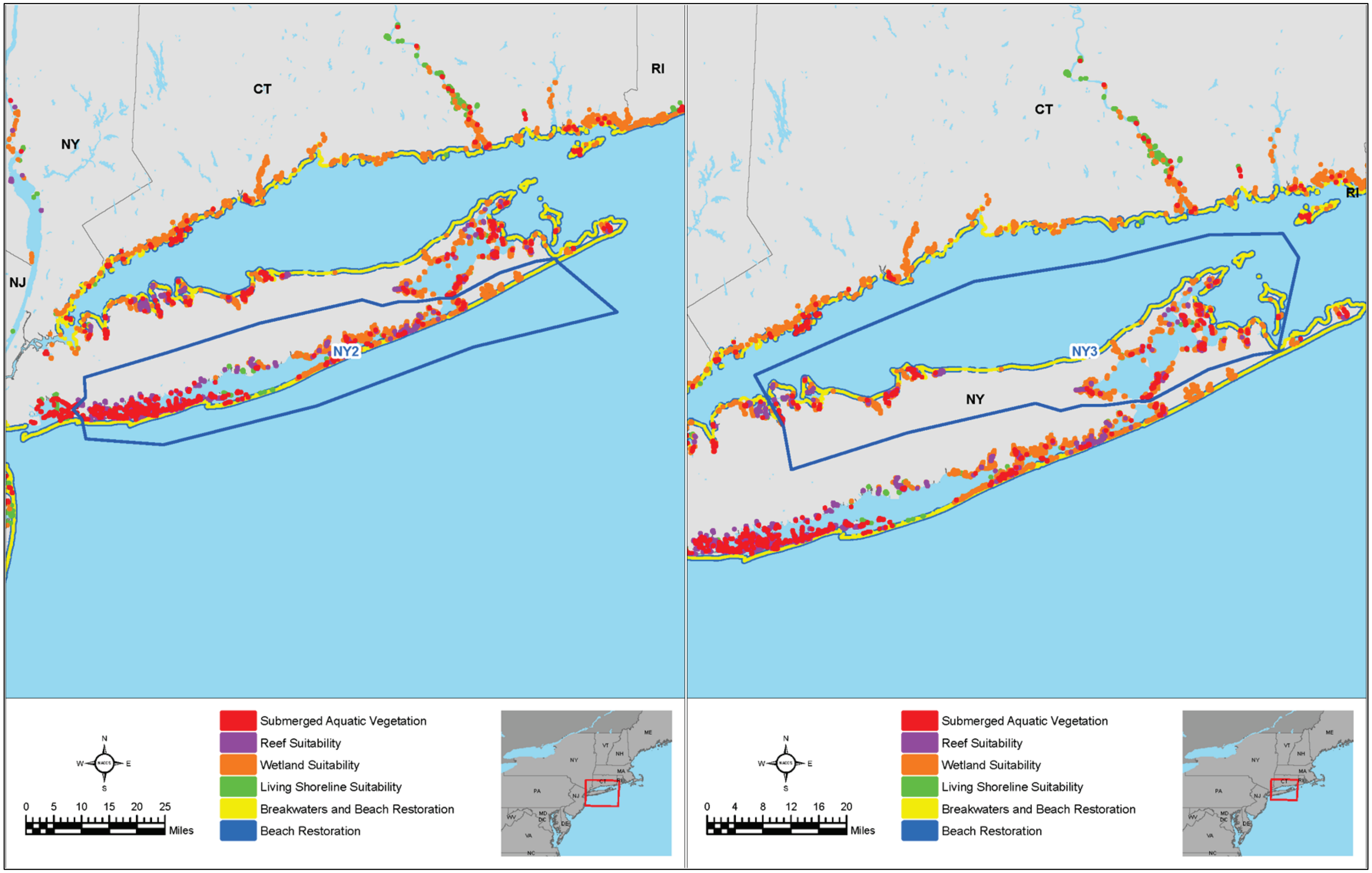


Figure 55. NNBF within NACCS planning reaches NY4 and NY5.

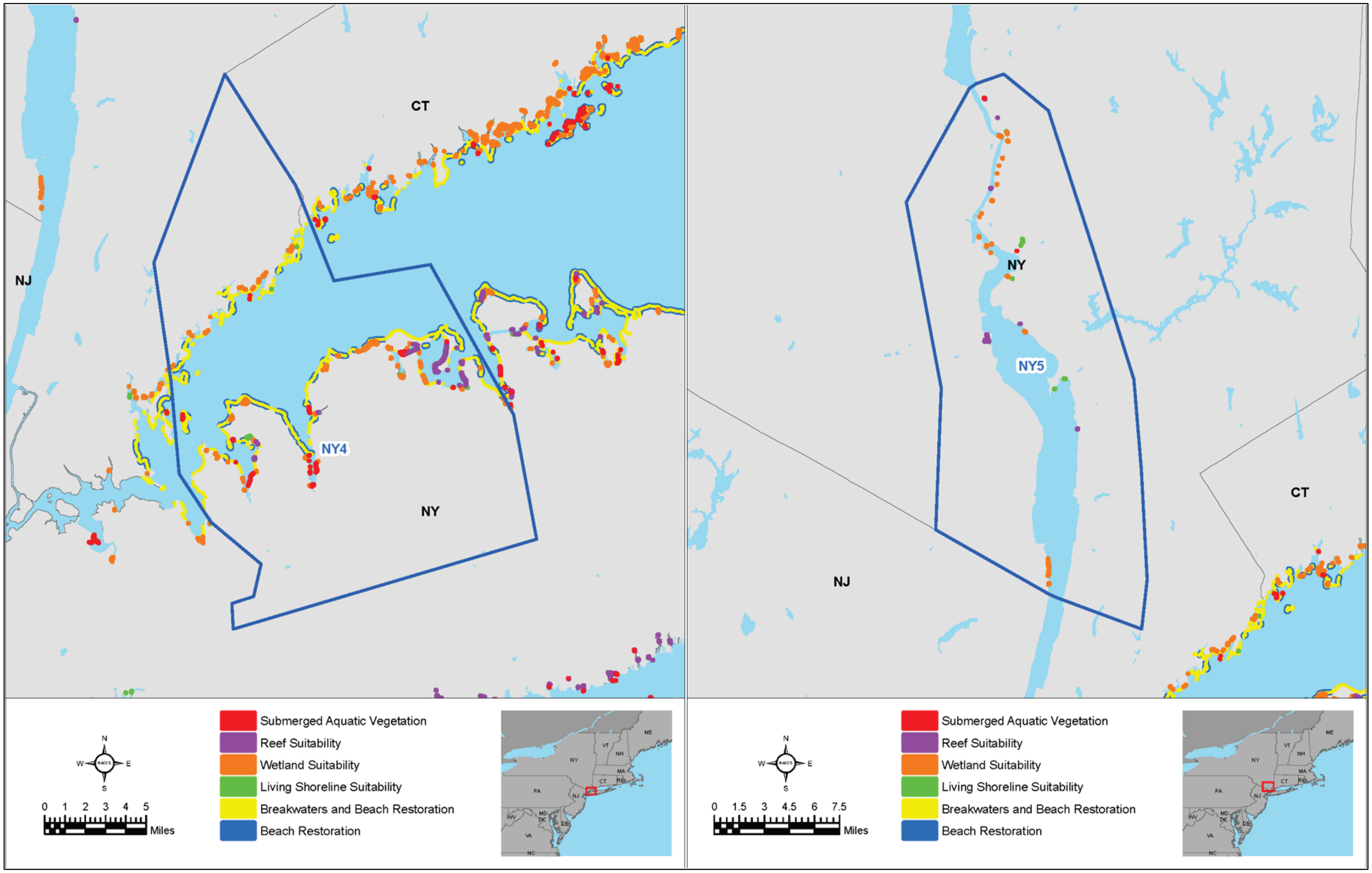


Figure 56. NNBF within NACCS planning reaches NY_NJ1 and NJ1.

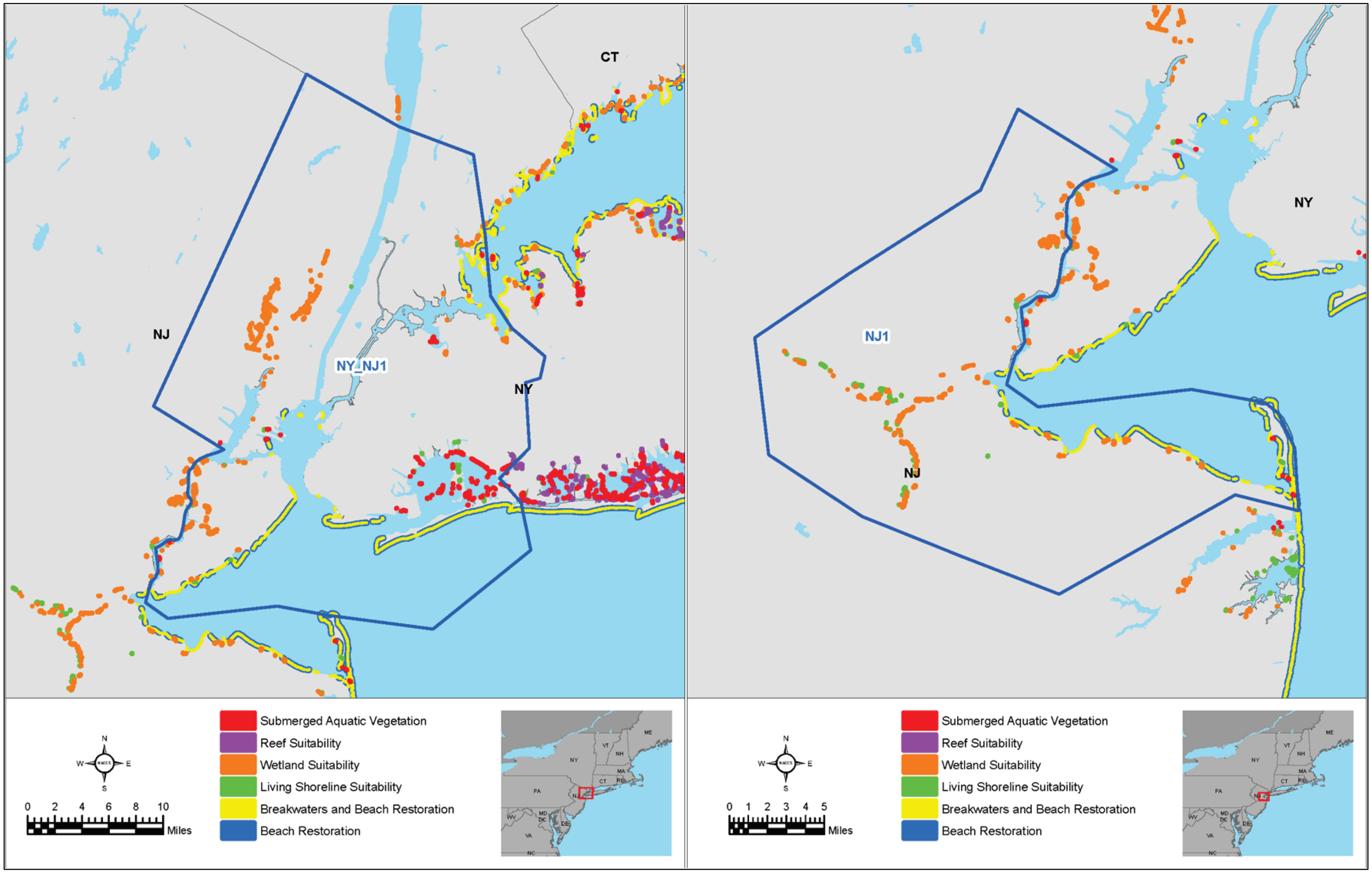


Figure 57. NNBF within NACCS planning reaches NJ2 and NJ3.

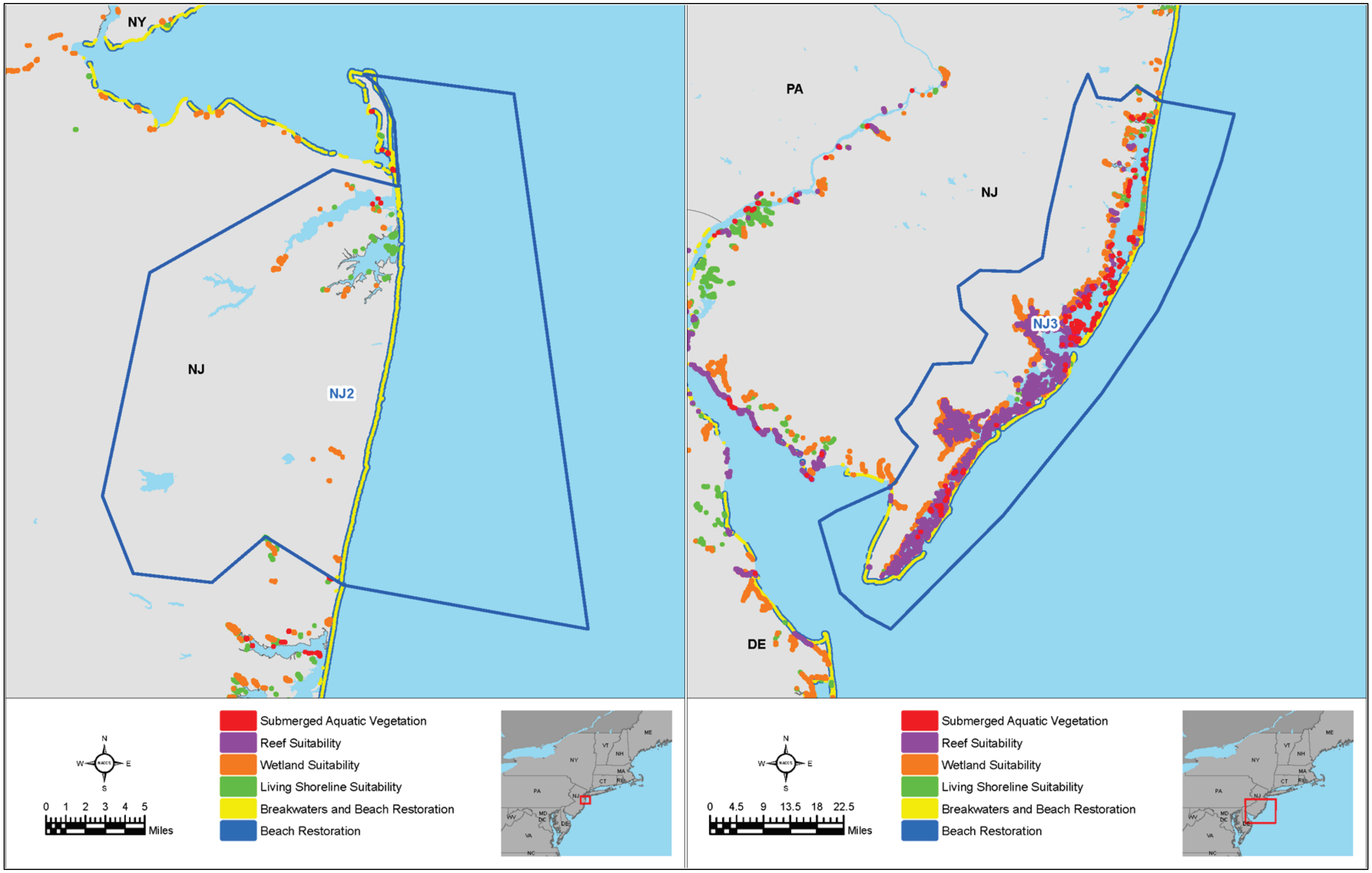


Figure 58. NNBF within NACCS planning reaches NJ4 and NJ5.

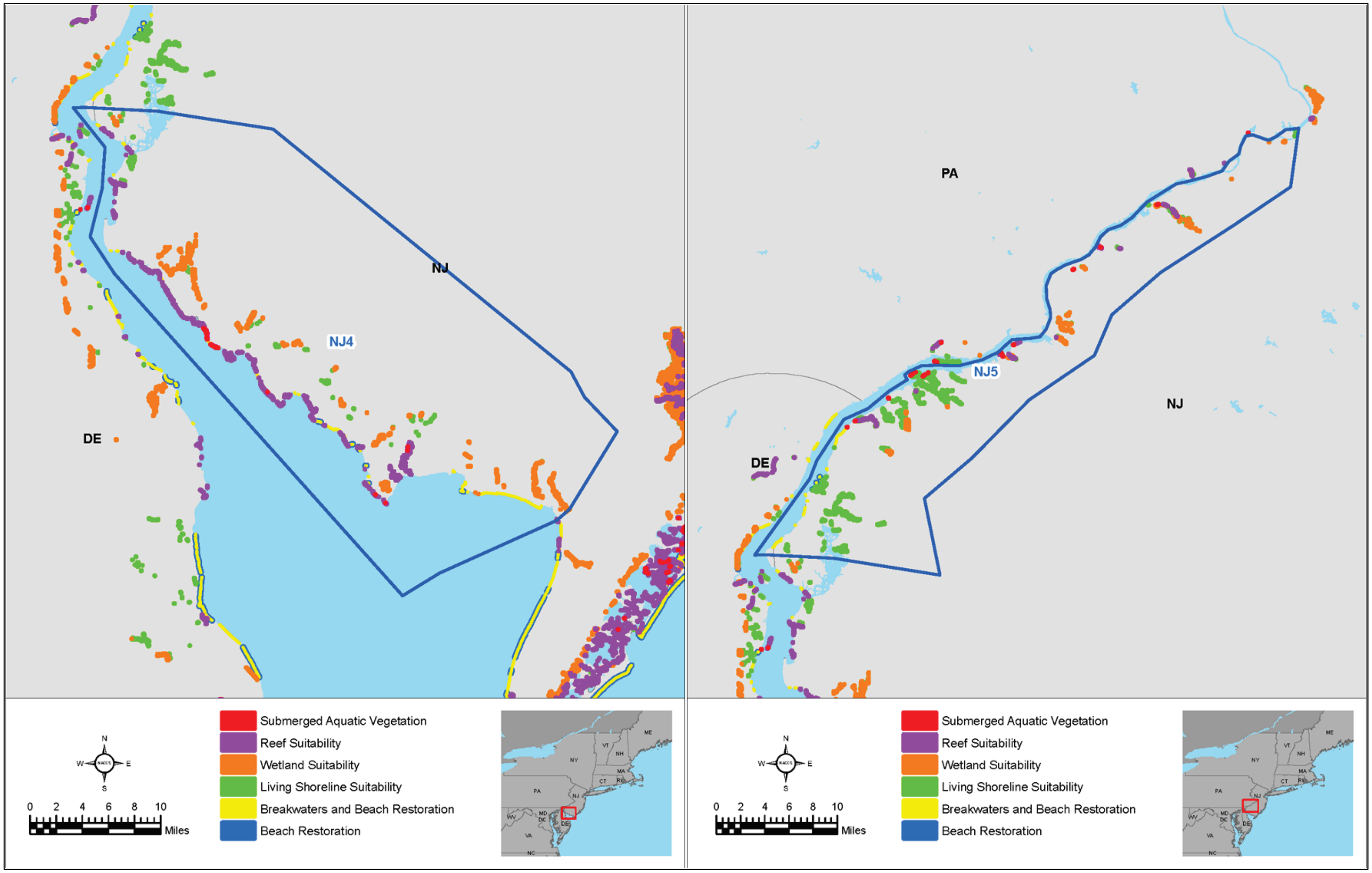


Figure 59. NNBF within NACCS planning reaches DE1 and PA1.

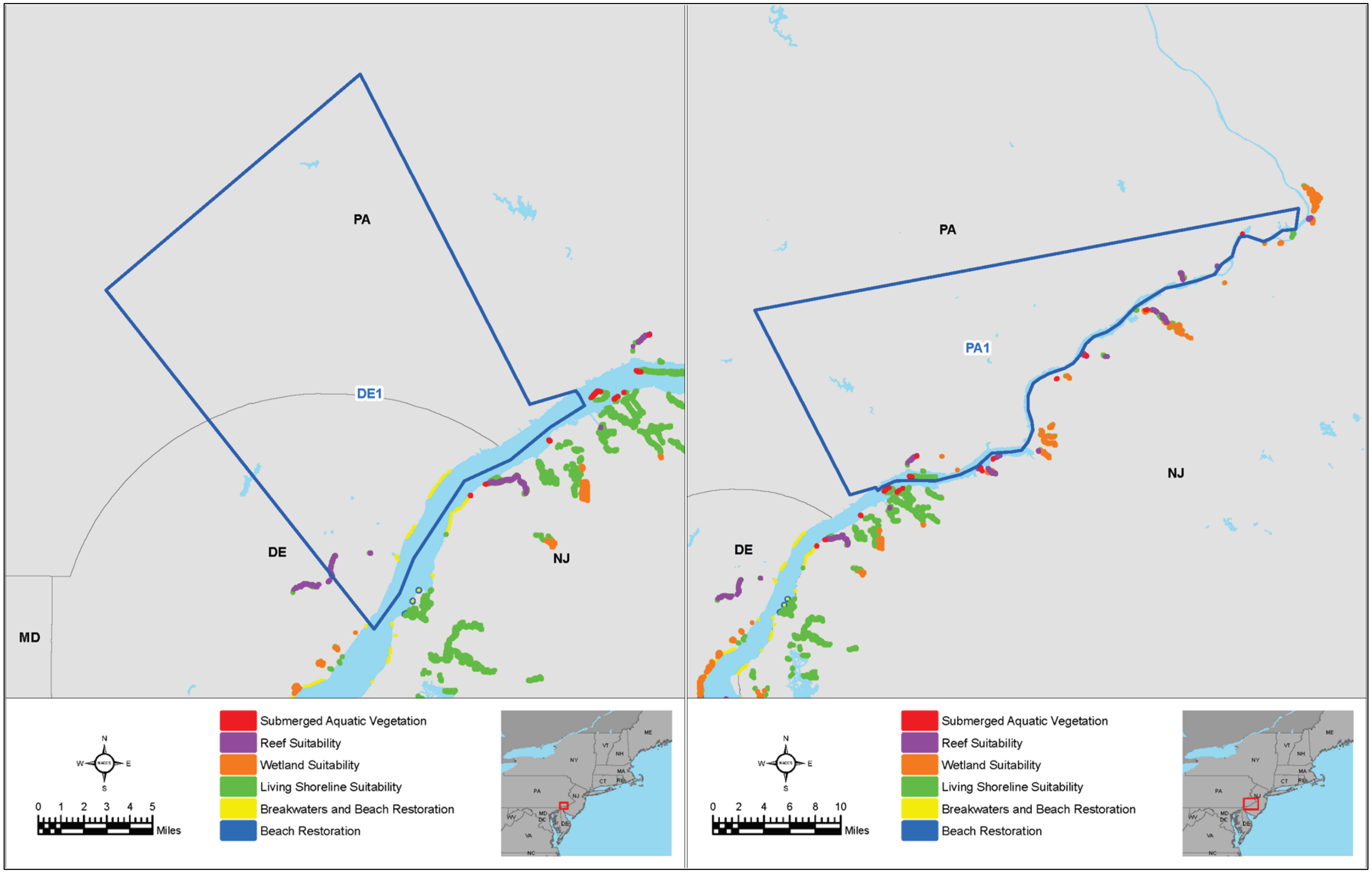


Figure 60. NNBF within NACCS planning reaches DE2 and DE3.

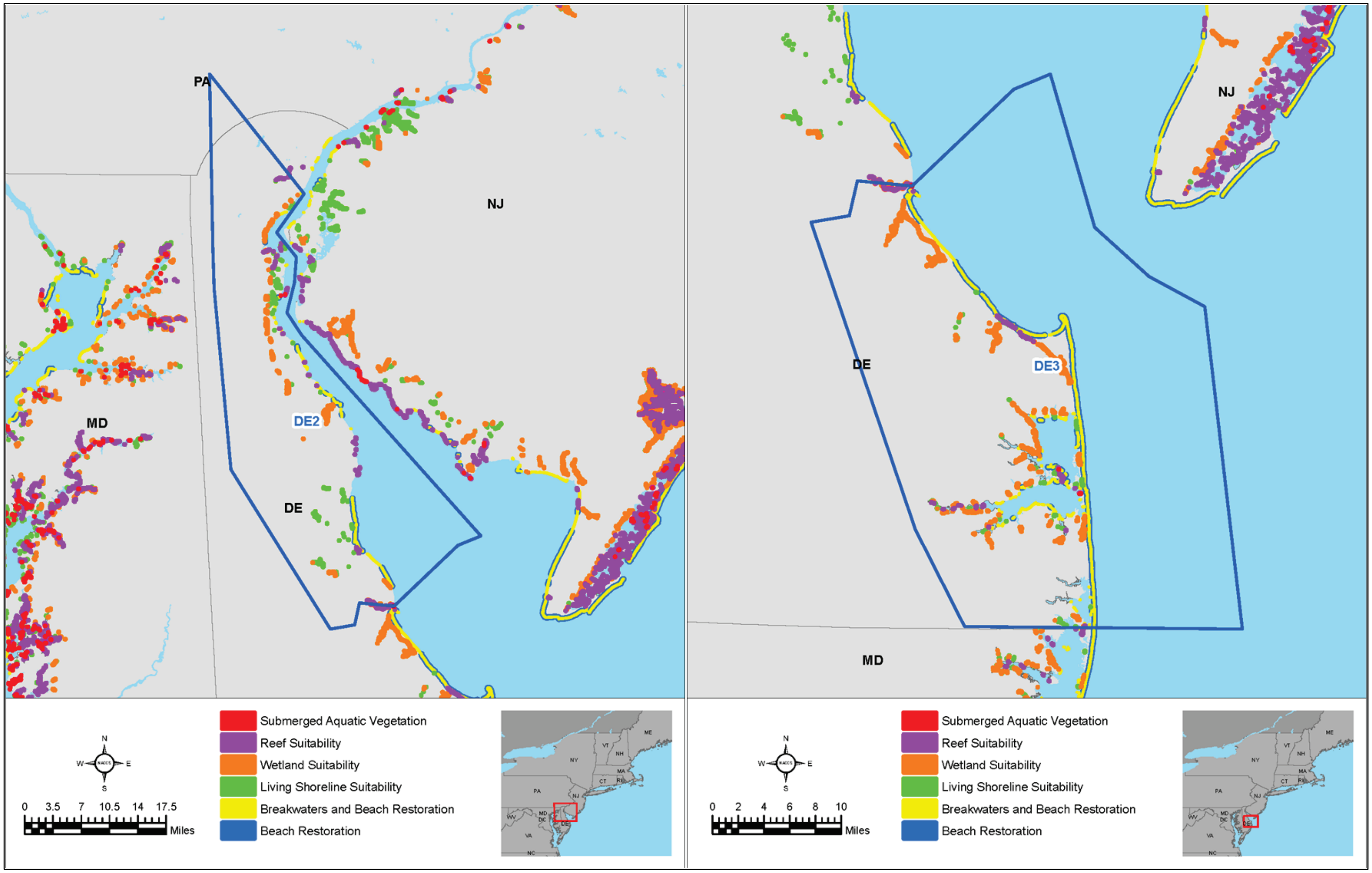


Figure 61. NNBF within NACCS planning reaches MD1 and MD2.

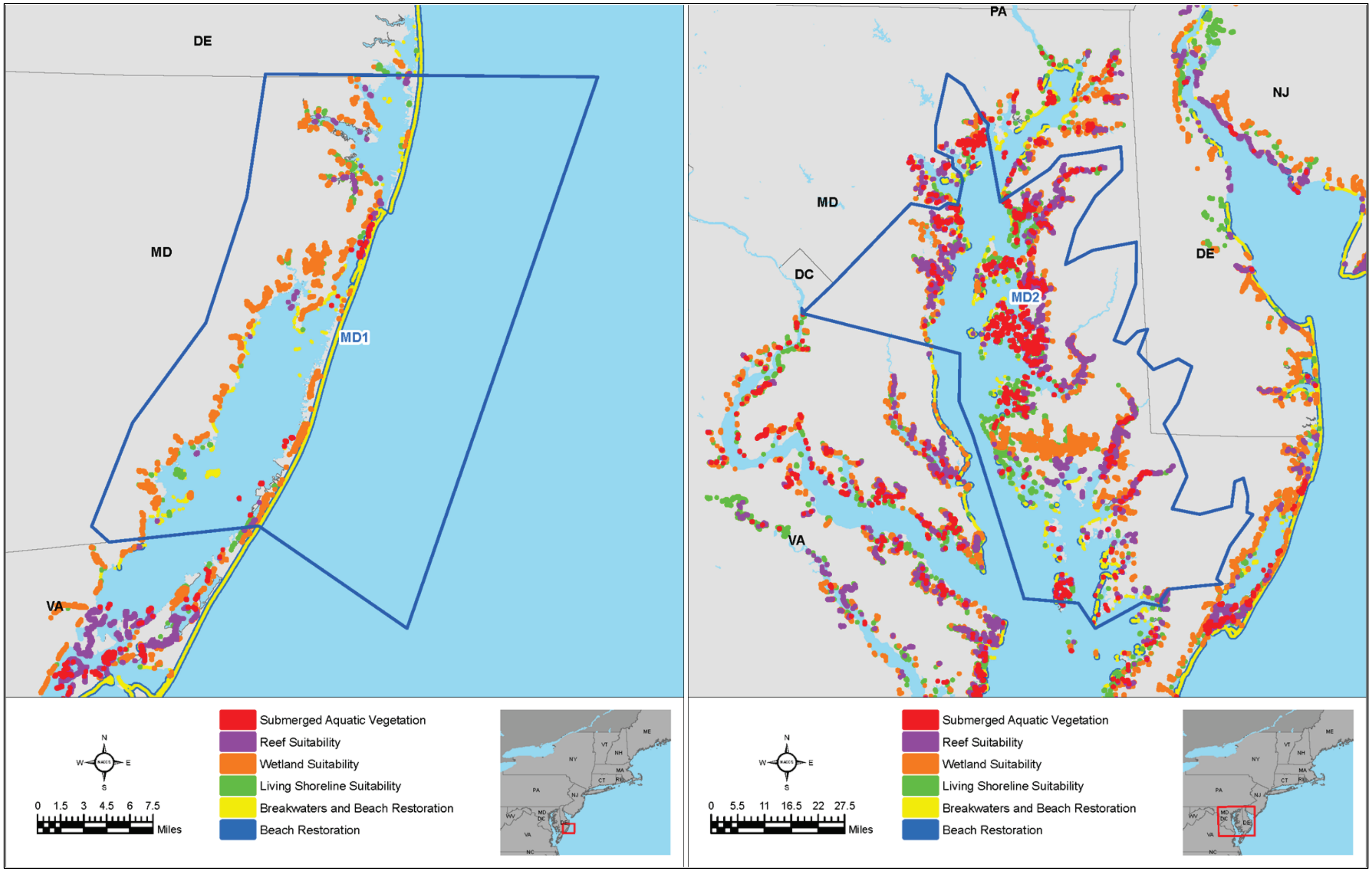


Figure 62. NNBF within NACCS planning reaches MD3 and MD4.

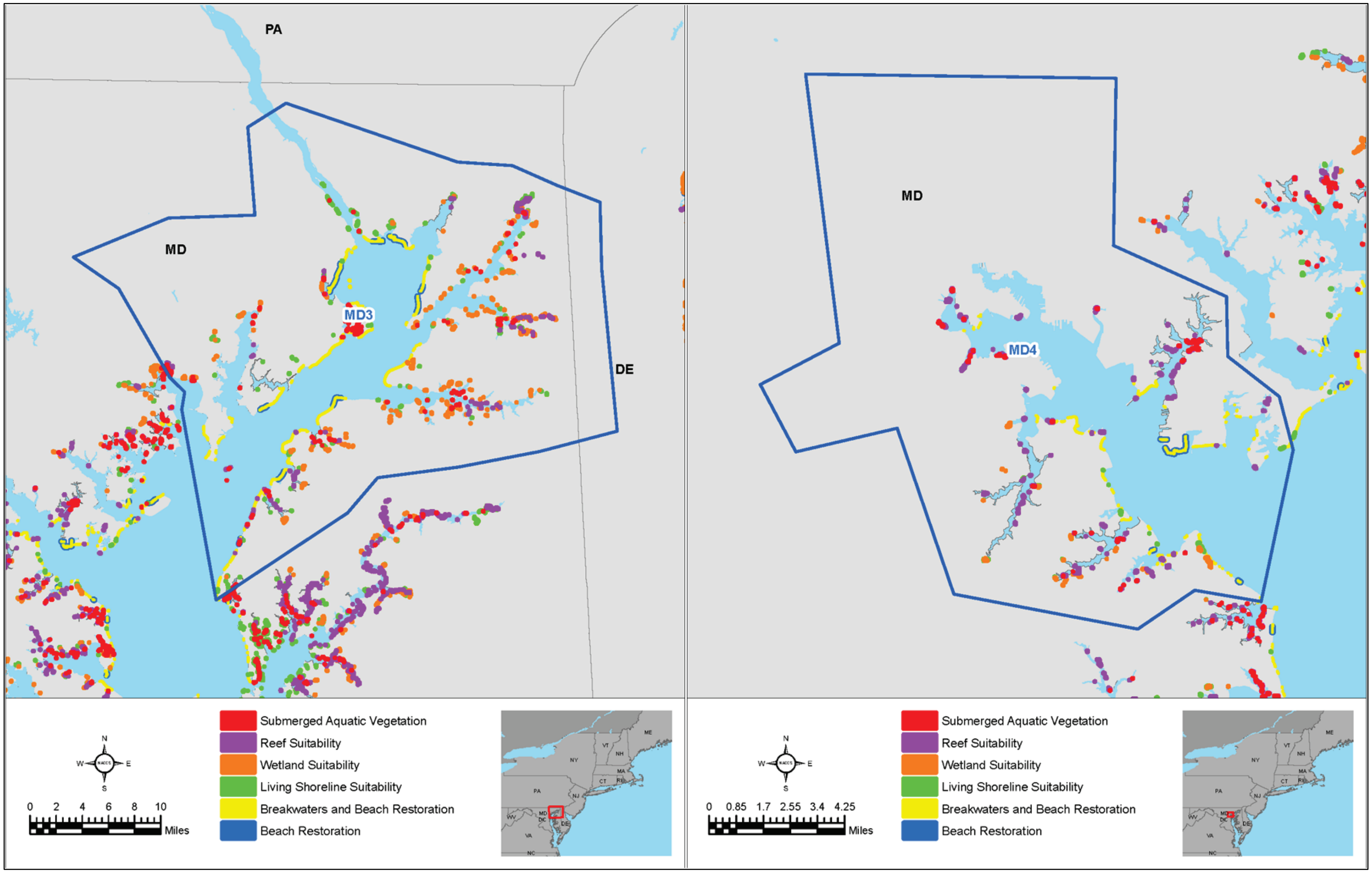


Figure 63. NNBF within NACCS planning reaches MD5 and DC1.

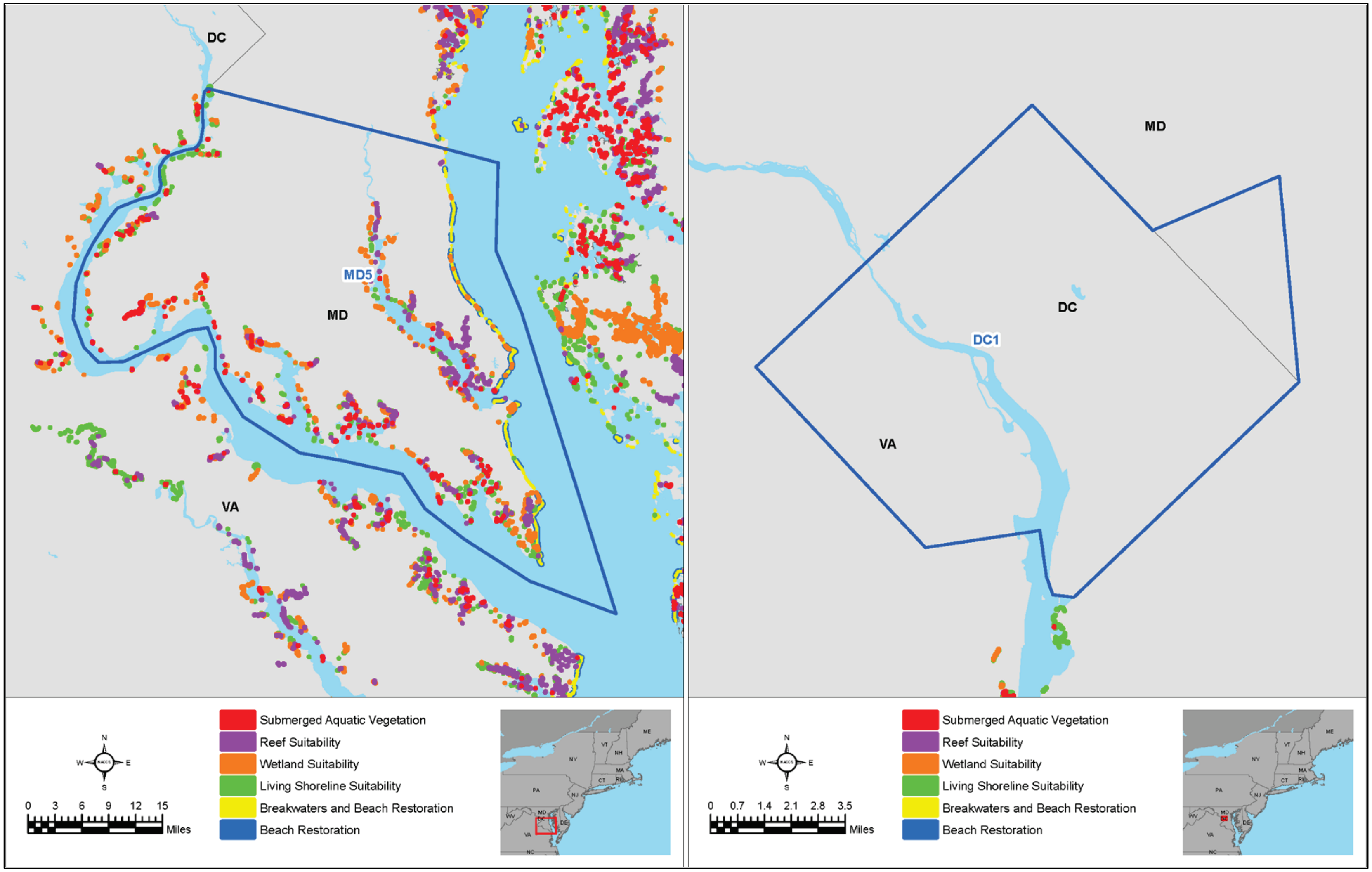


Figure 64. NNBF within NACCS planning reaches VA1 and VA2.

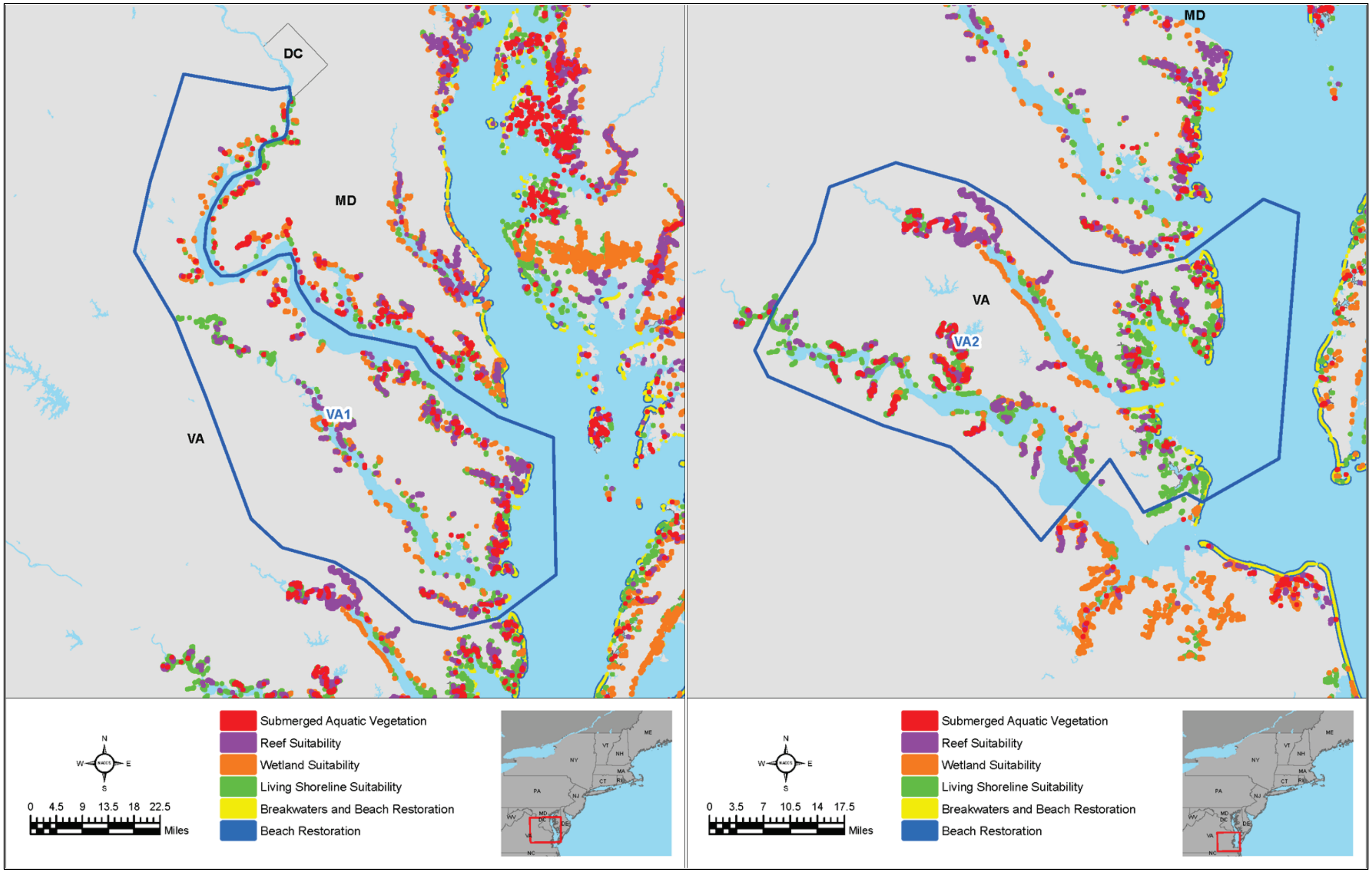


Figure 65. NNBF within NACCS planning reaches VA3 and VA4.

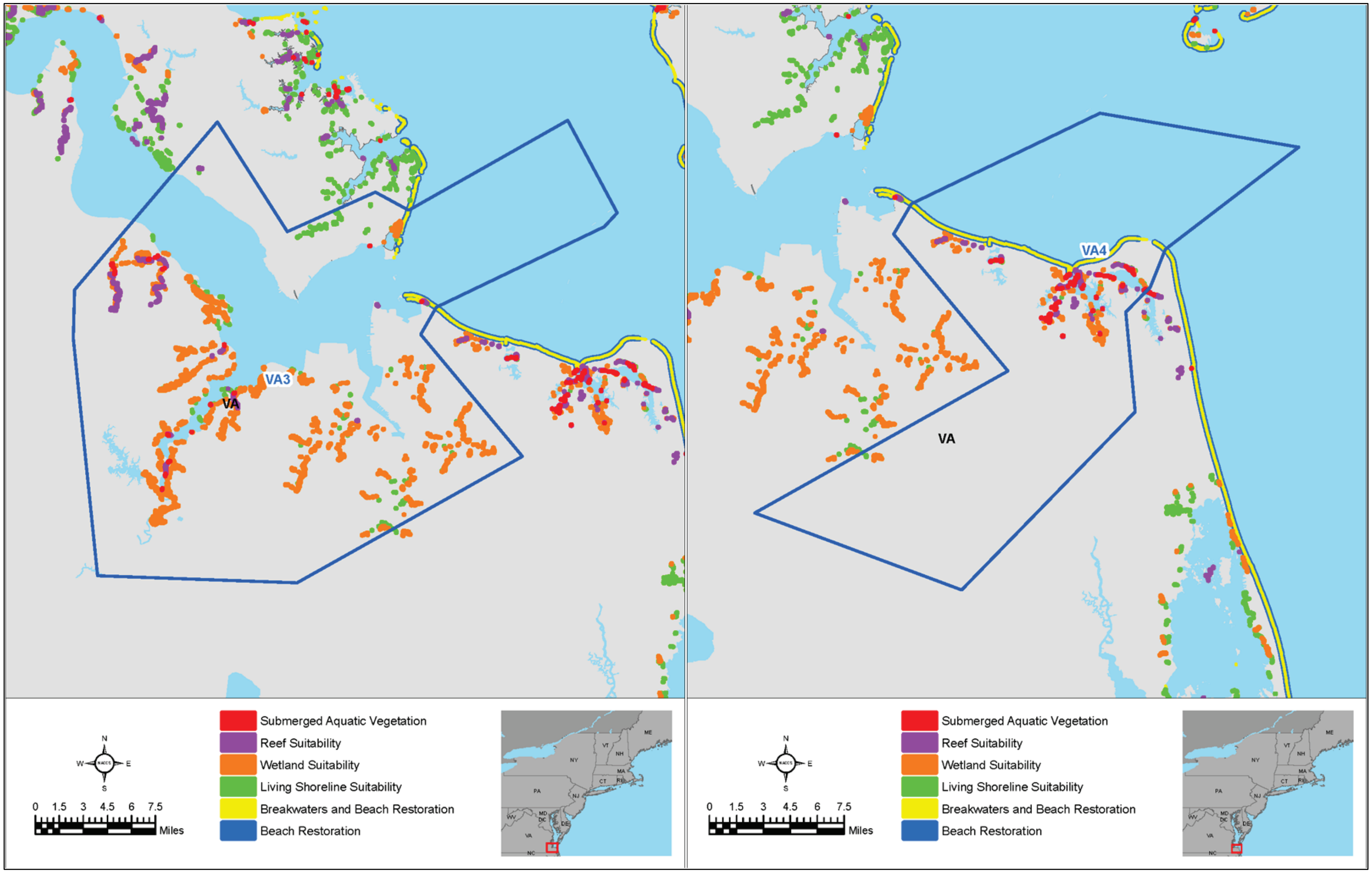


Figure 66. NNBF within NACCS planning reaches VA5 and VA6.

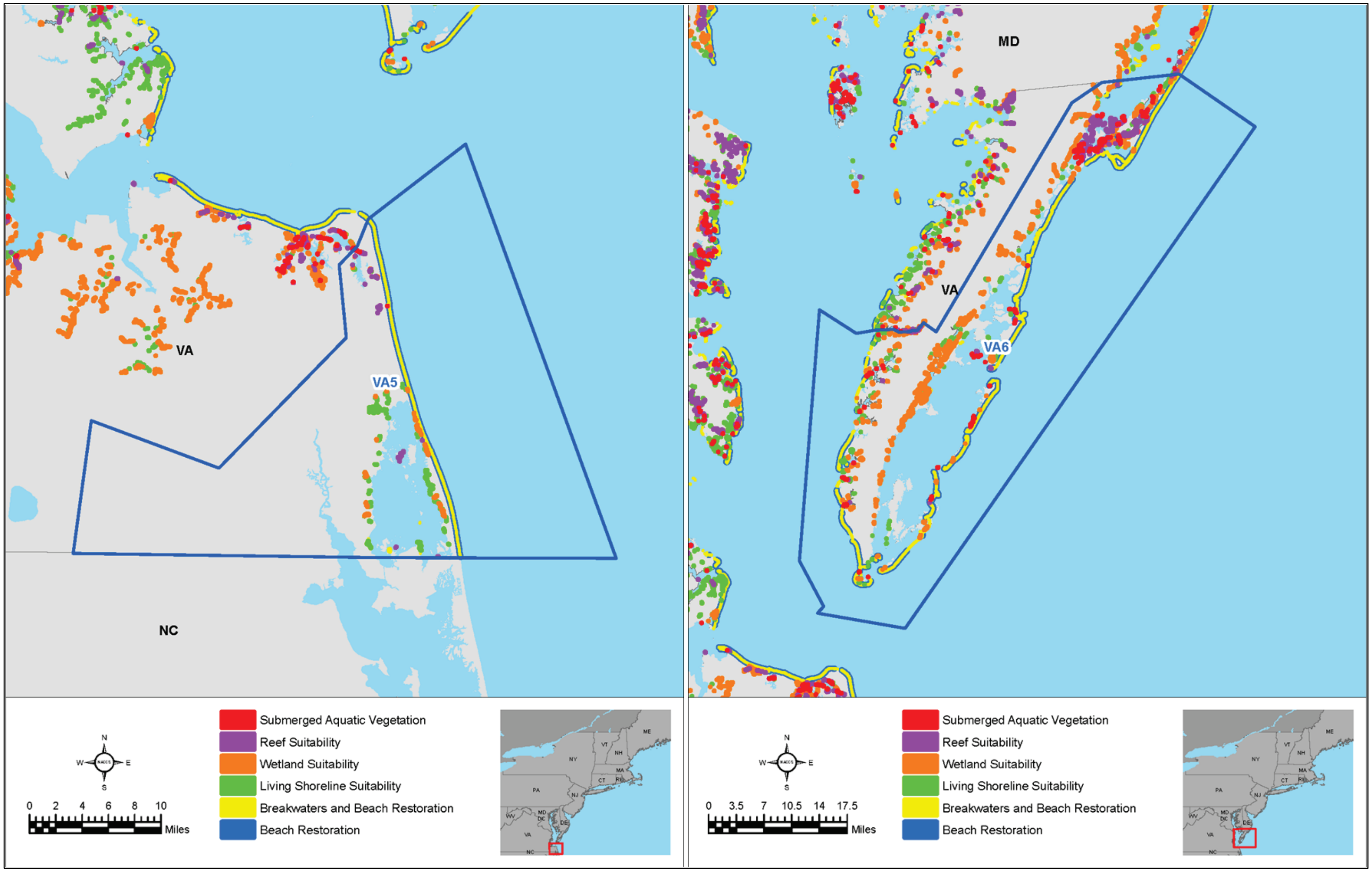
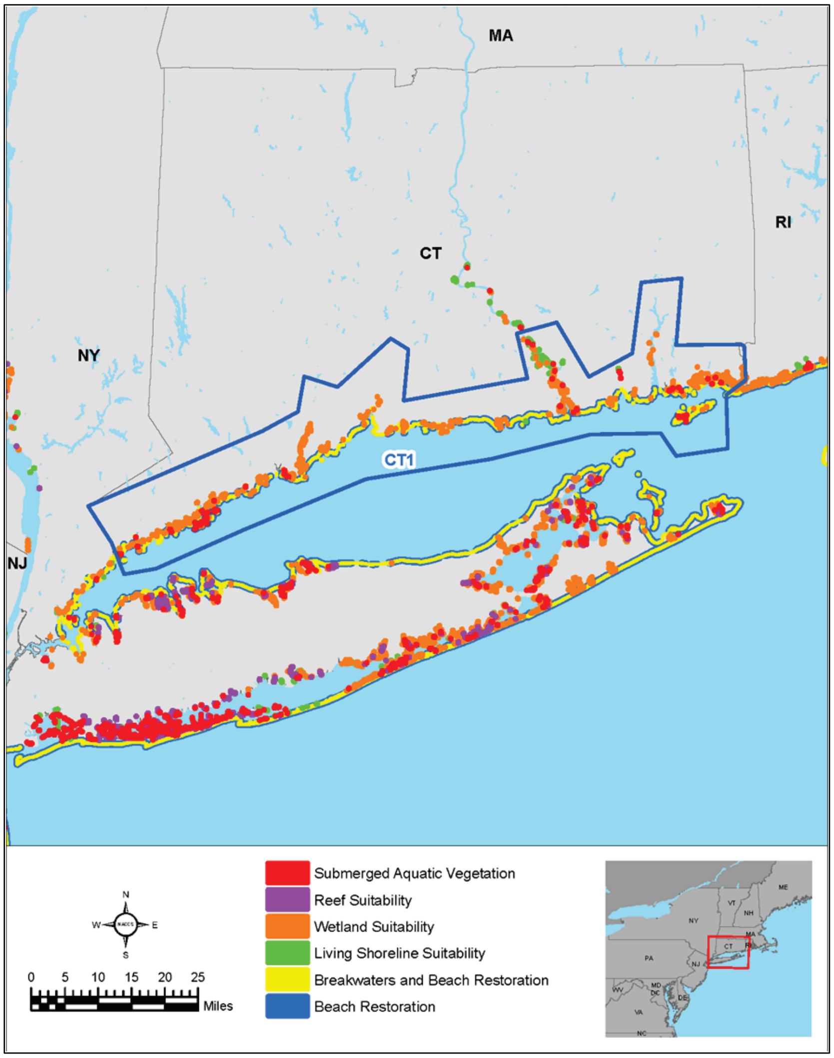


Figure 67. NNBF within NACCS planning reach CT1.



# Appendix B: Examples of Construction Costs of Nature-Based Infrastructure Projects

This appendix provides some examples and information of past construction cost and material costs as related to the creation, enhancement, or protection of NNBF. The cost of construction of future projects cannot be derived directly from these examples. Future projects would require site-specific engineering designs and cost evaluations.

The National Shoreline Management Study, authorized in the Water Resources Development Act of 1999, completed a comprehensive study of USACE Shore Protection Projects. A May 2003 report documented this study (USACE 2003) for USACE shore protection projects up through September 2002. Table 52 is taken from USACE (2003) and provides the date of construction, the project location and state, the type of project (structure, beach nourishment, or a combination of both), the initial construction cost, and the length of the protection project. The costs of construction as listed in the table have been converted into 2002 dollars.

Table 52. USACE shoreline protection costs converted to 2002 dollar ($) value (after USACE 2003).

| Initial Construction Complete, Specifically Authorized USACE Shore Protection Projects, by Year Construction Started | | | | | |
|---|---|---|---|---|---|
| Year Initial Construction Started | State | Project Name | Type of Project1 | Initial Construction Cost ($000)2 | Miles Protected |
| 1950 | MA | Quincy Shore Beach | Combined | 1,864 | 1.61 |
| 1952 | MS | Harrison County | Combined | 1,592 | 24.00 |
| 1956 | MA | Winthrop Beach | Combined | 530 | 0.76 |
| | PA | Presque Isle | Combined | 25,415 | 5.00 |
| 1957 | CT | Prospect Beach | Combined | 345 | 1.14 |
| 1958 | CT | Seaside Park | BN | 480 | 1.51 |
| | FL | Palm Beach County – Lake Worth Inlet to<br>South Lake Worth Inlet (sand transfer plant) | Structural | 577 | 0.00 |
| 1959 | CA | Channel Islands Harbor | Combined | 6,078 | 0.95 |
| 1961 | NC | Fort Macon | Combined | 952 | 1.45 |
| | CA | Oceanside | Combined | 1,348 | 2.84 |
| 1962 | CA | Ventura-Pierpoint Area | Combined | 1,234 | 2.20 |

| Initial Construction Complete, Specifically Authorized USACE Shore Protection Projects, by Year Construction Started | | | | | |
|---|---|---|---|---|---|
| Year Initial Construction Started | State | Project Name | Type of Project1 | Initial Construction Cost ($000)2 | Miles Protected |
| 1963 | TX | Galveston Seawall | Structural | 9,335 | 3.09 |
| 1964 | VA | Virginia Beach | BN | [3] 0 | 3.31 |
| 1965 | NY | South Shore of Long Island, Fire Island to Montauk Point, Moriches to Shinnecock Reach | Combined | 8,300 | 1.29 |
| | NY | South Shore of Long Island, Fire Island to Montauk Point, Southampton to Beach Hampton | Structural | 560 | 1.86 |
| | NJ | Raritan and Sandy Hook Bay, Madison and Matawan Townships | Combined | 1,314 | 2.97 |
| | NC | Wrightsville Beach | BN | 577 | 2.65 |
| | NC | Carolina Beach and Vicinity | Combined | 1,025 | 2.65 |
| 1966 | NH | Hampton Beach | Combined | 645 | 1.22 |
| 1968 | NJ | Raritan and Sandy Hook Bay, Keansburg and East Keansburg | Structural | 19,081 | 1.15 |
| | CA | Coast of California, Point Mugu to San Pedro | Combined | 2,448 | 2.23 |
| 1969 | FL | Pinellas County – Treasure Island Segment | Combined | 1,446 | 2.03 |
| 1970 | FL | Broward County – Segment II | BN | 1,759 | 11.60 |
| 1971 | FL | Fort Pierce Beach | BN | 621 | 1.30 |
| 1973 | FL | Palm Beach County – Delray Beach Segment | BN | 2,119 | 2.70 |
| | CA | Surfside/Sunset | Combined | 3,395 | 4.96 |
| 1974 | NY | Atlantic Coast of Long Island, Fire Island Inlet and Shore Westerly to Jones Inlet | BN | 13,150 | 3.41 |
| | NY | Hamlin Beach State Park | Combined | 2,378 | 0.80 |
| 1975 | RI | Cliff Walk | Structural | 1,361 | 3.41 |
| | NY | Atlantic Coast of New York City, East Rockaway Inlet to Rockaway Inlet and Jamaica Bay | Combined | 14,507 | 6.20 |
| | GA | Tybee Island | Combined | 4,111 | 2.58 |
| | FL | Brevard County – Cape Canaveral | BN | 1,026 | 2.80 |
| | FL | Dade County | Combined | 73,078 | 13.00 |

| Initial Construction Complete, Specifically Authorized USACE Shore Protection Projects, by Year Construction Started | | | | | |
|---|---|---|---|---|---|
| Year Initial Construction Started | State | Project Name | Type of Project1 | Initial Construction Cost ($000)2 | Miles Protected |
| 1977 | OH | Lakeview Park Cooperative | Combined | 1,674 | 0.28 |
| 1978 | TX | Corpus Christi Beach | Combined | 2,379 | 1.40 |
| 1978 | FL | Broward County – Segment III | BN | 10,982 | 6.80 |
| | FL | Duval County | BN | 9,579 | 10.00 |
| 1980 | NC | Fort Fisher | Structural | 5,970 | 0.58 |
| | FL | Pinellas County – Long Key Segment | Combined | 1,738 | 0.53 |
| 1981 | FL | Brevard County – Indialantic/Melbourne | BN | 3,552 | 2.10 |
| 1983 | NH | Wallis Sands State Park | Combined | 501 | 0.15 |
| | CT | Sherwood Island State Park | Combined | 1,226 | 1.48 |
| | OH | Point Place | Structural | 14,122 | 3.22 |
| 1985 | LA | Grand Isle and Vicinity | Combined | 10,818 | 7.00 |
| 1988 | FL | Palm Beach County – Boca Raton Segment | BN | 3,547 | 1.45 |
| 1989 | NJ | Cape May Inlet to Lower Township | Combined | 11,809 | 3.60 |
| | FL | Lee County – Captiva Island Segment | BN | 6,418 | 4.70 |
| 1990 | MD | Atlantic Coast of Maryland – Ocean City | Combined | 37,529 | 8.90 |
| 1991 | OH | Maumee Bay | Combined | 2,302 | 0.99 |
| 1992 | MA | Revere Beach | BN | 3,015 | 2.46 |
| | OH | Reno Beach | Structural | 6,554 | 4.01 |
| | NJ | Great Egg Harbor Inlet and Peck Beach | Combined | 29,437 | 4.28 |
| 1993 | SC | Folly Beach | Combined | 10,946 | 5.34 |
| | FL | Manatee County | BN | 17,499 | 4.70 |
| | FL | Pinellas County – Sand Key Segment | Combined | 31,621 | 7.90 |
| 1994 | NY | Atlantic Coast of NYC, Rockaway Inlet to Norton Point (Coney Island Area) | Combined | 9,100 | 2.95 |
| | IL | Casino Beach | Structural | 3,922 | 0.57 |
| | AK | Homer Spit Storm Damage Reduction | Structural | 2,645 | 0.21 |
| 1995 | SC | Myrtle Beach | BN | 48,212 | 25.30 |
| | FL | Palm Beach – Jupiter/Carlin | BN | 4,787 | 1.10 |
| | FL | Sarasota County – Venice Segment | BN | 19,280 | 1.59 |
| 1996 | NY | Fire Island Inlet to Montauk Point (Westhampton Interim) | Combined | 19,249 | 4.06 |

| Initial Construction Complete, Specifically Authorized USACE Shore Protection Projects, by Year Construction Started | | | | | |
|---|---|---|---|---|---|
| Year Initial Construction Started | State | Project Name | Type of Project1 | Initial Construction Cost ($000)2 | Miles Protected |
| | NC | Kure Beach | BN | 14,550 | 3.41 |
| | FL | Martin County | BN | 11,639 | 3.75 |
| | IN | Indiana Shoreline | BN | 350 | 2.08 |
| 1997 | NJ | Sandy Hook to Barnegat Inlet (Asbury Park to Manasquan) | Combined | 43,448 | 9.00 |
| | FL | Panama City Beaches | BN | 21,223 | 16.29 |
| | AK | Dillingham Snag Point | Structural | 3,600 | 0.30 |
| 1998 | FL | Palm Beach – Ocean Ridge Segment | BN | 6,894 | 1.40 |
| | AK | Homer Spit (extension) | Structural | 5,846 | 0.76 |
| 2000 | GA | Tybee Island (extension) | Combined | 576 | 0.47 |
| 2001 | NC | Ocean Isle, Brunswick Co. Beaches | BN | 6,200 | 3.25 |
| | FL | Brevard County – North Reach | BN | 21,379 | 6.60 |
| **Program Totals** | | **71 projects (plus the extension of 2 projects)** | | **$668,769** | **283.63** |

1 Structural: A project with only a structural component; BN: A project with only a beach nourishment component; Combined: A project that contains both structural and beach nourishment components.

2 Actual costs at time of construction. As these are initial costs, periodic nourishment and emergency costs are not included.

3 There were no initial restoration costs for the Virginia Beach project. Periodic nourishment began in 1963 when 215 CY were placed on the shoreline.

The USACE, Norfolk District, is developing an updated cost table for USACE projects in the North Atlantic Division. Table 53 includes a sampling of the more recent USACE projects that are being evaluated. All costs provided in the table were converted to 2013 dollars using the Civil Works Construction Cost Index System (CWCCIS) guidance (Bazzle 2013).

A more up-to-date cost for the construction of beach fills is provided by the USACE, New York District, which recently advertised for the construction of beach nourishment projects in response to storm damage. July 2013 bid offerings are in the range of $8/CY to $35/CY. Differences in the cost reflect the travel distance to the various sand barrow sites (Bocamazo 2013[1])

[1] Personal Communication. Lynn M. Bocamazo, P.E., D. CE., Chief, Hurricane Sandy Relief Branch, USACE, New York District, 29 July 2013.

Table 53. Shore protection projects costs converted to 2013 price levels (USACE, 2013).

| Location | Feature Type | Construction Date | Construction Cost in 2013 Dollars | L (ft) | TC/L | Width (ft) | H (ft) |
|---|---|---|---|---|---|---|---|
| Anderson Park | Stone revetment | 1979 | $2,465,416 | 1500 | $1,644 | 3.0 | 8.00 |
| Buckroe | Beachfill | 2005 | $5,401,849 | 3785 | $1,427 | 50.0 | 5.40 |
| Sandbridge Beach | Beachfill | 2003 | $11,226,628 | 26400 | $425 | 50.0 | 6.00 |
| Atlantic Coast Ocean City, NJ | Steel bulkhead/ beachfill/ vegetated dune | 1992 | $81,130,054 | 45,170.00 | $1,796 | 25.0 (dune) | 13.70 |
| Assateague | Beachfill | 2007 | $14,992,428 | 40,128.00 | $374 | 16.0 | 7.40 |
| Barnegat Inlet to Little Egg Inlet, NJ | Beachfill | 2012 | $251,753,000 | 26400 | $9,536 | 30 (dune) | 22.00 |
| Lower Cape May Meadows to Cape May Point, NJ | Beachfill/ wetlands restoration | 2005 | $133,900,000 | 10032 | $13,347 | 20 (berm) | 16.70 |
| East Point, NJ | Revetment | 2012 | $1,538,000 | 350 | $4,394 | 3.0 | 9.50 |
| West of Shinnecock Inlet, NY | Beachfill | 2005 | $23,797,505 | 4000 | $5,949 | 25.0 | 14.10 |
| Orient Point, NY | Revetment w/ concrete cap | 2011 | $818,903 | 350 | $2,340 | 5.0 | 8.40 |
| MD Living Shoreline Projects | Sill | 2003 | $26,848.50 | 119 | $303 | | |
| MD Living Shoreline Projects | Groins | 2003 | $22,300.00 | 220 | $136 | | |
| MD Living Shoreline Projects | Edging | 2002 | $12,986.00 | 151 | $115 | | |
| MD Living Shoreline Projects | Groins and marsh edging | 2000 | $15,452.00 | 348 | $70 | | |
| MD Living Shoreline Projects | Stone edging | 2000 | $6,162.00 | 76 | $127 | | |

Oyster beds and reefs have been constructed in bays and sound areas to increase habitat, to improve water quality in the bays, and to initiate wave breaking by reducing water depths in the bays and near the shorelines. Oysters require hard substrate for larval settlement. Lusk et al. (2011)

documented a coastal restoration project in the coastal bays of Virginia. Low-profile concrete forms were installed on the seabed to support oyster bed growth. Additionally, 180,544 bushels of shell were used to create 11.6 acres of oyster bed. Lusk et al. (2011) reported the cost of the shell placement to be $77,500/acre from a nonlocal shell source to $35,000/acre for shells collected from a local source. Schulte et al. (2009) compared the viability of alternate substrate sources for oyster growth and survivability. Concrete, granite, limestone, and oyster shell were compared, and all were found to be viable substrates for oyster habitat. The USACE (2012) provide cost information for the initial construction of oyster beds for use in Maryland and Virginia using the varied substrates. Table 54 is taken from USACE 2012. Additional costs for the oyster bed development include the cost of oyster seeding. Oyster seeding volume requirements are dependent upon water salinity and planned reseeding rates. Typical costs range from approximately $37,100/acre to $111,350/acre. Placement costs were not reported with the materials costs.

Table 54. Cost of substrates for use in oyster bed development (USACE 2012a).

| Maryland | | | | |
|---|---|---|---|---|
| | Limestone | Granite | Concrete | Fossil Shell |
| Average cost per acre | $137,400 | $133,400 | $86,700 | $58,300 |
| Virginia | | | | |
| | Limestone | Granite | Concrete | Fossil Shell |
| Average cost per acre | $148,800 | $141,200 | $93,000 | $59,400 |

Grabowski et al. (2012) reviewed costs reported for five coastal habitats in the United States and then converted the cost to 2011 price levels. Table 55 lists the relative cost of restoration of diverse habitats from Grabowski et al. (2012).

Table 55. Habitat restoration costs (Grabowski et al. 2012).

| Habitat Type | Area Restored (ha) | Restoration Costs (x $1000/ha) |
|---|---|---|
| Salt marsh | 36,625 | 3-242 |
| Seagrass | 3,946 | 29-65 |
| Mangrove | 1,399 | 50 |
| Coral reef | 150 | 20 |
| Oyster reef | 69 | 80-85 |

Devore (2013) provides a template for the planning and development of a living shoreline for. Shoreline stabilization can be accomplished using living plant material (emergent and submerged aquatic vegetation), oyster shells, earthen material or a combination of natural structures with rip rap or offshore breakwaters to protect the shoreline against erosion. Living shorelines provide a more natural approach for erosion control, while allowing access for coastal and estuarine organisms (Devore 2013). Table 56 through Table 59 are taken directly from Devore (2013) to suggest cost for living shoreline establishment.

Table 56. Vegetation cover costs (after Devore 2013).

| Plant | Unit | Cost Range ($/unit) | Cost Installed ($/unit) |
|---|---|---|---|
| Smooth cordgrass (*Spartina alterniflora*) | Plug | 1.25 | $2-3 Plug<br>$3 Gallon |
| Marshy cordgrass (*S. patens*) | Plug | $1.25 | $2-3 Plug<br>$3 Gallon |
| Mangrove | Gallon pot | $10 | $5 Gallon |
| Salt grass (*Distichlis spicata*) | Plug | 2" – $.60<br>4" – $1 | $2 Plug<br>$3 Plug |
| Bitter panicum (*Panicum vaginatum*) | Node | $1 | $2 Plug<br>$3 Plug |
| Freshwater species | Gallon pot | $5–$6 | |

Table 57. Soft or nonstructural stabilization (after Devore 2013).

| Technique | Unit | Cost Range ($/unit) |
|---|---|---|
| Snow fencing | 100 ft | $45.00 |
| Coir log | 10 ft lengths | $57.25 |
| Erosion control blankets<br>Straw blanket<br>Coconut straw blend<br>Coconut fiber | $yd^2$ | $0.29<br>$0.52<br>$0.65 |
| Geotextile tube<br>15 ft circumference<br>22 ft circumference<br>30 ft circumference | Linear foot (lf) | (2007 prices)<br>$115–$175<br>$175–$225<br>$140–$200 |

Table 58. Structures for living shorelines, bulkheads, seawalls, and revetments (after Devore 2013).

| Type | Unit | Cost Range ($/unit) |
|---|---|---|
| Vinyl | lf | $125–$200 |
| Vinyl w/toe protection | lf | $210–$285 |
| Wooden | lf | $115–$180 |
| Wooden w/toe protection | lf | $200–$265 |
| Concrete | lf | $500–$1,000 |
| Sheetpile | lf | $700–$1,200 |
| Revetment | $yd^3$ | $25–$45 ($120–$180/lf installed) |

Table 59. Nearshore breakwaters (after Devore 2013).

| Technique | Unit | Cost Range ($/unit) |
|---|---|---|
| Oyster shell | Loose shell bag ($yd^3$) | $50–$60<br>$5 ($30 for bag w/spat) |
| Concrete bags | Bag | $4–$6 (~$12–$16/lf) |
| Limestone rock | lf | $125–$200 |
| Reef balls delivery | lf–varies depending on distance | $44 installed<br>(~$36–$38 w/volunteers)<br>$1700–$2100 |
| Reef bulkhead | lf | $150 installed |
| Wave attenuation device | lf | $180–$250 |

Roux Associates designed the transformation of an 80-acre former municipal landfill into maritime grassland habitat for the New York City Department of Parks and Recreation (Ledlow 2013[1]). The project served as mitigation for the loss of grassland habitat. The objectives of the project were to increase biodiversity, create habitat for rare or special-status species, control invasive species, and improve shoreline stability. Table 60 is a detailed line-item estimate for construction and materials at the island as provided by Roux Associates. This example serves to estimate cost for individual features and tasks for the development of this island.

River bank stabilization costs from several studies are summarized in Allen et.al (2006) in a study of the Hudson River National Estuarine Research Reserve. Table 61 identifies the stabilization techniques, the cost per unit, and the reference source of the original study.

[1] Personal Communication. Amanda Ledlow, Principal Scientist with Roux Associates, July 2013.

Table 60. Engineers cost estimate for White Island restoration.

| ITEM | White Island Cost Estimate | | | | |
|---|---|---|---|---|---|
| NO. | | | TOTAL | | TOTAL |
| | ITEM DESCRIPTION | UNIT | QTY | PRICE | AMOUNT |
| 1 | Mobilization (n.t.e. 6% of total of all other items)–custom | LS | 1 | $651,567.58 | $ 651,567.58 |
| 2 | Rodent extermination | LS | 1 | | $1,785.00 |
| 3 | Construction sign on frame | EA | 2 | $1,650.00 | $3,300.00 |
| 4 | Construction fence–8 ft height | LF | 1,050 | $25.00 | $26,250.00 |
| 5 | Consultant's trailer office–custom | LS | 1 | $52,500.00 | $52,500.00 |
| 6 | Temporary snow fence boundary–custom | LF | 4,000 | $8.60 | $34,400.00 |
| 7 | Vegetation removal and grubbing–custom | LS | 1 | $175,000.00 | $175,000.00 |
| 8 | Services of a licensed land surveyor–Type A | LS | 1 | $75,000.00 | $75,000.00 |
| 9 | Sand-moving operations–custom | CY | 150,000 | $18.00 | $2,700,000.00 |
| 10 | Geotextile–separation–custom | SY | 30,000 | $7.50 | $225,000.00 |
| 11 | Catch basin silt sack–custom | EA | 1 | $250.00 | $250.00 |
| 12 | Temporary straw bale silt control–custom | LF | 5,720 | $12.00 | $68,640.00 |
| 13 | Temporary silt fence–custom | LF | 8,300 | $9.10 | $75,530.00 |
| 14 | Erosion-control blanket–custom | SY | 100 | $8.50 | $850.00 |
| 15 | Stabilized construction entrance–custom | SY | 8,700 | $30.00 | $261,000.00 |
| 16 | Plant shrub, arrowwood (*viburnum dentatum*), 1-gallon container | EA | 375 | $35.00 | $13,125.00 |
| 17 | Plant shrub, inkberry (*ilex glabra*), 1-gallon container | EA | 375 | $35.00 | $13,125.00 |
| 18 | Plant shrub, groundsel bush (*baccharis halimifolia*), 1-gallon container | EA | 375 | $35.00 | $13,125.00 |
| 19 | Plant grass, Atlantic coastal panic grass (*panicum amarum*), plug | EA | 54,000 | $9.00 | $486,000.00 |
| 20 | Plant grass, American beachgrass (*ammophila breviligulata*), plug or sprig | EA | 56,700 | $9.00 | $510,300.00 |
| 21 | Plant grass, smooth cordgrass (*spartina alterniflora*), plug | EA | 6,000 | $9.00 | $54,000.00 |
| 22 | Plant grass, salt meadow rush (*juncus gerardii*) plug | EA | 2,000 | $9.00 | $18,000.00 |
| 23 | Plant grass, saltgrass (*distichlis spicata*), plug | EA | 2,000 | $9.00 | $18,000.00 |
| 24 | Plant grass, saltmeadow cordgrass (*spartina patens*), plug | EA | 2,000 | $9.00 | $18,000.00 |
| 25 | Plant grass, Pennsylvania sedge (*carex pensylvanica*), plug | EA | 8,000 | $9.00 | $72,000.00 |
| 26 | Native tall warm-season grass mix–custom | SF | 474,804 | $0.55 | $261,142.20 |

<table>
<tr><td>ITEM</td><td>White Island Cost Estimate</td><td></td><td></td><td></td><td colspan="2"></td></tr>
<tr><td>NO.</td><td></td><td></td><td>TOTAL</td><td></td><td colspan="2">TOTAL</td></tr>
<tr><td>27</td><td>Native short warm-season grass mix–custom</td><td>SF</td><td>723,096</td><td>$0.55</td><td colspan="2">$397,702.80</td></tr>
<tr><td>28</td><td>Native maritime grass mix–custom</td><td>SF</td><td>749,232</td><td>$0.55</td><td colspan="2">$412,077.60</td></tr>
<tr><td>29</td><td>Native dune grass mix–custom</td><td>SF</td><td>1,045,440</td><td>$0.55</td><td colspan="2">$574,992.00</td></tr>
<tr><td>30</td><td>Low-permeable soil subgrade–custom</td><td>CY</td><td>7,000</td><td>$52.00</td><td colspan="2">$364,000.00</td></tr>
<tr><td>31</td><td>Armor stone–custom</td><td>TON</td><td>3,000</td><td>$175.00</td><td colspan="2">$525,000.00</td></tr>
<tr><td>32</td><td>Riprap (D50 24 in.)–custom</td><td>TON</td><td>900</td><td>$100.00</td><td colspan="2">$90,000.00</td></tr>
<tr><td>33</td><td>Riprap (D50 15 in.)–custom</td><td>TON</td><td>2,800</td><td>$75.00</td><td colspan="2">$210,000.00</td></tr>
<tr><td>34</td><td>Articulated concrete block (ACB)–custom</td><td>SY</td><td>10,600</td><td>$136.00</td><td colspan="2">$1,441,600.00</td></tr>
<tr><td>35</td><td>Cellular confinement (CCS)–custom</td><td>SY</td><td>10,700</td><td>$56.00</td><td colspan="2">$599,200.00</td></tr>
<tr><td>36</td><td>Chip existing vegetation–custom</td><td>LS</td><td>1</td><td>$243,225.00</td><td colspan="2">$243,225.00</td></tr>
<tr><td>37</td><td>Site access–custom</td><td>LS</td><td>1</td><td>$360,000.00</td><td colspan="2">$360,000.00</td></tr>
<tr><td>38</td><td>Phragmites removal–custom</td><td>LS</td><td>1</td><td>$50,000.00</td><td colspan="2">$100,000.00</td></tr>
<tr><td>39</td><td>Remove bridge structure–custom</td><td>LS</td><td>1</td><td>$50,000.00</td><td colspan="2">$50,000.00</td></tr>
<tr><td>40</td><td>Broken stone–loose measure–custom</td><td>CY</td><td>3,100</td><td>$65.10</td><td colspan="2">$201,810.00</td></tr>
<tr><td>41</td><td>Shoreline marine debris removal–custom</td><td>LS</td><td>1</td><td>$75,000.00</td><td colspan="2">$75,000.00</td></tr>
<tr><td>42</td><td>Native shoreline grass mix–custom</td><td>SF</td><td>162,000</td><td>$0.55</td><td colspan="2">$89,100.00</td></tr>
<tr><td>42A</td><td>Straw mulch–custom</td><td>ACRE</td><td>10</td><td>$1,500.00</td><td colspan="2">$15,000.00</td></tr>
<tr><td colspan="5" align="right">ENGINEER'S ESTIMATE:</td><td colspan="2">$11,576,597.18</td></tr>
<tr><td colspan="5" align="right">MOBILIZATION:</td><td colspan="2">$655,501.78</td></tr>
<tr><td>43</td><td>Import sand–custom</td><td colspan="2">CY</td><td>10,000</td><td>$30.00</td><td>$900.00</td></tr>
<tr><td colspan="5" align="right">ENGINEER'S ESTIMATE:</td><td colspan="2">$11,577,497.18</td></tr>
</table>

**Table 61. Approximate costs of riverbank stabilization technique (Allen et al. 2006).**

| Stabilization Techniques | Unit Capital Costs(1) | Reference |
|---|---|---|
| Vegetated geogrids | $16–$37/ft2 | Sotir and Fischenich (2003) |
| Live crib wall | $13–$33/ft2 | Gray and Sotir (1996) |
| Joint planting | $1–$5/ft2 (2) | Gray and Sotir (1996) |
| Bush mattress | $3–$14/ft2 | Allen and Fischenich (2001) |
| Vegetated rock gabions | $176–$527/yd3 of protection | Freeman and Fischenich (2000) |

(1)For comparison, all costs were adjusted to 2005 dollars due to inflation.

(2)Does not include riprap and assumes four cuttings/$yd^2$.

Allen et.al (2006) explored several shoreline restoration projects for the Hudson river and summarized the characteristics of the site, the primary erosion method, the existing shoreline condition, benefits expected, the project design, the area of the project, and the cost of the project in Table 62. Allen et.al (2006) can be consulted for the breakdown cost associated with the development of this table.

In summary, given in this example is some basic information on costs of materials and costs for construction of previous NNBF projects. The costs associated with NNBF projects vary greatly dependent upon the design parameters and the locality. Site-specific costs are be related to distance to the source of material. Moreover, NNBF projects require detailed knowledge of the project's objectives as well as the environmental conditions and forcing functions (e.g., winds, waves, surge) associated with the area.

Table 62. Shoreline restoration projects information and costs (adapted from Allen et al. 2006).

| Shoreline Restoration Site | River Mile | River Characteristics | Primary Erosional Forces | Existing Shoreline Conditions | Benefits Expected | Proposed Design | Unique Considerations | Area ($ft^2$) | Unit Costs ($\$/ft^2$) |
|---|---|---|---|---|---|---|---|---|---|
| Bowline Point Park | 35 | Approximately 2.8 miles wide, the largest fetch on the river | Natural wave action, vessel-induced waves | 1. Riprap<br>2. Brick debris concrete debris<br>3. Concrete bulkhead<br>4. Stone walls<br>5. SAV bed<br>6. Jetties | 1. Prevent erosion of shoreline<br>2. Maintain easy public access to shoreline<br>3. Potential future site for swimming | 1. Concrete bulkhead removed<br>2. Riprap installed as required<br>3. Live stakes installed<br>4. Large structures placed in water for refuge habitat | Public park with groomed landscaping | 24,000 | $3.75 |
| Newburgh | 60 | Approximately 4,000 ft with an average depth of approximately 30 ft | Natural wave action, vessel-induced waves, ice scour | 1. Riprap<br>2. Large armor stone<br>3. Concrete debris<br>4. Scrap metal<br>5. Heavy riparian vegetation | 1. Prevent erosion of shoreline<br>2. Increase public access to shoreline<br>3. Enhance fishing opportunities | 1. Remove scrap metal<br>2. Large armor stone and concrete moved below water for refuge habitat<br>3. Riprap installed as required<br>4. Live stakes installed | Remediated brownfield site; shoreline access limited; construction conducted from barge | 16,000 | $17.69 |
| Poughkeepsie | 76 | Approximately 2,600 ft wide and 50 ft deep. Steep bottom slope of 63% near shore. | Vessel-induced waves, ice scour | 1. Riprap<br>2. Deteriorating concrete bulkhead<br>3. Timber piles<br>4. Timber jetty | 1. Prevent erosion of shoreline<br>2. Public access to shoreline | 1. Concrete bulkhead removed<br>2. Riprap installed as required<br>3. Live stakes installed<br>4. Large structures placed in water for refuge habitat | River bottom is steep near shore | 19,160 | $7.36 |
| Henry Hudson Park | 138.5 | Approximately 1,100 ft with an average depth of approximately 20 ft | Vessel-induced waves, ice scour | 1. Deteriorating timber bulkhead with concrete cap<br>2. Breached in areas | 1. Prevent erosion of shoreline<br>2. Maintain future potential for swimming | 1. Concrete cap removed<br>2. Concrete structures placed in water for refuge habitat | Public park with groomed landscaping; large waves from passing ships | 18,000 | $13.67 |

# Appendix C: How to Determine Hydrodynamic and Meteorological Characteristics

## Open coast wave climatology

Open coast sites can have very complex wave climatology because they are impacted by locally generated waves and swell waves generated in other parts of the ocean basin. Typically, multiple wave trains may impact a site at any given time (waves of differing significant height and peak period from different directions). Two sources of data are available to characterize open coast site: measurements and hindcasts. Wave measurements are available through the NDBC web site (http://www.ndbc.noaa.gov/). Figure 68 shows an interactive map on the NDBC web site zoomed into the New York Bight region. Active gauges are indicated with yellow symbols and inactive gauges with red symbols. Inland sites provide atmospheric data (winds, pressures, temperature), and ocean sites typically provide both wave and atmospheric data. By clicking on a gauge location, users can download information about the gauge (location, water depth, sensor type, deployment history) and can download time history data (winds, pressures, temperature; wave heights, periods, directions, if available). The NDBC data typically provide very sparse spatial information with large gaps along the coast. Measurements may be lacking during storm peaks due gauge failures, so care must be taken when using these data to explore extreme conditions. Also, summary statistics are not available, so users must generate their own information on extreme wave heights and return periods. Data records may span from a few years to more than 20 yr. Additional wave gauge data may be available from other Federal, State, and local agencies and universities.

Wave hindcasts are computer simulations of wave fields driven by historic wind fields. The ERDC, Coastal and Hydraulics Laboratory (CHL), Wave Information Studies (WIS) provides a 20 yr hindcast for the U.S. Atlantic coast spanning the years 1980–1999 (http://wis.usace.army.mil/). Hindcast data are also available for the Gulf of Mexico (1980–1999), Pacific Coast and Hawaii (1980–2011), Alaska (1985–2011), and the Great Lakes (1979–2009). For the U.S. Atlantic coast, WIS hindcast information is saved at stations along the coast at approximately a 1/12 deg spacing (6–12 km) at nominal water depths of 20–40 m (deeper where the shelf slope is steep) and 0.5 deg spacing at a nominal depth of 100 m. Figure 69 shows the WIS interactive map viewed in Google Earth for the New York Bight region. The WIS stations provide more dense spatial coverage of the region than the NDBC buoy network. The hindcast provides consistent 3 hr wave data over the 20 hr Atlantic hindcast with no data gaps. WIS also provides summaries of the wave and wind climate (rose plots and summary tables), peak significant wave heights and associated periods for the ten highest wave events, and extremal analysis with estimates of the 50 yr and 100 yr return period wave heights. Figure 70 shows an example of an extremal plot for WIS Station 63126 near the mouth of New York Bay.

Figure 68. Example of NDBC wave and atmospheric measurement locations.


Figure 69. Example of WIS station locations.

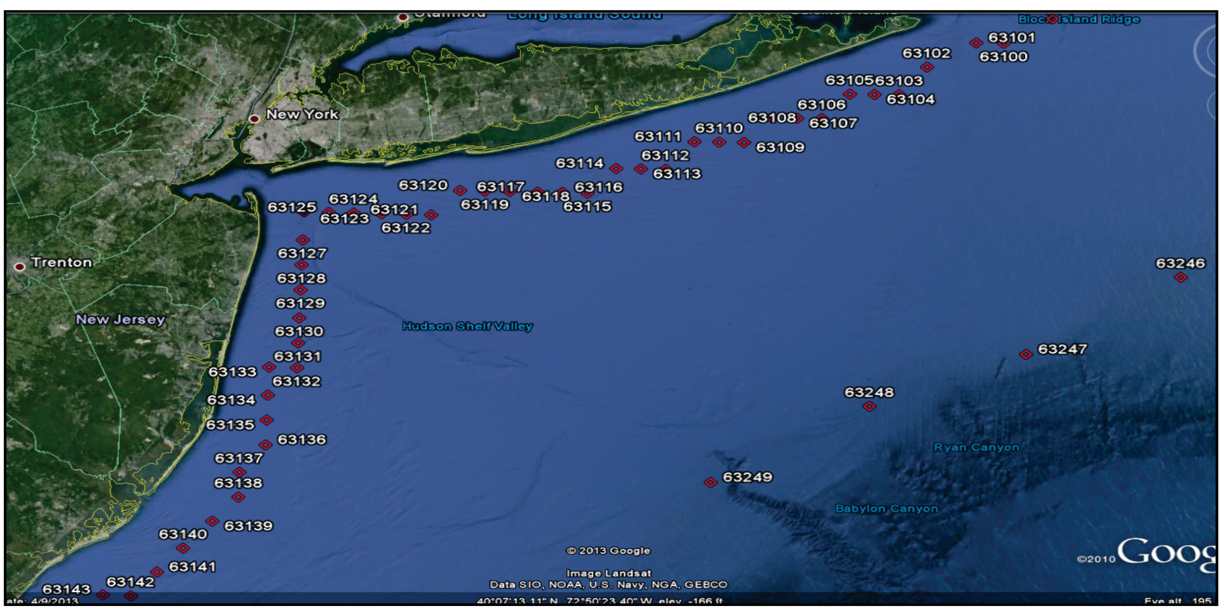
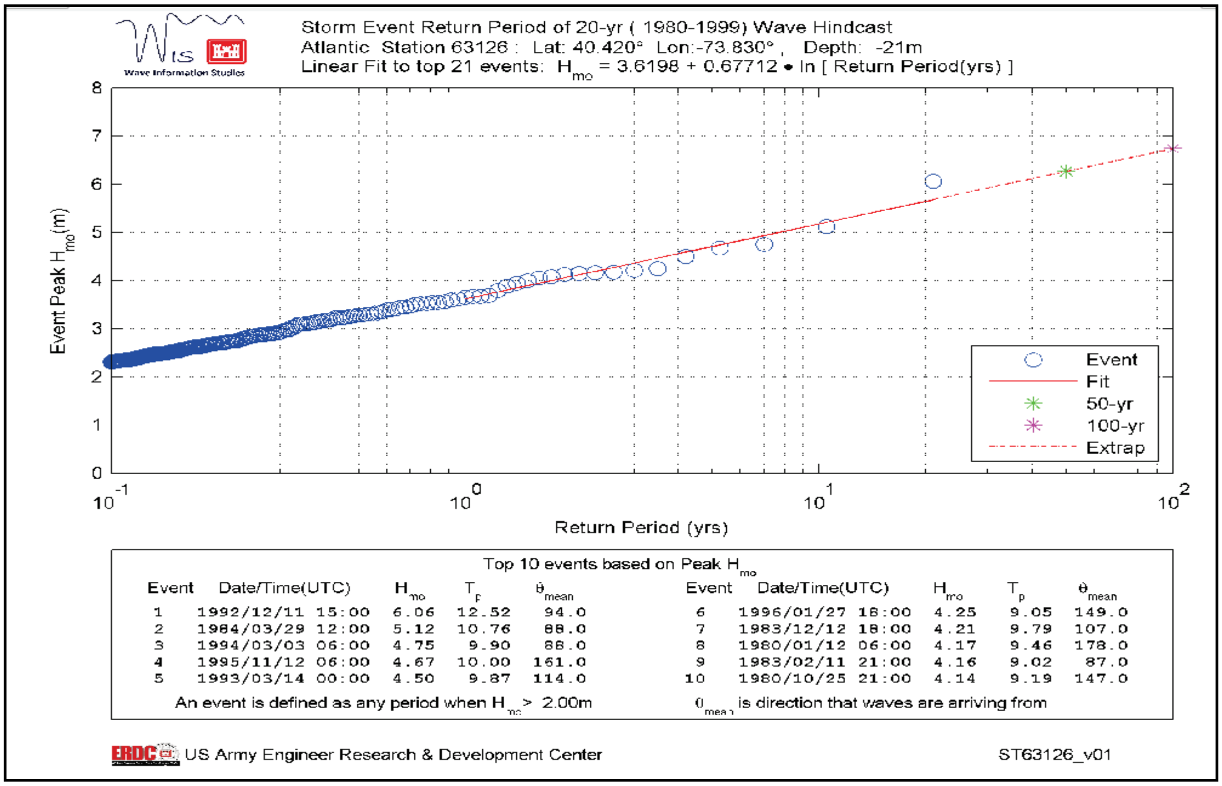


Figure 70. Example of WIS extremal analysis for Station 63125.




Gauge data provides the most reliable data for a given location, but there are large spatial gaps between gauges, and there are often gaps in time during gauge failures. Gauge data also has inherent measurement errors. Hindcast information has good spatial and temporal coverage but has errors due to input information (winds and bathymetry) and errors in the model. For detailed design studies, wave data (from gauges or hindcasts) must be transformed to the project location to estimate the impacts of refraction, shoaling, and breaking. This is often done with a nearshore spectral wave model, such as STWAVE (Massey et al. 2011). Wave energy is dissipated in very shallow water depths through wave breaking (where the wave height is approximately equal to the water depth, including depth increases due to tides, surge, and wind and wave setup).

Open coastal sites are often appropriate for sand or rock-based NNBF alternatives (dune construction, beach fill, revetments, rock reefs), but is typically too severe of an energy regime for wetlands or submerged vegetation.

## Bay or estuary wave climatology

Bays and estuaries generally have a mild wave climates because fetch lengths for wave generation are limited by the size and shape of the water body. Estimates of wave parameters within a bay or estuary are developed using the following steps (Resio et al. 2008):

Estimate wind speed and direction from wind measurements or other climatic information. Wind measurements may be available from buoys, airports, or Coast Guard stations. Wind speed and fetch may both vary by direction, so distribution by speed and direction should be analyzed. Wind speeds should be adjusted to a 10 m elevation:

$$U_{10} = U_z \left(\frac{10}{z}\right)^{\frac{1}{7}} \tag{1}$$

where U10 is the 10 m wind speed and Uz is the wind speed measured at elevation z (in meters).

Wind observations may be averaged over very short time periods (seconds to minutes). Winds must be averaged over a period long enough for fetch-limited waves to develop (typically 10s of minutes to an hour). Wind durations can be converted using:

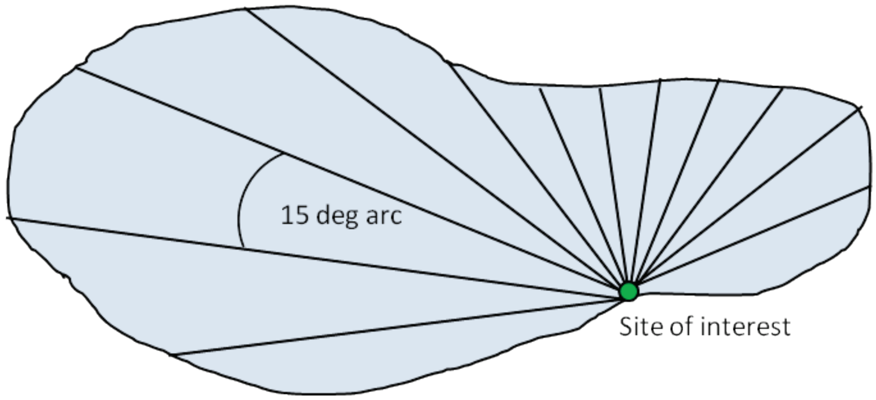
$$\frac{U_t}{U_{3600}} = 1.277 + 0.296 \tanh\left(0.9 \log_{10}\left[\frac{45}{t}\right]\right) \quad 1 \text{ sec} < t < 3600 \text{ sec} \tag{2}$$

$$\frac{U_t}{U_{3600}} = 1.5334 - 0.15 \log_{10} t \quad 3600 \text{ s} < t < 36{,}000 \text{ s} \tag{3}$$

where t is the averaging time.

Estimate fetch (X) by measuring from a map or chart. Starting from the shoreline of interest, draw radials extending to the opposite shoreline. Fetch should be averaged over approximately 15° arcs. Wave height is a function of fetch and wind speed, so if wind speed varies with direction, multiple combinations of wind speed and fetch should be tested. Figure 71 shows an example of estimating the fetch from a map.

Figure 71. Fetch estimate diagram.




Apply fetch-limited wave growth equations, apply consistent units for lengths (m), velocities (m/sec), and times (sec):

Drag coefficient: $$C_D = 0.001(1.1 + 0.035U_{10}) \quad (4)$$

Wind friction velocity: $$u_*^2 = C_D U_{10}^2 \quad (5)$$

Wave height: $$H_{mo} = 0.0413 \frac{u_*^2}{\sqrt{g}} X^{1/2} \quad (6)$$

Wave period: $$T_p = 0.751 \frac{u_*^{1/3}}{g^{2/3}} X^{1/3} \quad (7)$$

If the duration of high winds is relatively short, duration t can be converted to an equivalent fetch and applied to the equations above:

$$X = 0.00523 g^{1/2} u_*^{1/2} t^{3/2} \quad (8)$$

Check for depth-limited conditions. Wave period is limited by

$$T_p \approx 9.78 \left(\frac{d}{g}\right)^{\frac{1}{2}} \quad (9)$$

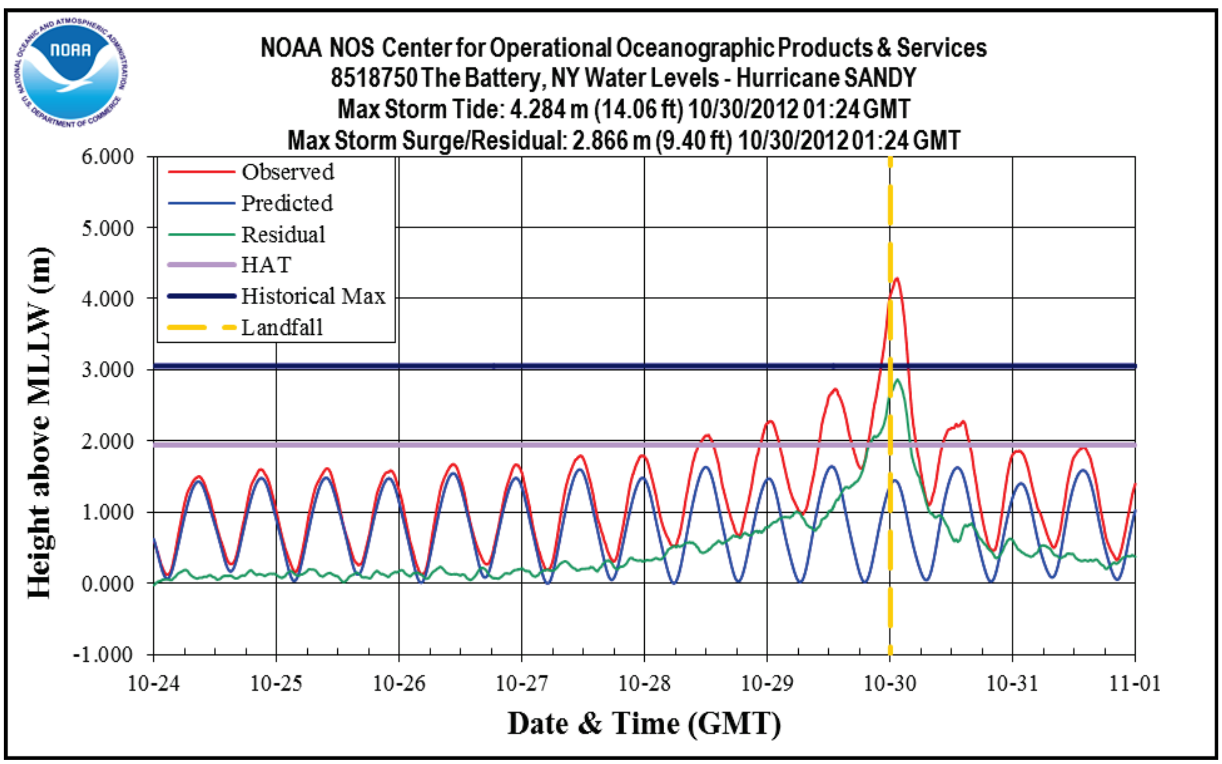
and significant wave height is limited by Hmo = 0.64 d

## Water levels and currents

Water levels and currents are driven by tides, waves, and winds. Tides are the rising and falling of the ocean surface caused primarily by the gravitational forces of the moon and sun. The magnitude and timing of the tidal variation is also a function of the ocean and local basin geometry and bathymetry. Tide ranges on the U.S. coast vary from less than 0.3 m to more than 10 m. The NOAA maintains a series of tide gauges around the U.S. coastline through CO-OPS (http://www.co-ops.nos.noaa.gov/). The CO-OPS website provides access to measured water level data and predicted tide levels around the U.S. coast, referenced to both fixed and tidal datums.

The difference between the measured water level and the predicted tide is the storm surge (Scheffner 2008). Storm surge is forced by winds, atmospheric pressure variations, and wave setup. Rainfall, the storm motion, and the rotation of the earth can also contribute to storm surge. Storm surge in Hurricane Katrina in Mississippi was more than 9 m. Figure 72 shows an example of measured water level, predicted tide, and storm surge (labeled residual) for the NOAA tide gauge at the Battery, NY, during Hurricane Sandy.

Figure 72. Storm surge at the Battery, NY, during Hurricane Sandy (2012).



The barometric pressure contribution to the surge can be estimated with the general rule of Dean and Dalrymple (2002):

$$\eta_b = 1.04\Delta p \qquad (10)$$

where ηb is the barometric tide in centimeters and Δp is the pressure deficit in millibars.

For example, a hurricane with a central pressure of 940 mb (assuming an atmospheric pressure away from the storm of 1013 mb) would produce a surge of approximately 0.8 m due to storm low pressure.

The wind is typically the largest contribution to storm surge. The wind effect is a function of the nearshore slope, the width of the shelf, and the wind speed. The wind contribution to storm surge can be estimated by (Dean and Dalrymple 2002)

$$\eta_w = h\left(\sqrt{1+\frac{2n\tau_s\ell}{\rho g h^2}}-1\right) \qquad (11)$$

where:

ηw = the wind-driven surge
h = water depth on the shelf
ℓ = shelf width
τs = the wind stress
n = the balance of bottom to surface stress (typically 1.15 to 1.13)
ρ = the density of water
g = gravitational acceleration.

Consistent units must be used. The wind stress is defined as

$$\tau_s = \rho C_f W^2 \qquad (12)$$

where:

Cf = the drag coefficient (1.2 to 3.4 x 10-6)
W = the wind speed.

Wave setup is a function of the breaking wave height and the nearshore slope. An estimate of maximum wave setup at the shoreline is approximately 20% of the breaking wave height. At the shoreline, waves excite a long-period oscillation called runup or swash. The elevation that the runup reaches can impact dune erosion and overwash. Runup is a function of wave height and period, beach slope, and beach roughness.

Storm surge and tides are routinely modeled with 2D or 3D circulation models based on the equations of continuity and momentum (e.g., the ADvanced CIRCulation model ADCIRC) (Luettich and Westerink 2004). Circulation models operate on a bathymetry grid that resolves important bathymetric and topographical features and are forced with fields of wind vectors, atmospheric pressure, wave stresses, and tidal potential. The complexity of the coastal environment requires high-resolution, high-fidelity modeling to accurately represent storm surge and tides.

Currents in the near-coast environment are also driven by tides, winds, and waves (Smith 2003) and can be modeled with the same circulation models used to represent water levels. Current measurements are available in some coastal locations from the NOAA CO-OPS web site (http://www.co-ops.nos.noaa.gov/). Wave-driven currents that run parallel to the coast are driven by waves breaking at an angle to the shoreline. The magnitude and direction of the current are determined by the breaking wave height and the breaking wave angle. The current velocity in the mid surf zone can be estimated by

$$V_{mid} = 1.17\sqrt{gH_{rms,b}}\sin\alpha_b\cos\alpha_b \tag{13}$$

where:

$V_{mid}$ = the current velocity in the mid surf zone (between where waves start to break and the shoreline)
$H_{rms,b}$ = the root-mean-square wave height
$\alpha_b$ = the wave angle at incipient breaking.

During storms, longshore currents may be 1–1.5 m/sec. Winds and tidal elevation differences can also drive currents in near-coast areas. Tidal currents are typically greatest at coastal inlets where flow is restricted (Seabergh 2008). Current velocities in inlets may peak at 1–2 m/sec, depending on the tidal elevation difference between the bay and ocean sides the inlet and flow resistance in the inlet.

## Winds

Winds are an important driving force for waves, currents, and transport of sediment on the subaerial beach. For driving wave or circulation calculations, winds are adjusted to a 10 m elevation with an averaging period of approximately 10–30 min. Sources of wind information include measurements from NOAA weather stations, NDBC buoys, airports, and Coast Guard stations. Hindcast wind information is available on the WIS website. Aeolian sand transport on beaches is responsible for the accretion and erosion of beaches and dunes (Hsu and Weggel 2002).

# Appendix D: Supplemental Vulnerability Data and Information

This Appendix provides supplemental data and information from selected previous studies that have demonstrated various approaches to coastal vulnerability assessment (Table 63 through Table 70).

## Previous vulnerability indices

Table 63. Thieler and Hammer-Klose (1999) ranking of coastal vulnerability for the U.S. Atlantic Coast.

| | Ranking of coastal vulnerability index | | | | |
|---|---|---|---|---|---|
| | Very low | Low | Moderate | High | Very high |
| VARIABLE | 1 | 2 | 3 | 4 | 5 |
| Geomorphology | Rocky, cliffed coasts<br>Fiords<br>Fiards | Medium cliffs<br>Indented coasts | Low cliffs<br>Glacial drift<br>Alluvial plains | Cobble beaches<br>Estuary<br>Lagoon | Barrier beaches<br>Sand Beaches<br>Salt marsh<br>Mud flats<br>Deltas<br>Mangrove<br>Coral reefs |
| Coastal Slope (%) | >0.115 | 0.115 – 0.055 | 0.055 – 0.035 | 0.035 –0.022 | < 0.022 |
| Relative sea-level change (mm/yr) | < 1.8 | 1.8 – 2.5 | 2.5 – 3.0 | 3.0 – 3.4 | > 3.4 |
| Shoreline erosion/ accretion (m/yr) | >2.0<br>Accretion | 1.0 –2.0<br>Accretion | -1.0 – +1.0<br>Stable | -1.1– -2.0<br>Erosion | < - 2.0<br>Erosion |
| Mean tide range (m) | > 6.0 | 4.1 – 6.0 | 2.0 – 4.0 | 1.0 –1.9 | < 1.0 |
| Mean wave height (m) | <0.55 | 0.55 – 0.85 | 0.85 – 1.05 | 1.05 –1.25 | >1.25 |

Table 64. Thieler and Hammer-Klose (2000a) ranking of coastal vulnerability for the U.S. Pacific Coast.

| | Ranking of coastal vulnerability index | | | | |
|---|---|---|---|---|---|
| | Very low | Low | Moderate | High | Very high |
| VARIABLE | 1 | 2 | 3 | 4 | 5 |
| Geomorphology | Rocky, cliffed coasts<br>Fiords<br>Fiards | Medium cliffs<br>Indented coasts | Low cliffs<br>Glacial drift<br>Alluvial plains | Cobble beaches<br>Estuary<br>Lagoon | Barrier beaches<br>Sand Beaches<br>Salt marsh<br>Mud flats<br>Deltas<br>Mangrove<br>Coral reefs |
| Coastal Slope (%) | > 1.9 | 1.3 – 1.9 | 0.9 – 1.3 | 0.6 –0.9 | < .6 |
| Relative sea-level change (mm/yr) | < -1.21 | -1.21 – 0.1 | 0.1 – 1.24 | 1.24 –1.36 | > 1.36 |
| Shoreline erosion/ accretion (m/yr) | >2.0<br>Accretion | 1.0 –2.0 | -1.0 – +1.0<br>Stable | -1.1– -2.0 | < - 2.0<br>Erosion |
| Mean tide range (m) | > 6.0 | 4.1 – 6.0 | 2.0 – 4.0 | 1.0 –1.9 | < 1.0 |
| Mean wave height (m) | <1.1 | 1.1 – 2.0 | 2.0 – 2.25 | 2.25 –2.60 | >2.60 |

Table 65. Thieler and Hammer-Klose (2000b) ranking of coastal vulnerability for the U.S. Gulf Coast.

| | Ranking of coastal vulnerability index | | | | |
|---|---|---|---|---|---|
| | Very low | Low | Moderate | High | Very high |
| VARIABLE | 1 | 2 | 3 | 4 | 5 |
| Geomorphology | Rocky, cliffed coasts<br>Fiords<br>Fiards | Medium cliffs<br>Indented coasts | Low cliffs<br>Glacial drift<br>Alluvial plains | Cobble beaches<br>Estuary<br>Lagoon | Barrier beaches<br>Sand Beaches<br>Salt marsh<br>Mud flats<br>Deltas<br>Mangrove<br>Coral reefs |
| Coastal Slope (%) | >0.115 | 0.115 – 0.055 | 0.055 – 0.035 | 0.035 –0.022 | < 0.022 |
| Relative sea-level change (mm/yr) | < 1.8 | 1.8 – 2.5 | 2.5 – 3.0 | 3.0 – 3.4 | > 3.4 |
| Shoreline erosion/ accretion (m/yr) | >2.0<br>Accretion | 1.0 –2.0 | -1.0 – +1.0<br>Stable | -1.1– -2.0 | < - 2.0<br>Erosion |
| Mean tide range (m) | > 6.0 | 4.1 – 6.0 | 2.0 – 4.0 | 1.0 –1.9 | < 1.0 |
| Mean wave height (m) | <0.55 | 0.55 – 0.85 | 0.85 – 1.05 | 1.05 –1.25 | >1.25 |

Table 66. Social variable descriptions used in social vulnerability index of Boruff et al. (2005).

| |
|---|
| Median age |
| Per capita income |
| Median dollar valued of owner-occupied housing |
| Median rent for renter-occupied housing |
| percent voting for leading political party |
| Birth rate |
| Net international migration |
| Land in farms as a percent of total land |
| percent African American |
| percent Native American |
| percent Asian |
| percent Hispanic |
| percent of Pop under 5 yr old |
| percent of Pop over 65 yr old |
| percent of civilian labor force that is unemployed |
| Average number of people per household |
| percent of household earning more than $100,000 |
| percent living in poverty |
| percent renter-occupied housing units |
| percent rural farm Pop |
| General local government debt to revenue ratio |
| percent of housing units that are mobile homes |
| percent of Pop 25 yr or older with no high school diploma |
| Number of housing units per square mile |
| Number of housing permits per new residential construction per square mile |
| Number of manufacturing establishments per square mile |
| Earnings in all industries per square mile |
| Number of commercial establishments per square mile |
| Value of all property and farm products sold per square mile |
| percent of Pop participating in the labor force |
| percent of females participating in civilian labor force |
| percent employed in primary extractive industries |
| percent employed in transportation, communications, and other public utilities |
| percent employed in service occupations |
| percent Pop change over last decade |
| percent urban Pop |
| percent females |
| percent female headed households, no spouse present |
| Per capita social security recipients |

Table 67. Factors that explain majority of vulnerability variance for U.S. coastal counties (Boruff et al. 2005).

| |
|---|
| Poverty |
| Age |
| Development density |
| Asian and immigrants |
| Rural/urban dichotomy |
| Race and gender |
| Pop decline |
| Ethnicity and farming |
| Infrastructure employment reliance |
| Income |

Table 68. Vulnerability rankings for national/regional scale from McLaughlin and Cooper (2010).

| | Factor | Very Low 1 | Low 2 | Moderate 3 | High 4 | Very High 5 |
|---|---|---|---|---|---|---|
| Coastal characteristics | Solid geology | Plutonic; volcanic; high/medium-grade metamorphics | Low-grade metamorphic; sandstone and conglomerate well cemented | Most sedimentary rocks | Coarse and/or poorly sorted unconsolidated sediments | Fine unconsolidated sediment, volcanic ash |
| | Drift geology | Bedrock; urban | Till/boulder clay | | Raised beach deposits | Alluvium; brown sand; peat; glacial sands and gravels; glacial outwash sands; recent marine |
| | Landform | High resistance cliff | Low resistance cliff | Multiple sand dune ridges | Single sand dune ridges; gravel and boulder ridges | Mudflat; salt marsh; beach–no dunes |
| | Elevation (m) | >30 | 20 to <30 | 10 to <20 | 5 to <10 | <5 |
| | Rivers | Absent | | | | Present |
| | Inland buffer (m from MHWM) | >500 | | | | 0 to <500 |
| Coastal forcing | Significant wave height (m) | 0 to <0.74 N<br>0 to <0.24 E | 0.74 to <1.49 N<br>0.24 to <0.48 E | 1.49 to <2.23N<br>0.48 to <0.72 E | 2.23 to <2.98 N<br>0.72 to <0.96 E | >2.98 N<br>>0.96 E |
| | Tidal range (m) | >5 | 3.5 to <5 | 2 to <3.5 | 1 to <2 | <1 |
| | Difference in modal and storm waves (m) | <0.10 N<br><0.10 S | 0.10 to 1.70 N<br>0.10 to <0.25 S | 1.70 to <3.30 N<br>0.25 to <0.40 S | 3.30 to <4.90 N<br>0.40 to <0.55 S | >4.9 N<br>>0.55 S |
| | Frequency of onshore storms (%) | 0 to <2.8 | 2.8 to <5.6 | 5.6 to <8.4 | 8.4 to <11.2 | >11.2 |
| | Morphodynamic state (Dean's parameter) | Rocky coasts and gravel beaches | <1.5 or >5.5 | 1.5 to 5.5 | 0 to >5.5 | 0 to >5.5 |
| Socioeconomic | Settlement | No settlement | Village | Small town | Large town | City |
| | Cultural heritage | Absent | | | | Present |

| | Factor | Very Low<br>1 | Low<br>2 | Moderate<br>3 | High<br>4 | Very High<br>5 |
|---|---|---|---|---|---|---|
| Socioeconomic | Land use | Water bodies; marsh/bog; sparsely vegetated areas; bare rocks | Natural grasslands; coastal areas | Forest | Agriculture | Urban and industrial infrastructure |
| | Pop (1000s of people) | 0 to <5 | 5 to <20 | 20 to <50 | 50 to <100 | >100 |
| | Roads | Absent | Minor roads (<4 m) | Minor roads (>4 m) | B-class roads | A-class roads |
| | Railways | Absent | | | | Present |
| | Conservation designation | Absent | | European international | | National |

Table 69. Vulnerability rankings for local scale from McLaughlin and Cooper (2010).

| | Factor | Very Low<br>1 | Low<br>2 | Moderate<br>3 | High<br>4 | Very High<br>5 |
|---|---|---|---|---|---|---|
| Coastal characteristics | Landform | High resistance cliff; seawall | Low resistance cliff | Multiple sand dune ridges | Single sand dune ridges; gravel and boulder ridges | Mudflat; salt marsh; beach–no dunes |
| | Elevation (m) | >30 | 20 to <30 | 10 to <20 | 5 to <10 | <5 |
| | Rivers | Absent | | | | Present |
| | Inland buffer (m from MHWM) | 300 to >1000 | | 50 to <300 | | 0 to <50 |
| Coastal forcing | Storm probability (based on coastal orientation) | North-easterly | Northerly, Easterly | North-westerly, South-easterly | Southerly, South-westerly | Westerly |
| | Morphodynamic state (Dean's parameter) | Rocky coasts and gravel beaches | <1.5 or >5.5 | 1.5 to 5.5 | 0 to >5.5 | 0 to >5.5 |
| Socioeconomic | Cultural heritage | Absent | | | | Present |
| | Land use | Rocky cliffs | Scrub | Beach; sand dunes; forest; rough | Agriculture; tee boxes, fairways; amenity grass | Urban; residential; car parks; greens |
| | Pop | Absent | | | | Present |
| | Roads | Absent | Footpaths | Minor access roads | B-class roads | A-class roads |

Table 70. Vulnerability rankings from Abuodha and Woodroffe (2006).

| Factor | Very Low<br>1 | Low<br>2 | Moderate<br>3 | High<br>4 | Very High<br>5 |
|---|---|---|---|---|---|
| Dune height (m) | >30.0 | 20.1 to 30.0 | 10.1 to 20.0 | 5.1 to 10.0 | 0.0 to 5.0 |
| Barrier type | Transgressive | Prograded | Stationary | Receded | Mainland beach |
| Beach type | Dissipative; longshore bar trough | Rhythmic bar beach | Transverse bar rip | Low-tide terrace | Reflective |
| Relative sea level change (mm/yr) | <−1.0<br>Land rising | −1.0 to 1.0 | 1.1 to 2.0 | 2.1 to 4.0 | >4.0<br>Land sinking |
| Shoreline erosion/accretion (m/yr) | >2.0<br>Accretion | 1.1 to 2.0 | −1.0 to 1.0 | −2.0 to −1.1 | <−2.0<br>Erosion |
| Mean tidal range (m) | <1.0<br>Microtidal | 1.0 to 1.9 | 2.0 to 4.0 | 4.1 to 6.0 | >6.0<br>Macrotidal |
| Mean wave height (m) | 0.0 to 2.9 | 3.0 to 4.9 | 5.0 to 5.9 | 6.0 to 6.9 | >6.9 |

## Details from work of Jimenez et al. (2009)

For the beaches considered by Jimenez et al. (2009), storm-induced inundation is mainly driven by wave runup. Therefore, a parameter to characterize inundation can be given as

$$I \propto \sqrt{HL} \tag{14}$$

where H is significant wave height and L is the deepwater wavelength. Equation 1 allows for a parameterization of the vulnerability associated only with the forcing. However, wave runup is also a function of the beach characteristics, and wave runup (R) can be estimated based on empirical equations such as Stockdon et al. (2006) or a numerical model such as CSHORE (Johnson et al. 2012).

Beach erosion from storms (E) can be parameterized based on the excess of Dean's parameter above an equilibrium value:

$$E \propto \left( | D - Deq |^{0.5} \tan\beta \right) \tau \tag{15}$$

where:

D = H/(wf T) = Dean's parameter
Deq = Dean's parameter at equilibrium
Wf = sediment fall velocity
T = wave period
tan β = beach slope
τ = storm duration.

Equation 2 considers both storm forcing and beach characteristics. To account only for differences associated with storm forcing, Equation 2 must be evaluated using consistent assumed beach characteristic values. To translate Equation 2 into an actual measure of shoreline displacement requires an approach similar to that documented by Mendoza and Jimenez (2006), but this is uncertain and requires some level of data. Erosion can also be estimated based on data available at a given site or on numerical models such as CSHORE (Johnson et al. 2012) or SBEACH (Larson and Kraus 1989).

The next step in the Jimenez framework is to compute an intermediate parameter that includes the ability of the coastal system to cope with the forcing. In the case of inundation, the runup elevation is divided by the dune elevation, or if no dune is present, the beach berm elevation:

$$Ivp = R / z \tag{16}$$

where:

R = the computed wave runup elevation
Z = the beach berm or dune height.

For erosion, the intermediate vulnerability parameter can be calculated as

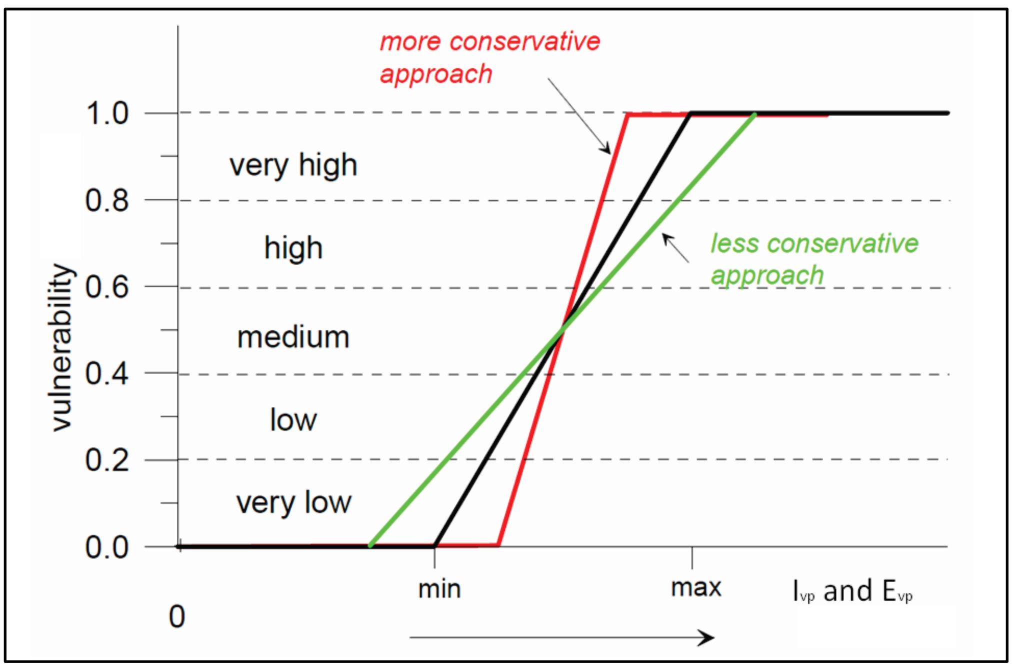
$$Evp = \Delta x / W \tag{17}$$

where:

Δx = the induced shoreline erosion
W = the beach width.

The results from Equations 3 and 4 can be translated into a vulnerability value by means of a functional relationship such as that plotted in Figure 73.

Figure 73. Example functional relationship to value vulnerability (Bosom and Jimenez 2011).



The vulnerability is scaled in a range from 0 (indicating a safe beach) to 1 (indicating an extremely vulnerable beach). Qualitative classes can also be assigned as indicated in

Figure 73 (Bosom and Jimenez 2011). Figure 73 assumes that vulnerability linearly depends on the parameterizations computed by Equations 16 and 17, but a nonlinear relationship could also be applied. By developing a function to define the vulnerability values, a continuum of vulnerability can be defined that appropriately considers thresholds. The framework introduced by Jimenez et al. (2009) can accommodate a probabilistic approach to vulnerability assessment as documented by Bosom and Jimenez (2011).

# Appendix E: Coastal Landscape Metrics

## Drowned river valley

Figure 74 illustrates a drowned river valley coast and is representative of a landscape found, for example, along Chesapeake and Delaware Bays. Following the process described, the set of metrics developed for this coastal landscape in determining vulnerability to coastal storms is given in Table 71. Table 71 also presents the reason each metric is included. The metrics in Table 71 are for consideration at the landscape scale.

Figure 74. Drowned river valley coast schematic.

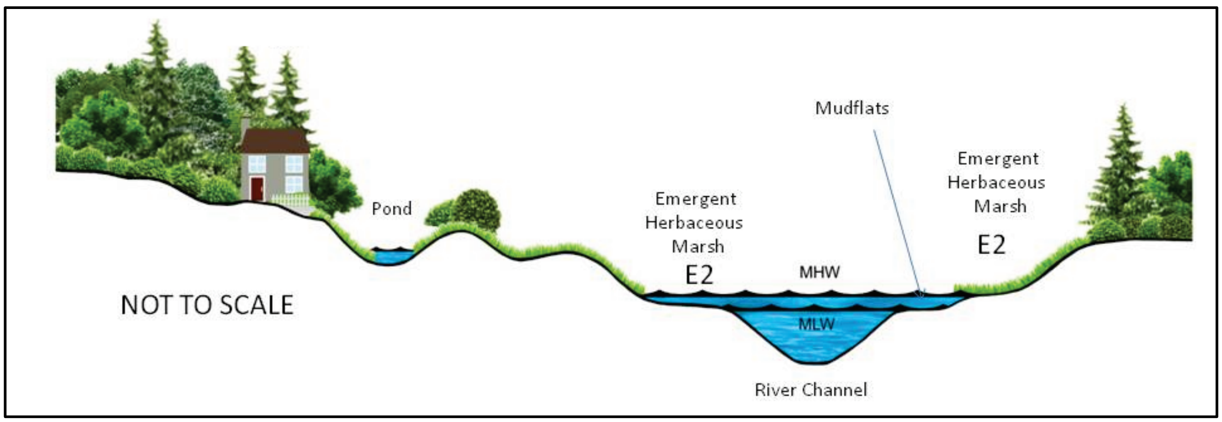



Table 71. Metrics for drowned river valley coastal landscape.

| Metric | Reason |
|---|---|
| Coastal Characteristics | |
| Average elevation at point of interest (m) | Primary driver of coastal vulnerability to storms and should always be included as a metric. |
| Max elevation between point of interest and nearest shoreline (m) | Considers the presence of protective features such as dunes, levees, hills, etc. |
| Shoreline sediment median grain size (mm) | Used as a measure of the erodibility of the coastline and the ability of the shoreline to recover (e.g., gravel vs. sand vs. clay) |
| Distance from point of interest to nearest shoreline (m) | Accounts for presence of the landmass, which dissipates wave energy, slows surge propagation, and provides a buffer for erosion. Shoreline could be considered at multiple datums such that subtidal features could be accounted for, if desired. |
| Land cover type along distance from point of interest to nearest shoreline (Manning n) | The coverage on a landmass also influences wave energy dissipation, surge propagation, and erodibility. |

| Metric | Reason |
|---|---|
| Open-water fetch from nearest shoreline (km) | In the absence of wave and water level data, can be used, along with wind data, as an indicator of the wave energy and storm surges a shoreline may be subject to. |
| Nearest shoreline change variance (m) | A proxy for measuring the storminess along a sandy coastline, particularly as an indicator of how storminess effects the erosion hazard. |
| Long-term nearest shoreline change rate (m) | An eroding shoreline is more vulnerable than an accreting shoreline, and recovery of a beach along a chronically eroding shoreline is less likely. |
| Mud flat area (km2) | Dissipates wave energy. |
| Oyster reef area (km2) | Dissipates wave energy. |
| **Forcing** | |
| Max still-water elevation (m) | Primary driver of coast coastal vulnerability to storms. Application of statistically derived values allows for the consideration of storminess over the temporal reference of interest. |
| Max wave height (m) | Important driver of coast coastal vulnerability to storms. Application of statistically derived values allows for the consideration of storminess over the temporal reference of interest. |
| Freshwater flow rate (m3/day) | The runoff from the watershed can be a significant contribution to storm water levels in these areas. In the absence of appropriate water level data, the flow rate or potential flow rate from the watershed should be considered. |
| Max wind speed (m/sec) | Should be considered as a damage driver and can also be used to estimate other metrics (such as wave heights) in the absence of that data. |
| Relative sea level rise (mm/yr) | Important consideration for vulnerability assessments with a long temporal reference. |
| Tidal range (m) | Shorelines with large tidal ranges typically dissipate more wave energy. |
| **Socioeconomic** | |
| Pop | Because vulnerability is based on human value judgments, the presence of humans on a coast must be a consideration and also increases the likelihood of planned adaptation. |
| Land cover | Indicator of coastal land use and the likelihood of planned adaptation and emergency response activities. |
| Median income ($) | Indicator of a community's ability to engage in planned adaptation and emergency response activities. |
| Property values ($) | Indicator of coastal land use and the likelihood of planned adaptation and emergency response activities. |
| Traffic volume | Indicator of the likelihood of planned adaptation and emergency response activities. |

## Drowned glacial erosional coast

Figure 75 illustrates a drowned glacial erosional coast and is representative of a landscape found, for example, along Massachusetts rocky shores. Following the process described earlier, the set of metrics developed for this coastal landscape in determining vulnerability to coastal storms is given in Table 72. Table 72 also presents the reason each metric is included. The metrics in Table  are for consideration at the landscape scale.

Figure 75. Drowned glacial erosional coast schematic.

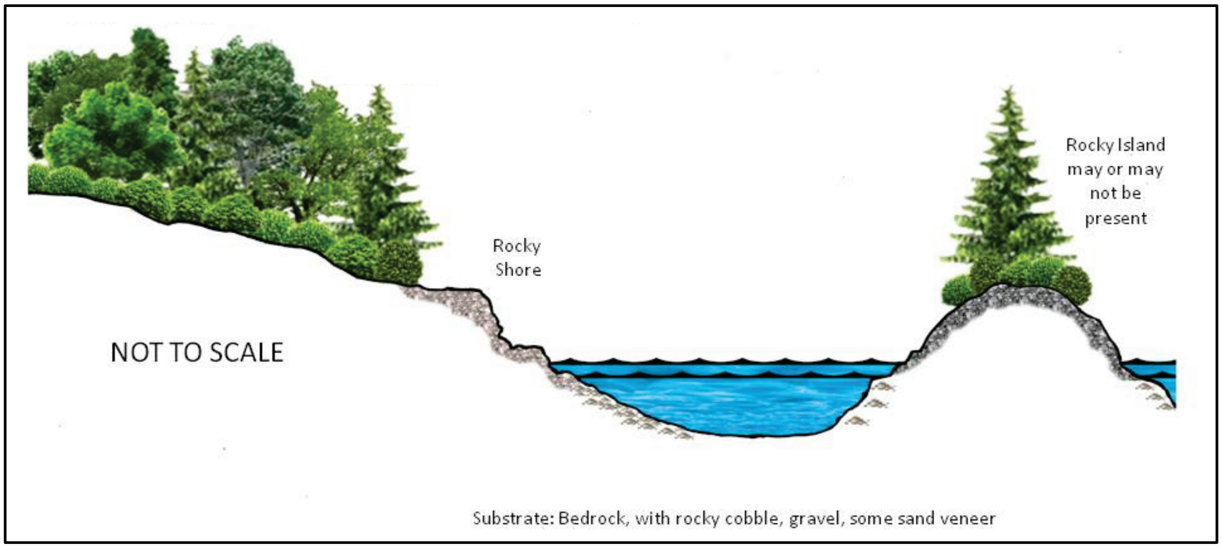



Table 72. Metrics for drowned glacial erosional coastal landscape.

| Metric | Reason |
|---|---|
| Coastal Characteristics | |
| Average elevation at point of interest (m) | Primary driver of coastal vulnerability to storms and should always be included as a metric. |
| Max elevation between point of interest and nearest shoreline (m) | Considers the presence of protective features such as large rock outcroppings, levees, etc. |
| Shoreline sediment median grain size (mm) | Used as a measure of the erodibility of the coastline and the ability of the shoreline to recover (e.g., gravel vs. sand vs. clay) |
| Distance from point of interest to nearest shoreline (m) | Accounts for presence of the landmass, which dissipates wave energy, slows surge propagation, and provides a buffer for erosion. Shoreline could be considered at multiple datums such that sub-tidal features could be accounted for, if desired. |
| Land cover type along distance from point of interest to nearest shoreline (Manning n) | The coverage on a landmass also influences wave energy dissipation, surge propagation, and erodibility. |
| Open-water fetch from nearest shoreline (km) | In the absence of wave and water level data, can be used, along with wind data, as an indicator of the wave energy and storm surges a shoreline may be subject to. |

| Metric | Reason |
|---|---|
| Nearest shoreline change variance (m) | A proxy for measuring the storminess along a sandy coastline, particularly as an indicator of how storminess effects the erosion hazard. |
| Long-term nearest shoreline change rate (m) | An eroding shoreline is more vulnerable than an accreting shoreline, and recovery of a beach along a chronically eroding shoreline is less likely. |
| Average max elevation between nearest shoreline and open coast (m) | Accounts for the presence of a landmass, such as a barrier island, offshore the nearest shoreline. |
| Landmass area between nearest shoreline and open coast (km2) | Accounts for the presence of a landmass, such as a barrier island, offshore the nearest shoreline. |
| Coastal slope (%) | In the absence of water level data, may be used as an indicator of storm surges that an area may experience during a storm. |
| Open coast shoreline sediment median grain size (mm) | Used as a measure of the erodibility of the coastline and the ability of the shoreline to recover (e.g., gravel vs. sand vs. clay) |
| Forcing | |
| Max still-water elevation (m) | Primary driver of coast coastal vulnerability to storms. Application of statistically derived values allows for the consideration of storminess over the temporal reference of interest. |
| Max wave height (m) | Important driver of coast coastal vulnerability to storms. Application of statistically derived values allows for the consideration of storminess over the temporal reference of interest. |
| Max wave runup elevation (m) | Not typically available directly from data, but may be calculated based on other available date (e.g., offshore wave height, period, and beach slope). May be the primary source of flooding on some coasts. |
| Max wind speed (m/sec) | Should be considered as a damage driver and can also be used to estimate other metrics (such as wave heights) in the absence of that data. |
| Relative sea level rise (mm/yr) | Important consideration for vulnerability assessments with a long temporal reference. |
| Tidal range (m) | Shorelines with large tidal ranges typically dissipate more wave energy. |
| Socioeconomic | |
| Pop | Because vulnerability is based on human value judgments, the presence of humans on a coast must be a consideration and also increases the likelihood of planned adaptation. |
| Land cover | Indicator of coastal land use and the likelihood of planned adaptation and emergency response activities. |
| Median Income ($) | Indicator of a community’s ability to engage in planned adaptation and emergency response activities. |
| Property values ($) | Indicator of coastal land use and the likelihood of planned adaptation and emergency response activities. |
| Traffic volume | Indicator of the likelihood of planned adaptation and emergency response activities. |

# Glacial depositional coast

## With bluffs

Figure 76 illustrates a glacial depositional coast with bluffs and is representative of a landscape found, for example, along the shores of New York, Connecticut, and Massachusetts. Following the process described earlier, the set of metrics developed for this coastal landscape in determining vulnerability to coastal storms is given in Table 73. Table 73 also presents the reason each metric is included. The metrics in Table 73 are for consideration at the landscape scale.

Figure 76. Glacial depositional coast with bluff schematic.

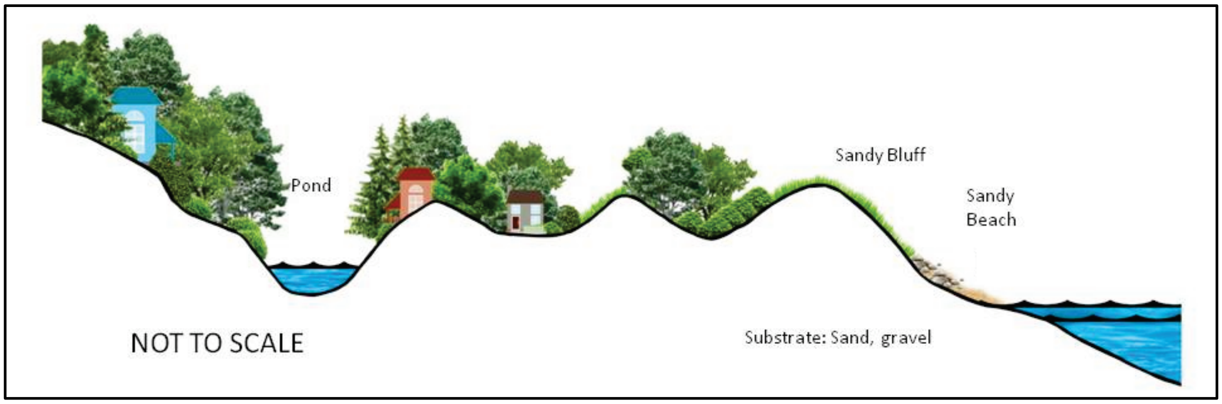



Table 73. Metrics for glacial depositional coastal landscape with bluffs.

| Metric | Reason |
|---|---|
| Coastal Characteristics | |
| Average elevation at point of interest (m) | Primary driver of coastal vulnerability to storms and should always be included as a metric. |
| Max elevation between point of interest and nearest shoreline (m) | Considers the presence of protective features such as hills, levees, etc. |
| Distance from point of interest to nearest shoreline (m) | Accounts for presence of the landmass, which dissipates wave energy, slows surge propagation, and provides a buffer for erosion. Shoreline could be considered at multiple datums such that subtidal features could be accounted for, if desired. |
| Land cover type along distance from point of interest to nearest shoreline (Manning N) | The coverage on a landmass also influences wave energy dissipation, surge propagation, and erodibility. |
| Open-water fetch from nearest shoreline (km) | In the absence of wave and water level data, can be used, along with wind data, as an indicator of the wave energy and storm surges a shoreline may be subject to. |
| Nearest shoreline change variance (m) | A proxy for measuring the storminess along a sandy coastline, particularly as an indicator of how storminess effects the erosion hazard. |

| Metric | Reason |
|---|---|
| Distance from point of interest to bluff edge (m) | Applicable for locations on profile landward of bluff edge. Locations in proximity to the edge of the bluff are more vulnerable to the erosion hazard than are location more distant. |
| Long-term nearest shoreline change rate (m) | An eroding shoreline is more vulnerable than an accreting shoreline, and recovery of a beach along a chronically eroding shoreline is less likely. |
| Average max elevation between nearest shoreline and open coast (m) | Accounts for the presence of a landmass, such as a barrier island, offshore the nearest shoreline. |
| Landmass area between nearest shoreline and open coast (km2) | Accounts for the presence of a landmass, such as a barrier island, offshore the nearest shoreline. |
| Beach berm width (m) | Beach protects the toe of the bluff from wave impact and erosion. The wider the beach the less vulnerable the toe of the bluff and therefore the less vulnerable locations landward of the bluff edge are to coastal storms. |
| Beach slope (%) | Influences wave runup and therefore the likelihood that the toe of a bluff will be subjected to wave runup impact. |
| Open coast shoreline sediment median grain size (mm) | Used as a measure of the erodibility of the coastline and the ability of the shoreline to recover (e.g., gravel vs. sand vs. clay). |
| Forcing | |
| Max still-water elevation (m) | Primary driver of coast coastal vulnerability to storms. Application of statistically derived values allows for the consideration of storminess over the temporal reference of interest. |
| Max wave height (m) | Important driver of coast coastal vulnerability to storms. Application of statistically derived values allows for the consideration of storminess over the temporal reference of interest. |
| Max wave runup elevation (m) | Not typically available directly from data, but may be calculated based on other available date (e.g., offshore wave height, period, and beach slope). May be the primary source of flooding on some coasts. |
| Max wind speed (m/sec) | Should be considered as a damage driver and can also be used to estimate other metrics (such as wave heights) in the absence of that data. |
| Relative sea level rise (mm/yr) | Important consideration for vulnerability assessments with a long temporal reference. |
| Tidal range (m) | Shorelines with large tidal ranges typically dissipate more wave energy. |
| Socioeconomic | |
| Pop | Because vulnerability is based on human value judgments, the presence of humans on a coast must be a consideration and also increases the likelihood of planned adaptation. |
| Land cover | Indicator of coastal land use and the likelihood of planned adaptation and emergency response activities. |
| Median Income ($) | Indicator of a community's ability to engage in planned adaptation and emergency response activities. |
| Property values ($) | Indicator of coastal land use and the likelihood of planned adaptation and emergency response activities. |
| Traffic volume | Indicator of the likelihood of planned adaptation and emergency response activities. |

## No bluffs

Figure 77 illustrates a glacial depositional coast and is representative of a landscape found, for example, along the shores of New York and Connecticut. Following the process described earlier, the set of metrics developed for this coastal landscape in determining vulnerability to coastal storms is given in Table 74. Table 74 also presents the reason each metric is included. The metrics in Table 74 are for consideration at the landscape scale.

Figure 77. Glacial depositional coast schematic.

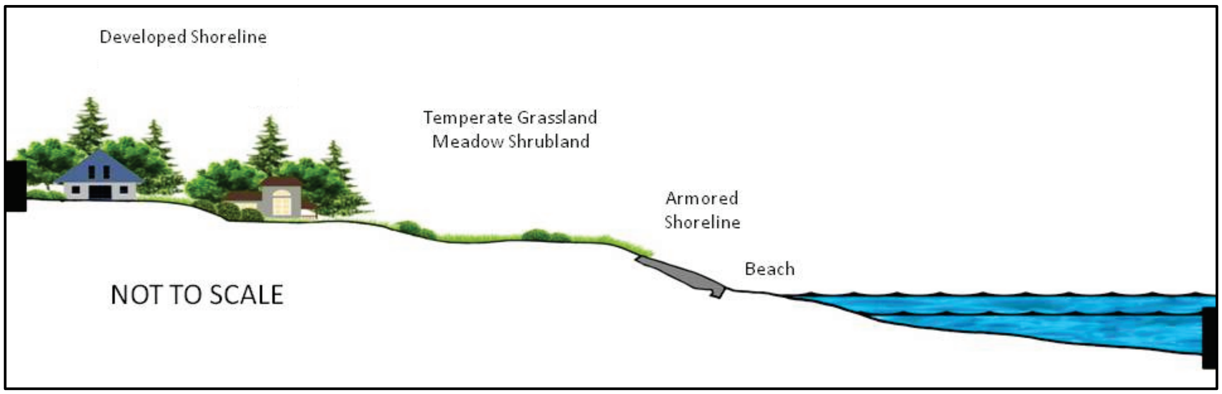



Table 74. Metrics for glacial depositional coastal landscape without bluffs.

| Metric | Reason |
|---|---|
| **Coastal Characteristics** | |
| Average elevation at point of interest (m) | Primary driver of coastal vulnerability to storms and should always be included as a metric. |
| Max elevation between point of interest and nearest shoreline (m) | Considers the presence of protective features such as hills, dunes, levees, etc. |
| Distance from point of interest to nearest shoreline (m) | Accounts for presence of the landmass, which dissipates wave energy, slows surge propagation, and provides a buffer for erosion. Shoreline could be considered at multiple datums such that subtidal features could be accounted for, if desired. |
| Land cover type along distance from point of interest to nearest shoreline (Manning n) | The coverage on a landmass also influences wave energy dissipation, surge propagation, and erodibility. |
| Open-water fetch from nearest shoreline (km) | In the absence of wave and water level data, can be used, along with wind data, as an indicator of the wave energy and storm surges a shoreline may be subject to. |
| Nearest shoreline change variance (m) | A proxy for measuring the storminess along a sandy coastline, particularly as an indicator of how storminess effects the erosion hazard. |
| Long-term nearest shoreline change rate (m) | An eroding shoreline is more vulnerable than an accreting shoreline, and recovery of a beach along a chronically eroding shoreline is less likely. |

| Metric | Reason |
|---|---|
| Average max elevation between nearest shoreline and open coast (m) | Accounts for the presence of a landmass, such as a barrier island, offshore the nearest shoreline. |
| Landmass area between nearest shoreline and open coast (km2) | Accounts for the presence of a landmass, such as an island, offshore the nearest shoreline. |
| Beach berm width (m) | Beach protects the upland from wave impact and erosion. The wider the beach the less vulnerable it is and the less vulnerable the upland is to coastal storms. |
| Beach slope (%) | Influences wave runup and therefore the likelihood of flooding from wave runup. |
| Open coast shoreline sediment median grain size (mm) | Used as a measure of the erodibility of the coastline and the ability of the shoreline to recover (e.g., gravel vs. sand vs. clay) |
| **Forcing** | |
| Max still-water elevation (m) | Primary driver of coast coastal vulnerability to storms. Application of statistically derived values allows for the consideration of storminess over the temporal reference of interest. |
| Max wave height (m) | Important driver of coast coastal vulnerability to storms. Application of statistically derived values allows for the consideration of storminess over the temporal reference of interest. |
| Max wave runup elevation (m) | Not typically available directly from data, but may be calculated based on other available date (e.g., offshore wave height, period, and beach slope). May be the primary source of flooding on some coasts. |
| Max wind speed (m/sec) | Should be considered as a damage driver and can also be used to estimate other metrics (such as wave heights) in the absence of that data. |
| Relative sea level rise (mm/yr) | Important consideration for vulnerability assessments with a long temporal reference. |
| Tidal range (m) | Shorelines with large tidal ranges typically dissipate more wave energy. |
| **Socioeconomic** | |
| Pop | Because vulnerability is based on human value judgments, the presence of humans on a coast must be a consideration and also increases the likelihood of planned adaptation. |
| Land cover | Indicator of coastal land use and the likelihood of planned adaptation and emergency response activities. |
| Median Income ($) | Indicator of a community’s ability to engage in planned adaptation and emergency response activities. |
| Property values ($) | Indicator of coastal land use and the likelihood of planned adaptation and emergency response activities. |
| Traffic volume | Indicator of the likelihood of planned adaptation and emergency response activities. |

# Appendix F: Vulnerability Metric Quantification Example

An example metric quantification was performed for a portion of the New Jersey coastline that exhibits a barrier island beach and dune system. The 20 km stretch of coast north of Barnegat Inlet, NJ, was chosen since the area is primarily uninhabited. High resolution light detection and ranging (Lidar) bathymetry and topography were used to provide the spatial data needed for extracting coastal characteristics. This data was collected as part of the USACE's National Coastal Mapping Program (NCMP[1]) which is executed by the Joint Airborne Lidar Bathymetry Technical Center of Expertise (Wozencraft et al. 2007). A standard data product produced by the NCMP includes bare earth grids. These grids are generated based on the classification of points within the point cloud as ground vs. nonground. The bare earth grids were used for the analysis to prevent the inclusion of vegetation elevation in the volume calculations. Geomorphic metrics that are extracted from the dataset include beach slope, beach width, average barrier island width, minimum barrier island width, distance to nearest inlet, average dune elevation, dune field volume, dune vegetation coverage, alongshore dune height variance, and distance from dune to backline. Auxiliary data sources were used to determine average fetch length, long-term and short-term shoreline change rate, sediment grain size, maximum still-water elevation, maximum runup elevation, significant wave height, tidal range, wind speed, and dune age. The extracted metric values are listed in Table 75.

Table 75. Metrics values for the Marine Depositional Barrier Coast example.

| New Jersey 20 km north of Barnegat Inlet | |
|---|---|
| Beach slope (%) | 8 |
| Beach width (m) | 35.8 |
| Average barrier island width (m) | 457 |
| Min barrier island width (m) | 185 |
| Average fetch length (back barrier) (m) | 5000 |
| Distance to inlet (km) | 0-20 |
| Short-term shoreline change rate (m/yr) | −0.2 |

[1] http://shoals.sam.usace.army.mil/Mapping.aspx.

| | |
|---|---|
| Long-term shoreline change rate (m/yr) | –0.8 |
| Average dune elevation (m) | 6.2 |
| Average dune field area ($m^2$) | 8513 |
| Average dune field volume ($m^3$) | 28778 |
| Dune vegetation coverage (%) | * |
| Alongshore dune height variance (m) | 1.2 |
| Average distance from sound shoreline to dune (m) | 372 |
| Dune age (yr) | 36 |
| Sediment grain size | fine-medium sand with 1%–5% shells |
| Max still-water elevation (m) | 1.2 above MHHW |
| Max runup elevation (m) | 2.7 |
| Significant wave height (m) | 6.6 |
| Tidal range (m) | 0.7 |
| Wind speed (m/s) | 23 |
| Traffic volume | N/A |
| Median income | N/A |
| Property value | N/A |

*Note that the hyperspectral imagery needed to extract the vegetation coverage parameter was not processed for the spatial location. Subsequent datasets may have this information available.

The geomorphic metrics (beach slope, beach width, shoreline change variance, average dune elevation, dune field volume, alongshore dune height variance, and distance from backline to dune crest) were extracted from the 1 m lidar-derived topography. The 1 m resolution provided the spatial resolution needed to extract detailed geomorphic values on a local scale. These values were then averaged to provide an overall view of the vulnerability of the coastal zone. Geomorphic values were extracted using the Environmental Systems Research Institute (ESRI), Geographic Information System (GIS), desktop software ArcGIS 10.1 (ESRI 2013).

Dune elevations alongshore were extracted using a transect based approach within Matlab to identify the peaks in the profile. The first seaward dune crest above a specific threshold was selected as the primary dune. The average primary dune elevation is 6.2 m for the 20 km stretch of coast. The dune crest information was then brought back into the GIS for further analysis and mapping. Contour lines for 0.75 m and 3 m were extracted from the topographic grids to represent the shoreline and dune toe, respectively. A landward boundary behind the dune line was digitized in the GIS to form a backline for volume calculations. The beach width was calculated every 50 m based on the intersection of shore normal transects bounded by the shoreline and dune toe line along the coast. The average beach width for the region is 35.8 m. The barrier island width was calculated in a similar way as beach width but used the back bay shoreline and the seaward shoreline as bounds. The average barrier island width is 457 m and the minimum width is 185 m. Similarly, the average distance from back bay shoreline to dune was found to be 372 m. Beach slope was quantified for the region using the beach width transects and a slope analysis within the GIS. The average beach slope percentage for the region is 8. Dune field volume was found by creating polygon features with the backline as the landward boundary and the dune toe as the seaward boundary. Transects were used to bound the regions alongshore. Volume of sediment was then calculated within each of these bins using tools within the GIS. The average dune field volume was 28,000 m3. Volumes are directly related to the bin area. Larger areas correlate to greater distance between the backline and dune toe lines since the alongshore spacing was uniform at 50 m.

Long-term and short-term shoreline change rate was determined based on data available from the USGS within the Digital Shoreline Analysis System (DSAS) (Thieler et al. 2009). The shorelines within DSAS range from the 1800s through the 2000s. Long-term shoreline change rates are calculated using all available shorelines for the area. A linear regression rate-of-change statistic was calculated within DSAS by fitting a least-squares regression line to all the available shoreline points along a particular transect (Thieler et al. 2009). Long-term shoreline change rate for the 20 km stretch of coast was found to be –0.8 m/yr. Short-term shoreline change rates are calculated using approximately 30 yr of available data. The average short-term shoreline change rate was found to be –0.2 m/yr. The vegetation coverage and density are parameters that can be extracted from the fused hyperspectral imagery and lidar datasets; however, at the time of this study, the fused data were not processed for the spatial area of interest. Therefore, vegetation coverage and density were not calculated for this example. The cross-shore sound fetch length was averaged based on a manual interpretation of 15 measurements along the 20 km stretch of coast within Google Earth, as the position of the sound-side shoreline was unavailable from the JALBTCX data set. The average fetch length for this spatial region is approximately 5000 m.

Sediment grain size was one of two geomorphic parameters that could not be calculated from available data products and was instead determined off of a 2013 geologic map made jointly by the Department of Environmental Protection, Water Resources Management, and the New Jersey Geological and Water Survey for the Forked River and Barnegat Light quadrangles. Beach sand was identified as fine-to-medium sand with few (1%–5%) shells deposited by waves during the Holocene. Dune sand was identified as similar to the beach sand (fine-medium sand).

A literature review of scientific studies of Island Beach State Park was used to identify the dune-age parameter. This parameter is included to help differentiate between older compacted dunes that may be more resistant to erosion and newer, artificially created dunes which have not yet had time to compact. Therefore, historical topographic or imagery data could also be used if available to document the age of the dune. Island Beach State Park encompasses the majority of the 20 km study site. The region was used heavily for beach recreation before it was established as a park in 1953, after which houses were removed (Gares 1992). In 1962, a large Nor'easter destroyed much of the foredune, and sand fencing was installed along the length of the park to help rebuild dunes (Gares and Nordstrom 1988). Gares and Nordstrom (1988) used stereo photogrammetry techniques from aerial photographs to determine that by 1977, much of the foredune had been rebuilt. Since then, no human modification has been allowed within the southern 10 km of the park. Given these findings, 36 yr were selected (2013–1977) as the approximate age of the foredune along this stretch of coastline; however, it is always important to remember that dunes are continuously evolving in response to wave action and wind.

The values for the forcing metrics (surge, wave height, wind, runup) were calculated for a 25 yr return-period storm, similar to the example vulnerability study highlighted in the text. The Federal Emergency Management Agency (FEMA) is currently conducting a coastal flood study to produce updated flood hazard information, which includes storm-surge and overland wave modeling from the Advanced CIRCulation (ADCIRC) model and the Simulating Waves Nearshore (SWAN) model for a suite of storms. These data were not yet available for FEMA Region II, where the study site is found, so metric parameters were calculated from the next best available source, though consulting the final FEMA reports when available is recommended.

Forcing metrics must be quantified based on the temporal reference of the vulnerability assessment to be performed. For the example, a 25 yr period was selected. The 25 yr return-period surge elevation was retrieved from the closest available NOAA tide station, in this case Atlantic City, NJ. NOAA has calculated annual exceedance probability curves based on a generalized extreme value (GEV) probability distribution fit to observed data. The 25 yr return period surge elevation was found to be 1.2 m above MHHW. The 25 yr return period significant wave height was found by averaging the values provided by the USACE WIS project at WIS station 63135 in 23 m of water depth off of Barnegat Inlet and WIS station 63134 in 21 m of water depth approximately 10 km farther north. Return period curves for WIS data are calculated by fitting a linear fit to the top 21 events in the 1980–1999 Wave Hindcast data set. The average 25 yr return period significant wave height for this 20 km in ~20 m of water depth is 6.6 m. The 25 yr return period maximum runup elevation for this stretch was calculated using the empirical relationship for the 2% exceedance elevation of runup defined by Stockdon et al. 2006. Beach slope was extracted from topographic lidar data (see prior section), and the 25 yr return period significant wave height and associated wavelength from the WIS data were used after being linearly reverse-shoaled to their deep-water equivalents. Wavelength was calculated using a Pierson-Moskowitz spectra for 6.6 m waves and an alpha = 0.0081 to get peak period and converted to wavelength using linear wave theory. The 25 yr return period wind speed has also been calculated by USACE for each WIS station along this region as part of a wind study for the U.S. Bureau of Safety and Environmental Enforcement (BSEE). The average 25 yr return period wind speed for WIS stations 63135 and 63134 is 23 m/sec. Tide range, defined here as the difference between MHW and MLW, was calculated based on values provided by NOAA for Barnegat Inlet (ocean side) and found to be 0.7 m. Since this stretch of coastline is undeveloped barrier island, socioeconomic metrics such as traffic volume, median income, property value, and scheduled renourishment interval were not applicable. Spatial maps of the extracted metrics at 1 m alongshore resolution are presented in Figure 78 through Figure 80.

Figure 78. Spatial map of (A) beach slope, (B) beach width, and (C) barrier island width metrics.

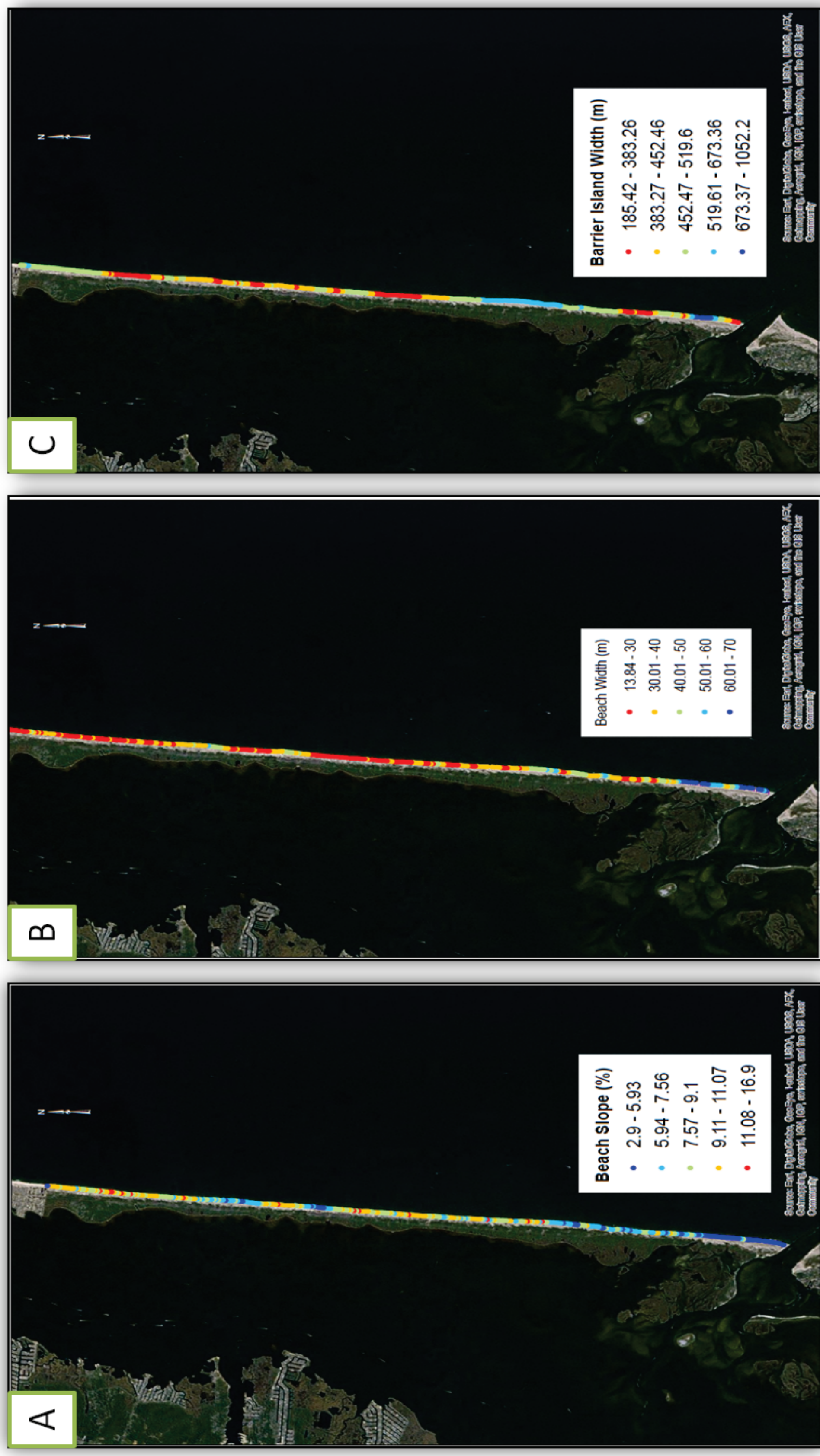
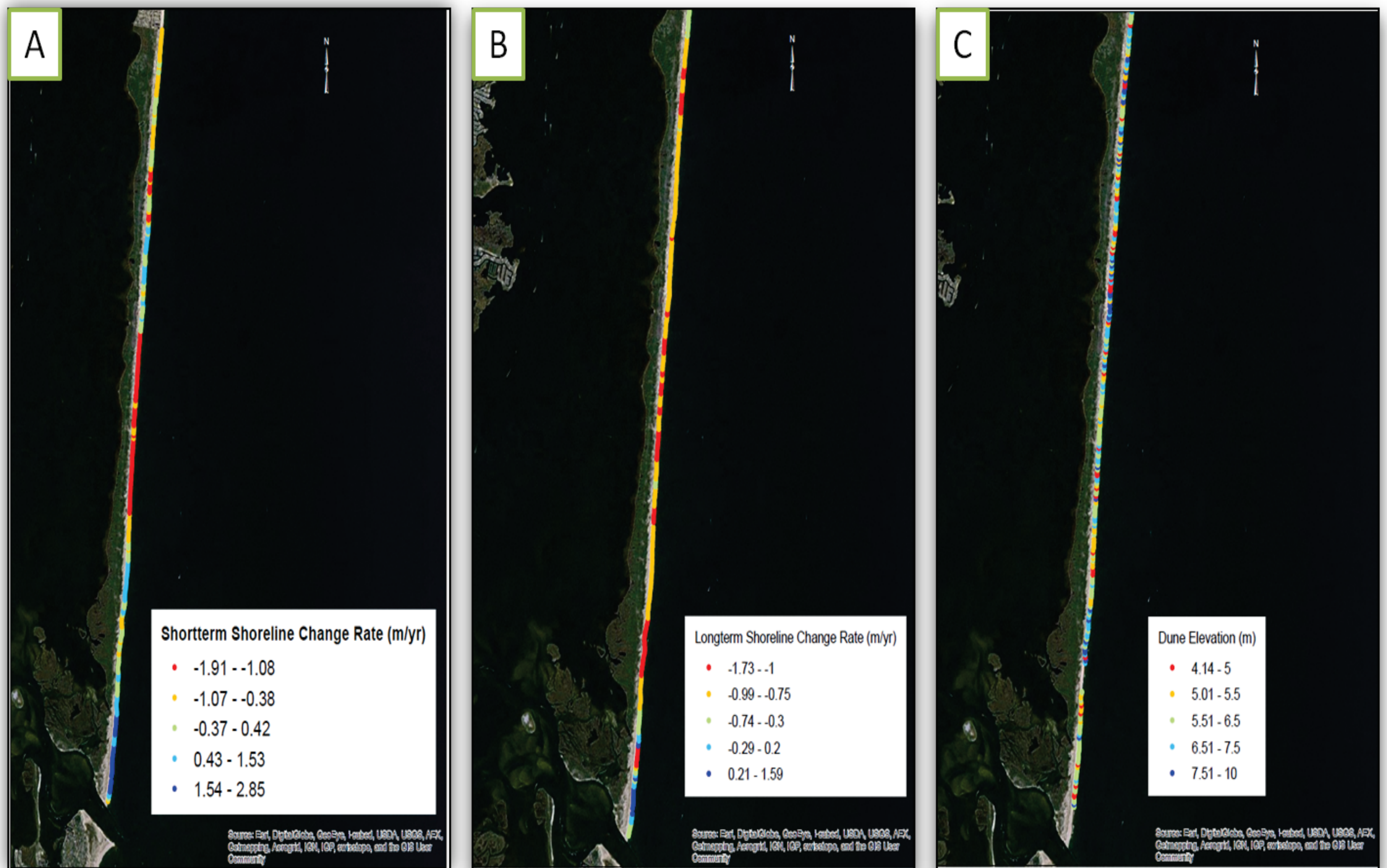


Figure 79. Spatial map of (A) short-term shoreline change rate, (B) long-term shoreline change rate, and (C) dune elevation metrics.



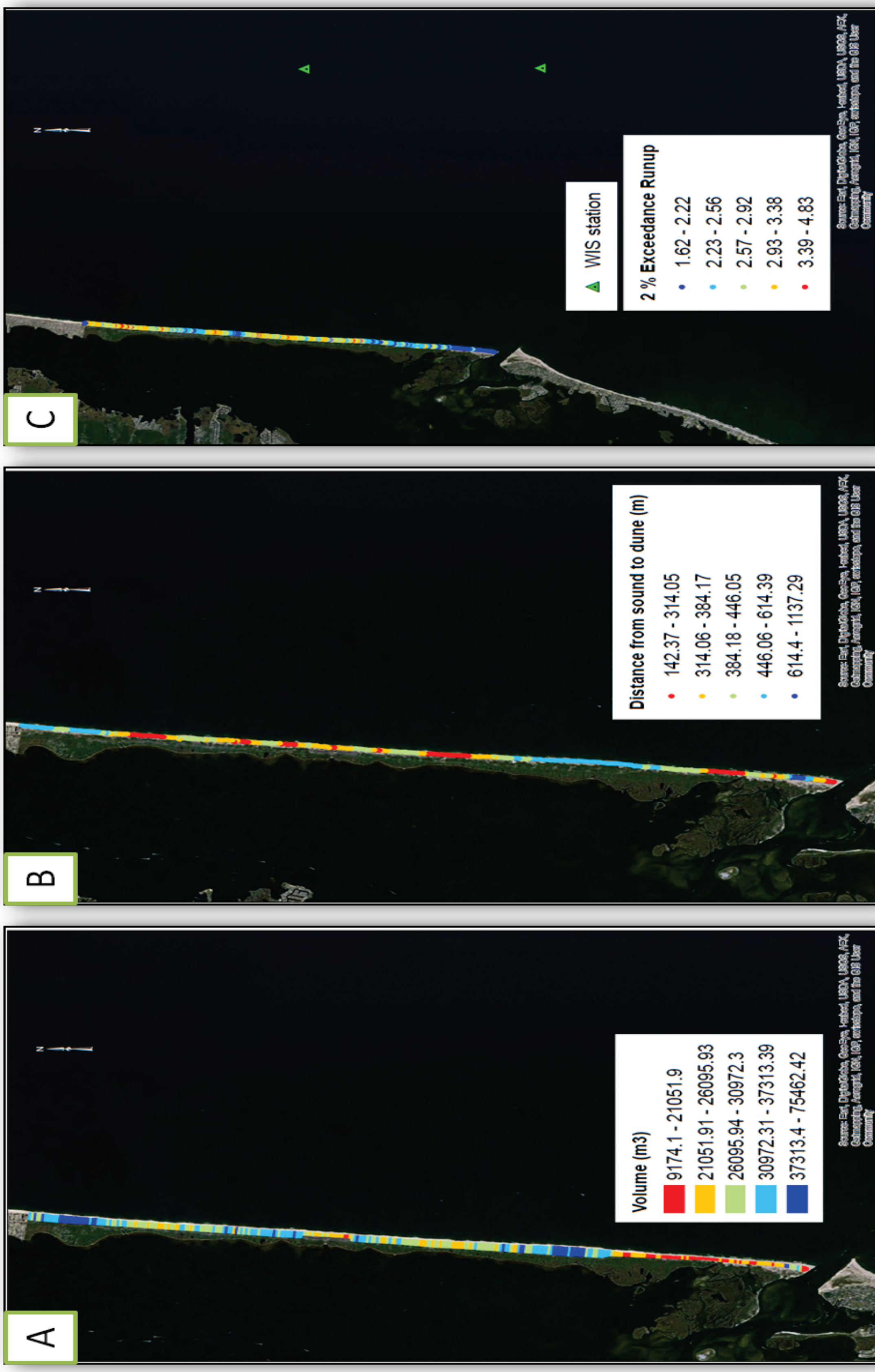



Figure 80. Spatial map of (A) dune volume, (B) distance from sound to dune, and (C) wave runup metrics.

# Appendix G: Features-Services Matrix

As mentioned in the main body of the report, the matrix that follows (Table 76 through Table 78) was developed first from an extensive review of the refereed literature and then was subjected to a series of spiral analyses to elicit expert opinions from the subject matter experts on the PDT (Figure 18). The following papers were central to the development of these feature-service relationships:

Atkins, J. P., D. Burdon, M. Elliott, A. J. Gregory. 2011. Management of the marine environment: Integrating ecosystem services and societal benefits with the DPSIR framework in a systems approach. *Marine Pollution Bulletin* 62: 215–226.

Balmford, A., B. Fisher, R. E. Green, R. Naidoo, B. Strassburg, R. K. Turner, A. S. L. Rodrigues. 2011. Bringing ecosystem services into the real world: An operational framework for assessing the economic consequences of losing wild nature. *Environmental Resource Economics* 48: 161–175.

Barbier, E. B., I. Y. Georgiou, B. Enchelmeyer, D. J. Reed. 2013. The value of wetlands in protecting southeast Lousiana from storm surges. *Public Library of Science One* 8: e58715.

Barbier, E. B., S. D. Hacker, C. Kennedy, E. Koch, A. C. Stier, B. R. Silliman. 2011. The value of estuarine and coastal ecosystem services. *Ecological Monographs* 81: 169–193.

Boyd, J., S. Banzhaf. 2007. What are ecosystem services? The need for standardized environmental accounting units. *Ecological Economics* 63: 616–626.

de Groot, R. S., R. Alkemade, L. H. Braat, L. Wilemen. 2010. Challenges in integrating the concept of ecosystem services and values in landscape planning, management and decision making. *Ecological Complexity* 7: 260–272.

de Groot, R. S., M. A. Wilson, R. M. J. Boumans. 2002. A typology for the classification, description and valuation of ecosystem functions, goods and services. *Ecological Economics* 41: 393–408.

Gómez-Baggethun, E., D. N. Barton. 2013. Classifying and valuing ecosystem services for urban planning. *Ecological Economics* 86: 235–245.

Haines-Young, R., and M. Potschin. 2010. The links between biodiversity, ecosystem services, and human well-being. In *Ecosystem ecology*, ed. D. G. Raffaelli and C. L. J. Frid, 110–139. Cambridge, MA: Cambridge University Press.

McLeod, K. L., H. M. Leslie. 2009. Why ecosystem-based management? In *Ecosystem-based management for the oceans*, ed. K. L. McLeod and H. M. Leslie, 3–12.Washington, DC: Island Press.

National Research Council (NRC). 2005. *Valuing ecosystem services: Toward better environmental decision making*. Washington, DC: National Academies Press.

Turner, R. K., S. Georgiou, B. Fisher. 2008. *Valuing ecosystem services: The case of multifunctional wetlands*. London, UK: Earthscan.

Table 76. Feature-Services matrix for NNBF produced by the PDT for the study based on literature and expert opinion. Goods and services highlighted in blue indicate primary concerns of the NACCS recovery efforts.

| Ecosystem Goods and Services | Bluff or scarp (any material, if sand, assume eroding dune) | Submerged aquatic vegetation or aquatic veg. bed (fresh or saline) | Beach (sand, gravel, cobble) | Mudflat / sandflat or tidal flat | Pond | Dune / swale complex | Shrub-scrub wetlands (fresh) | Flooded swamp forest (fresh) | Terrestrial grassland | Terrestrial shrubland | Terrestrial forest | Maritime grassland | Maritime shrubland | Maritime forest | Riparian buffer | Emergent herbaceous marsh / wetland (fresh) | Salt marsh (emergent herbaceous) | Shrub-scrub wetlands (brackish) | Flooded swamp forest (brackish) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Aesthetics–appreciation of natural scenery (other than deliberate recreational activities); inspiration for culture, art, and design | X | X | X | X | X | X | X | X | X | X | X | X | X | X | X | X | X | X | X |
| Biological diversity (biodiversity) | X | X | X | X | X | X | X | X | X | X | X | X | X | X | X | X | X | X | X |
| Carbon sequestration | | X | | | | | X | X | X | X | X | X | X | X | X | X | X | X | X |
| Clean water provisioning (sediment, nutrients, pathogens, salinity, other) | | X | | X | X | X | X | X | X | X | X | X | X | X | X | X | X | X | X |
| Commercial harvestable fish and wildlife production | | | X | X | X | | | | | | | | | | | | | X | X |
| Cultural heritage and identity–sense of place; spiritual and religious inspiration | X | X | X | X | X | X | X | X | X | X | X | X | X | X | X | X | X | X | X |
| Education and scientific opportunities (for training and education) | X | X | X | X | X | X | X | X | X | X | X | X | X | X | X | X | X | X | X |
| Erosion protection and control (water and wind, any source) | | | X | | | X | X | X | X | X | X | X | X | X | X | X | X | X | X |
| Habitat for fish and wildlife provisioning (nursery, refugium, food) | X | X | X | X | X | X | X | X | X | X | X | X | X | X | X | X | X | X | X |
| Increase or maintain land elevation, land-building, sediment source reduction | | X | | | | X | X | X | X | X | X | X | X | X | X | X | X | X | X |

| Ecosystem Goods and Services | Bluff or scarp (any material, if sand, assume eroding dune) | Submerged aquatic vegetation or aquatic veg. bed (fresh or saline) | Beach (sand, gravel, cobble) | Mudflat / sandflat or tidal flat | Pond | Dune / swale complex | Shrub-scrub wetlands (fresh) | Flooded swamp forest (fresh) | Terrestrial grassland | Terrestrial shrubland | Terrestrial forest | Maritime grassland | Maritime shrubland | Maritime forest | Riparian buffer | Emergent herbaceous marsh / wetland (fresh) | Salt marsh (emergent herbaceous) | Shrub-scrub wetlands (brackish) | Flooded swamp forest (brackish) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Maintain background suspended sediment in surface waters | | X | X | X | X | X | X | X | X | X | X | X | X | X | X | X | X | X | X |
| Nutrient sequestration or conversion | | X | X | X | X | X | X | X | X | X | X | X | X | X | X | X | X | X | X |
| Property value protection | X | X | X | X | X | X | X | X | X | X | X | X | X | X | X | X | X | X | X |
| Provision/storage of groundwater supply | | | | | X | | X | X | X | X | X | X | X | X | X | X | X | X | X |
| Raw materials production (e.g., timber, fiber and fuel) | | | | | | | | | | | X | | | | X | | | | |
| Recreation–opportunities for tourism and recreational activities | X | X | X | X | X | X | X | X | X | X | X | X | X | X | X | X | X | X | X |
| Reduce hazardous or toxic materials in water or landscape | | X | | X | | X | X | X | X | X | X | X | X | X | X | X | X | X | X |
| Reduce storm surge and related flooding | X | | X | X | X | X | X | X | X | X | | X | X | X | X | X | X | X | X |
| Reduce the peak flood height and lengthen the time to peak flood | | | | | X | X | X | X | X | X | X | X | X | X | X | X | X | X | X |
| Reduce wave attack | X | | X | X | | X | | | | | | X | X | X | | X | X | | X |
| TES species protection | X | X | X | X | X | X | X | X | X | X | X | X | X | X | X | X | X | X | X |
| **Total Services per Feature** | **10** | **14** | **14** | **15** | **15** | **17** | **18** | **18** | **18** | **18** | **18** | **19** | **19** | **19** | **19** | **19** | **19** | **19** | **20** |

Table 77. Feature-Services matrix for NNBF and structural feature complexes produced by the PDT for the study based on literature and expert opinion. Goods and services highlighted in blue indicate primary concerns of the NACCS recovery efforts.

| Ecosystem Goods and Services | Breakwater, submerged (nearshore berm, sill, artificial reef; if containing living organisms or plants, see reef) | Living shoreline (vegetation w/ sills, benches, breakwaters, etc.) | Reef or mollusk reef, intertidal or submerged (also see breakwater) | Island (can include one or more of beach, mudflat, dune, breakwater, bluff, marsh, maritime forest, other veg | Breakwater, subaerial, or emergent (nearshore berm, sill, reef; can contain mollusks, rock, shells, SAV, emergent or herbaceous vegetation) | Barrier island (can include one or more of beach, mudflat, dune, breakwater, bluff, marsh, maritime forest, other veg) |
|---|---|---|---|---|---|---|
| Aesthetics–appreciation of natural scenery (other than deliberate recreational activities); inspiration for culture, art, and design | X | X | X | X | X | X |
| Biological diversity (biodiversity) | X | X | X | X | X | X |
| Carbon sequestration | | X | | X | X | X |
| Clean water provisioning (sediment, nutrients, pathogens, salinity, other) | | X | X | X | X | X |
| Commercial harvestable fish and wildlife production | X | | X | X | X | X |
| Cultural heritage and identity–sense of place; spiritual and religious inspiration | X | | X | X | X | X |
| Education and scientific opportunities (for training and education) | X | X | X | X | X | X |
| Erosion protection and control (water and wind, any source) | X | X | X | X | X | X |
| Habitat for fish and wildlife provisioning (nursery, refugium, food) | X | X | X | X | X | X |
| Increase or maintain land elevation, land-building, sediment source reduction | X | X | | X | X | X |
| Maintain background suspended sediment in surface waters | | X | X | X | X | X |
| Nutrient sequestration or conversion | X | X | X | X | X | X |
| Property value protection | X | X | X | X | X | X |
| Provision/storage of groundwater supply | | | | | | |
| Raw materials production (e.g., timber, fiber and fuel) | | | | | | |
| Recreation–opportunities for tourism and recreational activities | X | | X | X | X | X |
| Reduce hazardous or toxic materials in water or landscape | | X | X | X | X | X |
| Reduce storm surge and related flooding | X | X | X | | X | X |
| Reduce the peak flood height and lengthen the time to peak flood | | | | | | |
| Reduce wave attack | X | X | X | X | X | X |
| TES species protection | X | X | X | X | X | X |
| **Total Services per Feature** | **14** | **15** | **16** | **17** | **18** | **18** |

Table 78. Feature-Services matrix for structural features produced by the PDT for the study based on literature and expert opinion. Goods and services highlighted in blue indicate primary concerns of the NACCS recovery efforts.

| Ecosystem Goods and Services | Levee | Seawall / Revetment / Bulkhead | Groin | Storm Surge Barrier | Breakwater |
|---|---|---|---|---|---|
| Aesthetics–appreciation of natural scenery (other than deliberate recreational activities); inspiration for culture, art, and design | X | X | X | X | X |
| Biological diversity (biodiversity) | | | X | X | X |
| Carbon sequestration | | | | | |
| Clean water provisioning (sediment, nutrients, pathogens, salinity, other) | | | | X | X |
| Commercial harvestable fish and wildlife production | | | | X | X |
| Cultural heritage and identity–sense of place; spiritual and religious inspiration | X | X | X | X | X |
| Education and scientific opportunities (for training and education) | X | X | X | X | X |
| Erosion protection and control (water and wind, any source) | X | X | X | X | X |
| Habitat for fish and wildlife provisioning (nursery, refugium, food) | | | X | | X |
| Increase or maintain land elevation, land-building, sediment source reduction | X | X | X | X | X |
| Maintain background suspended sediment in surface waters | | | | X | X |
| Nutrient sequestration or conversion | | | X | | X |
| Property value protection | X | X | X | X | X |
| Provision/storage of groundwater supply | | | | | |
| Raw materials production (e.g., timber, fiber and fuel) | | | | | |
| Recreation–opportunities for tourism and recreational activities | | | X | | X |
| Reduce hazardous or toxic materials in water or landscape | | | | X | X |
| Reduce storm surge and related flooding | X | X | | X | X |
| Reduce the peak flood height and lengthen the time to peak flood | X | X | | | |
| Reduce wave attack | X | X | | X | X |
| TES species protection | | | | X | X |
| Total Services per Feature | 9 | 9 | 10 | 14 | 17 |

# Appendix H: Ecosystem Goods and Services per Feature Tables

This appendix serves as a catalogue of potential metrics that could be deployed by USACE and/or its partners to characterize benefits derived from the use of NNBF in coastal recovery efforts. In the next several tables (Table 79 through Table 104), there are examples of 72 NNBF-relevant performance metrics, expressed in terms of 21 ecosystem-based goods and services, that can be used to characterize (either qualitatively or quantitatively) the benefits generated by 21 natural, nature-based, structural features and feature complexes. An abundance of expert opinion has been used to derive these metrics, but the team supplemented its knowledge with examples from peer-reviewed literature where possible. Please note that these metrics have not been applied to date, nor have they been fully tested or published in the peer-review literature. While their constructs can serve as a good beginning, future feasibility study teams will need to consider issues of model validation, verification, and planning certification[1] when the time comes to deploy these in the field.

[1] Refer to EC 1105-2-407 to obtain guidance on USACE policies regarding planning model certification (http://planning.usace.army.mil/toolbox/library/ECs/EC1105-2-407_31May2005.pdf, Accessed February 2014).

Table 79. NNBF: Beach (sand, gravel, cobble).

| Influential Structure and Components | Processes and Functions | Ecosystem Goods and Services | Benefits | Performance Metric |
|---|---|---|---|---|
| Characteristic intertidal substrate | Geomorphologic diversity and natural ecosystem components | Aesthetics–appreciation of natural scenery (other than through deliberate recreational activities); inspiration for culture, art, and design | Scenic beauty, nature-inspired design, art, and culture | Pop density in Plan Reach |
| Substrate type and cross-sectional and longitudinal distribution | Series of ecosystem elements that support a variety of native biota | Biological diversity (biodiversity) | Self-sustaining diverse ecosystem biota | (Landfire veg cover x Prop native)1/2 x ((25 - % imp cover in 100 m radius)/15 + (50 - % ag cover in 100 m radius)/25)/2 |
| Characteristic intertidal substrate | Ecosystem conditions that support self-sustaining wildlife Pops | Commercial harvestable fish and wildlife production | Environmentally sustainable and profitable fishery or wildlife crops | n/a |
| Characteristic intertidal substrate | Persistent native ecosystem structure, function, and dynamic processes | Cultural heritage and identity–sense of place and belonging; spiritual and religious inspiration | Culture and spirituality tied to nature; religion that supports nature | Pop density in Plan Reach |
| Substrate type and cross-sectional and longitudinal distribution | Variety of ecosystem types with balanced processes | Education and scientific opportunities (for training and education) | Educated constituency, environmental stewardship | (Pop density in Plan Reach + enrolled students in Plan Reach)/2 |
| Substrate type and cross-sectional and longitudinal distribution | Attenuation of erosive processes | Erosion protection and control (water and wind, any source) | Decreased erosion, sediment transport to open water | Veg cover |
| Characteristic intertidal substrate | Variety of appropriate ecosystem elements interacting to produce diverse niches suited to the setting | Habitat for fish and wildlife provisioning (e.g., nursery, refugium, food sources) | Healthy fish and wildlife Pops | (Veg cover x Prop native x NPP coefficient)1/3 x ((25 - % imp cover in 100 m radius)/15 + (50 - % ag cover in 100 m radius)/25)/2 |

| Influential Structure and Components | Processes and Functions | Ecosystem Goods and Services | Benefits | Performance Metric |
|---|---|---|---|---|
| Substrate type and vertical accretion | Sediment detention and deposition | Maintain background suspended sediment in surface waters | Reduced damages associated with sediment (and potentially pollutant) laden storm surge and flood waters | Veg cover |
| Characteristic intertidal substrate | Nutrient cycling | Nutrient sequestration or conversion | Reduced nutrient pollution | ((Veg cover x NPP coefficient)1/2 + (% hydric soils x % organic matter)1/2)/2 |
| Characteristic intertidal substrate | Processes or ecosystem elements that either prevent damage or enhance aesthetics or other values | Property value protection | Property values maintained or enhanced | (90th % height/17.3 x width/200 x )1/2 |
| Characteristic intertidal substrate | Ecosystem elements that allow public access and use, with similar processes that influence aesthetics and cultural inspiration | Recreation–opportunities for tourism and recreational activities | Environmentally sustainable and potentially profitable availability of private and public use areas | (Public beach [0.1 or 1] x Appropriate width (75-200 = 1) x Pop density in planning reach)1/3 |
| Substrate type, beach slope, surface water storage | Ecosystem structure that interferes with storm loadings (e.g., flood attenuation, diversion) | Reduce storm surge and related flooding | Reduced storm-surge related flooding damages | (90th % height/17.3 x width/200)1/2 |
| Substrate type, beach slope, topographic diversity | Ecosystem roughness elements that break incoming waves and slow water velocity | Reduce wave attack | Lower wave attack related structural damages | Max height/3.28 - 1 |
| Appropriate substrate type | Variety of appropriate ecosystem elements interacting to produce diverse niches suited to the setting | TES species protection | Compliance with the law, preservation of culturally agreed-upon important biological heritage | 1 = TES species can use,<br>0 = TES species cannot use |

Table 80. NNBF: Mudflat / Sandflat or Tidalflat.

| Influential Structure and Components | Processes and Functions | Ecosystem Goods and Services | Benefits | Performance Metric |
|---|---|---|---|---|
| Substrate type and quality | Maintain habitat diversity | Aesthetics–appreciation of natural scenery (other than through deliberate recreational activities); inspiration for culture, art, and design | Scenic beauty, nature-inspired design, art, and culture | Pop density in Plan Reach |
| Mineral and organic substrate type and ecotone | Lunar semidiurnal tides; ecotone effect | Biological diversity (biodiversity) | Self-sustaining sediment exchange and shell fish habitat | ((25 - % imp cover in 100 m radius)/15 + (50 - % ag cover in 100 m radius)/25)/2 |
| Mineral and organic substrate type and ecotone | Biogeochemical processes and contact time; semidiurnal tides | Clean water provisioning (sediment, nutrients, pathogens, salinity, other pollutants) | Sequestration and transformation of pollutants; water quality enhancement | n/a |
| Mineral and organic substrate type and ecotone | Supports life stage(s) of edible species of fish and shell fish | Commercial harvestable fish and wildlife production | Socio-economic enhancement | Same as Habitat Provisioning |
| Mineral and Organic Substrate Type and Ecotone | Maintain habitat diversity | Cultural heritage and identity–sense of place and belonging; spiritual and religious inspiration | Culture and spirituality tied to nature; religion that supports nature | Pop density in Plan Reach |
| Mineral and organic substrate type and ecotone | Sustainability of diverse flora and fauna | Education and scientific opportunities (for training and education) | Educated constituency, environmental stewardship | (Pop density in Plan Reach + enrolled students in Plan Reach)/2 |
| Mineral and organic substrate type and ecotone | Mosaic of dendritic tidal creeks, emergent marsh vegetation, and flats; carbon export | Habitat for fish and wildlife provisioning (e.g., nursery, refugium, food sources) | Healthy fish and wildlife Pops | NPP coefficient x ((25 - % imp cover in 100 m radius)/15 + (50 - % ag cover in 100 m radius)/25)/2 |

| Influential Structure and Components | Processes and Functions | Ecosystem Goods and Services | Benefits | Performance Metric |
|---|---|---|---|---|
| Mineral and organic substrate type, sediment stability and ecotone | Sediment vertical accretion and stability | Maintain background suspended sediment in surface waters | Water clarity; maintains community metabolism and primary production of SAVs | n/a |
| Mineral and organic substrate type and ecotone | Biogeochemical processes and contact time; semidiurnal tides | Nutrient sequestration or conversion | Reduced nutrient pollution and maintain nutrient exchange | NPP coefficient |
| Mineral and organic substrate type and ecotone | Natural shoreline features | Property value protection | Provides resilient buffer and protection of property and infrastructure | n/a |
| Mineral and organic substrate type and ecotone | Mosaic of dendritic tidal creeks, emergent marsh vegetation, and flats | Recreation–opportunities for tourism and recreational activities | Environmentally sustainable and potentially profitable availability of private and public use areas | (Public beach [0.1 or 1] x Pop density in planning reach)1/2 |
| Mineral and organic substrate type, sediment stability and ecotone | Biogeochemical processes and contact time; semidiurnal tides | Reduce hazardous or toxic materials in water or landscape | Reduces uptake of toxic substances into the food web | NPP coefficient |
| Mineral and organic substrate type, sediment stability and ecotone | Temporary storage of stormwater; high Manning's n from shell fish production | Reduce storm surge and related flooding | Reduced storm-surge related flooding risk/damages | n/a |
| Mineral and organic substrate type, sediment stability and ecotone | Temporary storage of stormwater and gradient to emergent vegetation | Reduce wave attack | Lower wave attack related structural damages | Width |
| Mineral and organic substrate type, sediment stability and ecotone | Maintenance of critical habitat and life requisites for TES species | TES species protection | Maintains breeding, resting and feeding habitat for TES species | 1 = TES species can use, 0 = TES species cannot use |

Table 81. NNBF: Bluff or Scarp (any material, if sand assume eroding dune).

| Influential Structure and Components | Processes and Functions | Ecosystem Goods and Services | Benefits | Performance Metric |
|---|---|---|---|---|
| Structural and substrate variability | Geomorphologic diversity and natural ecosystem components | Aesthetics–appreciation of natural scenery (other than through deliberate recreational activities); inspiration for culture, art, and design | Scenic beauty, nature-inspired design, art, and culture | (SD of elevation x Pop density in Plan Reach)1/2 |
| Structural and substrate variability; rooted vegetation | Series of ecosystem elements that support a variety of habitat types | Biological diversity (biodiversity) | Clean sediment source to maintain beach systems | (Veg cover x Prop native)1/2 x ((25 - % imp cover in 100 m radius)/15 + (50 - % ag cover in 100 m radius)/25)/2 |
| Structural and substrate variability; rooted vegetation | Maintain normal rates of erosion and deposition | Cultural heritage and identity–sense of place and belonging; spiritual and religious inspiration | Culture and spirituality tied to nature; religion that supports nature | (SD of elevation x Pop density in Plan Reach)1/2 |
| Structural and substrate variability; rooted vegetation | Sustainability of diverse bluff and cliff habitat | Education and scientific opportunities (for training and education) | Educated constituency, environmental stewardship | (SD of elevation x (Pop density in Plan Reach + enrolled students in Plan Reach)/2)1/2 |
| Structural and substrate variability; rooted vegetation | Maintain bluff geomorphologic complexity | Habitat for fish and wildlife provisioning (e.g., nursery, refugium, food sources) | Habitat for wildlife specially adapted to bluff ecosystem | (Veg cover x Prop native x NPP coefficient)1/3 x ((25 - % imp cover in 100 m radius)/15 + (50 - % ag cover in 100 m radius)/25)/2 |
| Structural and substrate variability; rooted vegetation | Maintain normal rates of erosion and deposition | Property value protection | Provides resilient buffer and protection of property and infrastructure | n/a |

| Influential Structure and Components | Processes and Functions | Ecosystem Goods and Services | Benefits | Performance Metric |
|---|---|---|---|---|
| Structural and substrate variability; rooted vegetation | Maintain complex bluff systems | Recreation–opportunities for tourism and recreational activities | Environmentally sustainable and potentially profitable availability of private and public use areas | (Public beach [0.1 or 1] x Pop density in planning reach)1/2 |
| Structural and substrate variability; rooted vegetation | Coarse material/geomorphologic complexity | Reduce storm surge and related flooding | Reduced storm-surge related flooding risk/damages | n/a |
| Structural and substrate variability; rooted vegetation | Coarse material/rooted vegetation/geomorphologic complexity | Reduce wave attack | Lower wave attack related structural damages | n/a |
| Structural and substrate variability; rooted vegetation | Maintenance of critical habitat and life requisites for TES species | TES species protection | Maintains breeding, resting and feeding habitat for TES species | 1 = listed TES that can use habitat OR its critical habitat in county , 0 = Otherwise |

Table 82. NNBF: Dune / Swale Complex.

| Influential Structure and Components | Processes and Functions | Ecosystem Goods and Services | Benefits | Performance Metric |
|---|---|---|---|---|
| Structural diversity, macrotopographic complexity | Geomorphologic diversity and natural ecosystem components | Aesthetics–appreciation of natural scenery (other than through deliberate recreational activities); inspiration for culture, art, and design | Scenic beauty, nature-inspired design, art, and culture | (SD of elevation x Pop density in Plan Reach)1/2 |
| Structural diversity, rooted vegetation, macrotopographic complexity | Series of ecosystem elements that support a variety of native biota | Biological diversity (biodiversity) | Self-sustaining diverse ecosystem biota | (Landfire veg cover x Prop native)1/2 x ((25 - % imp cover in 100 m radius)/15 + (50 - % ag cover in 100 m radius)/25)/2 |

| Influential Structure and Components | Processes and Functions | Ecosystem Goods and Services | Benefits | Performance Metric |
|---|---|---|---|---|
| Structural diversity, rooted vegetation, macrotopographic complexity | Biogeochemical processes and contact time; semidiurnal tides | Clean water provisioning (sediment, nutrients, pathogens, salinity, other pollutants) | Sequestration and transformation of pollutants; water quality enhancement | n/a |
| Structural diversity, rooted vegetation, macrotopographic complexity | Persistent native ecosystem structure, function, and dynamic processes | Cultural heritage and identity–sense of place and belonging; spiritual and religious inspiration | Culture and spirituality tied to nature; religion that supports nature | (SD of elevation x Pop density in Plan Reach)1/2 |
| Structural diversity, rooted vegetation, macrotopographic complexity | Variety of ecosystem types with balanced processes | Education and scientific opportunities (for training and education) | Educated constituency, environmental stewardship | (SD of elevation x (Pop density in Plan Reach + enrolled students in Plan Reach)/2)1/2 |
| Structural diversity, rooted vegetation, macrotopographic complexity, soil stability | Attenuation of erosive processes | Erosion protection and control (water and wind, any source) | Decreased erosion, sediment transport to open water | Veg cover |
| Structural diversity, rooted vegetation, macrotopographic complexity, soil stability | Diverse dunal geomorphologic complexity (fore-, inter- and back dune complex) | Habitat for fish and wildlife provisioning (e.g., nursery, refugium, food sources) | Habitat for wildlife specially adapted to dunal system | (Veg cover x Prop native x NPP coefficient)1/3 x ((25 - % imp cover in 100 m radius)/15 + (50 - % ag cover in 100 m radius)/25)/2 |
| Structural diversity, rooted vegetation, macrotopographic complexity, soil stability | Sediment vertical/ diagonal accretion and stability | Increase or maintain land elevation, land-building, sediment source reduction | Land building processes; offsets loss of habitat due to sea level rise | n/a |
| Structural diversity, rooted vegetation, macrotopographic complexity, soil stability | Sediment vertical accretion and stability | Maintain background suspended sediment in surface waters | Water clarity; maintains community metabolism and primary production of SAVs | Veg cover |
| Soil and vegetation properties | Biogeochemical processes and contact time; semidiurnal tides | Nutrient sequestration or conversion | Reduced nutrient pollution and maintain nutrient exchange | ((Veg cover x NPP coefficient)1/2 + (% hydric soils x % organic matter)1/2)/2 |

| Influential Structure and Components | Processes and Functions | Ecosystem Goods and Services | Benefits | Performance Metric |
|---|---|---|---|---|
| Structural diversity, rooted vegetation, macrotopographic complexity, soil stability | Natural shoreline features | Property value protection | Provides resilient buffer and protection of property and infrastructure | (90th % height/17.3 x width/200)1/2 |
| Structural diversity, rooted vegetation, macrotopographic complexity, soil stability | Maintain complex dunal systems | Recreation–opportunities for tourism and recreational activities | Environmentally sustainable and potentially profitable availability of private and public use areas | (Public beach [0.1 or 1] x Pop density in planning reach)1/2 |
| Structural diversity, rooted vegetation, macrotopographic complexity, soil stability | Biogeochemical processes and contact time; semidiurnal tides | Reduce hazardous or toxic materials in water or landscape | Reduces uptake of toxic substances into the food web | ((Veg cover x NPP coefficient)1/2 + (% hydric soils x % organic matter)1/2)/2 |
| Structural diversity, rooted vegetation, macrotopographic complexity, soil stability | Rooted vegetation/geomorphologic complexity | Reduce storm surge and related flooding | Reduced storm-surge related flooding risk/damages | (90th % height/17.3 x width/200)1/2 |
| Structural diversity, rooted vegetation, macrotopographic complexity, soil stability | Rooted vegetation/geomorphologic complexity | Reduce the peak flood height and lengthen the time to peak flood | Reduction in flood risk and wind buffer | n/a |
| Structural diversity, rooted vegetation, macrotopographic complexity, soil stability | Rooted vegetation/geomorphologic complexity | Reduce wave attack | Lower wave attack related structural damages | Max height/3.28 - 1 |
| Structural diversity, rooted vegetation, macrotopographic complexity, soil stability | Maintenance of critical habitat and life requisites for TES species | TES species protection | Maintains breeding, resting and feeding habitat for TES species | 1 = listed TES that can use habitat OR its critical habitat in county , 0 = Otherwise |

Table 83. NNBF: Salt Marsh (emergent herbaceous).

| Influential Structure and Components | Processes and Functions | Ecosystem Goods and Services | Benefits | Performance Metric |
|---|---|---|---|---|
| Salt-tolerant vegetation structure | Maintain immense/resilient sustainable marsh vegetation | Aesthetics–appreciation of natural scenery (other than through deliberate recreational activities); inspiration for culture, art, and design | Scenic beauty, nature-inspired design, art, and culture | (Veg cover x Pop density in Plan Reach)1/2 |
| Diverse salt marsh vegetation | Lunar semidiurnal tides | Biological diversity (biodiversity) | Self-sustaining diverse ecosystem biota | (Veg cover x Prop native)1/2 x ((25 - % imp cover in 100 m radius)/15 + (50 - % ag cover in 100 m radius)/25 + Ditch density)/3 |
| Dense vegetation structure | P/R ≥ 1; net primary productivity high | Carbon sequestration | Maintain carbon compartment and balance with atmospheric carbon | (Veg cover x NPP coefficient)1/2 |
| Dense vegetation structure and substrate properties | Biogeochemical processes and contact time; semidiurnal tides | Clean water provisioning (sediment, nutrients, pathogens, salinity, other pollutants) | Sequestration and transformation of pollutants; water quality enhancement | n/a |
| Dense vegetation structure and substrate properties | Maintain immense/resilient sustainable vegetation | Cultural heritage and identity–sense of place and belonging; spiritual and religious inspiration | Culture and spirituality tied to nature; religion that supports nature | (Veg cover x Pop density in Plan Reach)1/2 |
| Dense vegetation structure and substrate properties | Sustainability of diverse marsh flora and fauna | Education and scientific opportunities (for training and education) | Educated constituency, environmental stewardship | (Veg cover x (Pop density in Plan Reach + enrolled students in Plan Reach)/2)1/2 |

| Influential Structure and Components | Processes and Functions | Ecosystem Goods and Services | Benefits | Performance Metric |
|---|---|---|---|---|
| Dense vegetation structure and substrate properties | Resilient rooted marsh vegetation | Erosion protection and control (water and wind, any source) | Decreased erosion, sediment transport to open water | Veg cover |
| Dense vegetation structure, habitat diversity and substrate properties | Mosaic of dendritic tidal creeks, emergent marsh vegetation, and flats; carbon export | Habitat for fish and wildlife provisioning (e.g., nursery, refugium, food sources) | Healthy fish and wildlife Pops | (Veg cover x Prop native x NPP coefficient)1/3 x ((25 - % imp cover in 100 m radius)/15 + (50 - % ag cover in 100 m radius)/25 + Ditch density)/3 |
| Structural diversity, rooted vegetation, macrotopographic complexity, soil stability | Sediment vertical accretion and stability | Increase or maintain land elevation, land-building, sediment source reduction | Land building processes; offsets loss of habitat due to sea level rise | (Veg cover x NPP coefficient)1/2 |
| Structural diversity, rooted vegetation, macrotopographic complexity, soil stability | Sediment vertical accretion and stability | Maintain background suspended sediment in surface waters | Water clarity; maintains community metabolism and primary production of SAVs | Veg cover |
| Dense vegetation structure, habitat diversity and substrate properties | Biogeochemical processes and contact time; semidiurnal tides | Nutrient sequestration or conversion | Reduced nutrient pollution and maintain nutrient exchange | ((Veg cover x NPP coefficient)1/2 + (% hydric soils x % organic matter)1/2)/2 |
| Dense vegetation structure, habitat diversity and substrate properties | Natural shoreline features | Property value protection | Provides resilient buffer and protection of property and infrastructure | (Veg cover x Width)1/2 |
| Dense vegetation structure and substrate properties | High soil porosity and surface/groundwater exchange | Provision and storage of groundwater supply | Enhancement of surface/groundwater exchange | n/a |
| Dense vegetation structure, habitat diversity and substrate properties | Mosaic of dendritic tidal creeks, emergent marsh vegetation, and flats | Recreation–opportunities for tourism and recreational activities | Environmentally sustainable and potentially profitable availability of private and public use areas | (Public beach, park, or open space [0.1 or 1] x Veg cover x Pop density in Plan Reach)1/3 |

| Influential Structure and Components | Processes and Functions | Ecosystem Goods and Services | Benefits | Performance Metric |
|---|---|---|---|---|
| Structural diversity, rooted vegetation, macrotopographic complexity, soil stability | Biogeochemical processes and contact time; semidiurnal tides | Reduce hazardous or toxic materials in water or landscape | Reduces uptake of toxic substances into the food web | ((Veg cover x NPP coefficient)1/2 + (% hydric soils x % organic matter)1/2)/2 |
| Dense vegetation structure, habitat diversity and substrate properties | High vegetation density/Manning's n and flat topography | Reduce storm surge and related flooding | Reduced storm-surge related flooding risk/damages | (Veg cover x Width)1/2 |
| Dense vegetation structure and substrate properties | High vegetation density/Manning's n and flat topography | Reduce the peak flood height and lengthen the time to peak flood | Reduction in flood risk | n/a |
| Dense vegetation structure, habitat diversity and substrate properties | High vegetation density/Manning's n and flat topography | Reduce wave attack | Lower wave attack related structural damages | (Veg cover x Width)1/2 |
| Diverse salt marsh vegetation and habitat types | Maintenance of critical habitat and life requisites for TES species | TES species protection | Maintains breeding, resting and feeding habitat for TES species | 1 = listed TES that can use habitat OR its critical habitat in county , 0 = Otherwise |

Table 84. NNBF: Shrub-scrub Wetlands (brackish).

| Influential Structure and Components | Processes and Functions | Ecosystem Goods and Services | Benefits | Performance Metric |
|---|---|---|---|---|
| Vegetation structure | Maintain immense/resilient sustainable marsh vegetation | Aesthetics–appreciation of natural scenery (other than through deliberate recreational activities); inspiration for culture, art, and design | Scenic beauty, nature-inspired design, art, and culture | (Veg cover x Veg height x Pop density in Plan Reach)1/3 |
| Diverse salt marsh vegetation | Spatial reach and extent of lunar semidiurnal tides | Biological diversity (biodiversity) | Self-sustaining diverse ecosystem biota | (Veg cover x Veg Height x Prop native)1/3 x ((25 - % imp cover in 100 m radius)/15 + (50 - % ag cover in 100 m radius)/25 + Ditch density)/3 |
| Vegetation structure | P/r ≥ 1; net primary productivity high | Carbon sequestration | Maintain carbon compartment and balance with atmospheric carbon | (Veg cover x Veg height x NPP coefficient)1/3 |
| Vegetation structure and substrate properties | Biogeochemical processes and contact time; semidiurnal tides | Clean water provisioning (sediment, nutrients, pathogens, salinity, other pollutants) | Sequestration and transformation of pollutants; water quality enhancement | n/a |
| Vegetation structure, habitat diversity and substrate properties | Ecosystem conditions that support self-sustaining wildlife pops | Commercial harvestable fish and wildlife production | Environmentally sustainable and profitable fishery or wildlife production | biological diversity x NPP coefficient x Living Resources GDP/aquatic resource area of County |
| Vegetation structure and substrate properties | Maintain immense/resilient sustainable vegetation | Cultural heritage and identity–sense of place and belonging; spiritual and religious inspiration | Culture and spirituality tied to nature; religion that supports nature | (Veg cover x Veg height x Pop density in Plan Reach)1/3 |

| Influential Structure and Components | Processes and Functions | Ecosystem Goods and Services | Benefits | Performance Metric |
|---|---|---|---|---|
| Vegetation structure and substrate properties | Sustainability of diverse shrub flora and associated fauna | Education and scientific opportunities (for training and education) | Educated constituency, environmental stewardship | (Veg cover x Veg height x (Pop density in Plan Reach + enrolled students in Plan Reach)/2)1/3 |
| Vegetation structure and substrate properties | Resilient rooted scrub vegetation | Erosion protection and control (water and wind, any source) | Decreased erosion, sediment transport to open water | (Veg cover x Veg height)1/2 |
| Vegetation structure, habitat diversity and substrate properties | Mosaic of drainage patterns, detrital storage, and incipient flooding; carbon export | Habitat for fish and wildlife provisioning (e.g., nursery, refugium, food sources) | Healthy fish and wildlife Pops | (Veg cover x Veg Height x Prop native x NPP coefficient)1/4 x ((25 - % imp cover in 100 m radius)/15 + (50 - % ag cover in 100 m radius)/25 + Ditch density)/3 |
| Structural diversity, rooted vegetation, macrotopographic complexity, soil stability | Sediment vertical accretion and stability | Increase or maintain land elevation, land-building, sediment source reduction | Land building processes; offsets loss of habitat due to sea level rise | (Veg cover x Veg height x NPP coefficient)1/3 |
| Vegetation structure, habitat diversity and substrate properties | Sediment vertical accretion and stability | Maintain background suspended sediment in surface waters | Water clarity; maintains community metabolism and primary production of SAVs | (Veg cover x Veg height)1/2 |
| Vegetation structure, habitat diversity and substrate properties | Biogeochemical processes and contact time; semidiurnal tides | Nutrient sequestration or conversion | Reduced nutrient pollution and maintain nutrient exchange | ((Veg cover x Veg height x NPP coefficient)1/3 + (% hydric soils x % organic matter)1/2/2 |
| Vegetation structure, habitat diversity and substrate properties | Maintain adequate buffer | Property value protection | Provides resilient buffer and protection of property and infrastructure | (Veg cover x Veg height x Width)1/3 |

| Influential Structure and Components | Processes and Functions | Ecosystem Goods and Services | Benefits | Performance Metric |
|---|---|---|---|---|
| Vegetation structure and substrate properties | High soil porosity and surface/groundwater exchange | Provision and storage of groundwater supply | Enhancement of surface/groundwater exchange | n/a |
| Vegetation structure, habitat diversity and substrate properties | Mosaic of drainage patterns, detrital storage, and incipient flooding; carbon export | Recreation–opportunities for tourism and recreational activities | Environmentally sustainable and potentially profitable availability of private and public use areas | (Public beach, park, or open space [0.1 or 1] x Veg cover x Veg height x Pop density in Plan Reach)1/4 |
| Diverse salt marsh vegetation and habitat types | Biogeochemical processes and contact time; semidiurnal tides | Reduce hazardous or toxic materials in water or landscape | Reduces uptake of toxic substances into the food web | ((Veg cover x Veg height x NPP coefficient)1/3 + (% hydric soils x % organic matter)1/2/2 |
| Vegetation structure, habitat diversity and substrate properties | High vegetation density/Manning's n and flat topography | Reduce storm surge and related flooding | Reduced storm-surge related flooding risk/damages | (Veg cover x Veg height x Width)1/3 |
| Vegetation structure and substrate properties | High vegetation density/Manning's n and flat topography | Reduce the peak flood height and lengthen the time to peak flood | Reduction in flood risk | n/a |
| Structural diversity, rooted vegetation, macrotopographic complexity, soil stability | Maintenance of critical habitat and life requisites for TES species | TES species protection | Maintains breeding, resting and feeding habitat for TES species | 1 = listed TES that can use habitat OR its critical habitat in county, 0 = Otherwise |

Table 85. NNBF: Flooded Swamp Forest (brackish).

| Influential Structure and Components | Processes and Functions | Ecosystem Goods and Services | Benefits | Performance Metric |
|---|---|---|---|---|
| Vegetation structure | Maintain immense/resilient sustainable plant community | Aesthetics–appreciation of natural scenery (other than through deliberate recreational activities); inspiration for culture, art, and design | Scenic beauty, nature-inspired design, art, and culture | (Veg cover x Veg height x Pop density in Plan Reach)1/3 |
| Diverse vegetation | Spatial reach and extent of lunar semidiurnal tides | Biological diversity (biodiversity) | Self-sustaining diverse ecosystem biota | (Veg cover x Veg Height x Prop native)1/3 x ((25 - % imp cover in 100 m radius)/15 + (50 - % ag cover in 100 m radius)/25 + Ditch density)/3 |
| Vegetation structure | P/R ≥ 1; net primary productivity high | Carbon sequestration | Maintain carbon compartment and balance with atmospheric carbon | (Veg cover x Veg height x NPP coefficient)1/3 |
| Vegetation structure and substrate properties | Biogeochemical processes and contact time; semidiurnal tides | Clean water provisioning (sediment, nutrients, pathogens, salinity, other pollutants) | Sequestration and transformation of pollutants; water quality enhancement; phosphorus storage | n/a |
| Vegetation structure, habitat diversity and substrate properties | Ecosystem conditions that support self-sustaining wildlife Pops | Commercial harvestable fish and wildlife production | Environmentally sustainable and profitable fishery or wildlife production | n/a |
| Vegetation structure and substrate properties | Maintain immense/resilient sustainable vegetation | Cultural heritage and identity–sense of place and belonging; spiritual and religious inspiration | Culture and spirituality tied to nature; religion that supports nature | (Veg cover x Veg height x Pop density in Plan Reach)1/3 |

| Influential Structure and Components | Processes and Functions | Ecosystem Goods and Services | Benefits | Performance Metric |
|---|---|---|---|---|
| Vegetation structure and substrate properties | Sustainability of diverse forested flora and characteristic fauna | Education and scientific opportunities (for training and education) | Educated constituency, environmental stewardship | (Veg cover x Veg height x (Pop density in Plan Reach + enrolled students in Plan Reach)/2)1/3 |
| Vegetation structure and substrate properties | Resilient rooted woody vegetation | Erosion protection and control (water and wind, any source) | Decreased erosion, sediment transport to open water | (Veg cover x Veg height)1/2 |
| Vegetation structure, habitat diversity and substrate properties | Mosaic of drainage patterns, lateral channel migration, detrital storage, and incipient flooding; carbon export | Habitat for fish and wildlife provisioning (e.g., nursery, refugium, food sources) | Healthy fish and wildlife Pops | (Veg cover x Veg Height x Prop native x NPP coefficient)1/4 x ((25 - % imp cover in 100 m radius)/15 + (50 - % ag cover in 100 m radius)/25 + Ditch density)/3 |
| Structural diversity, rooted vegetation, macrotopographic complexity, soil stability | Sediment vertical accretion and stability | Increase or maintain land elevation, land-building, sediment source reduction | Land building processes; offsets loss of habitat due to sea level rise | (Veg cover x Veg height x NPP coefficient)1/3 |
| Structural diversity, rooted vegetation, macrotopographic complexity, soil stability | Sediment vertical accretion and stability | Maintain background suspended sediment in surface waters | Water clarity; maintains community metabolism and primary production of SAVs | (Veg cover x Veg height)1/2 |
| Vegetation structure, habitat diversity and substrate properties | Biogeochemical processes and contact time; semidiurnal tides | Nutrient sequestration or conversion | Reduced nutrient pollution and maintain nutrient exchange | ((Veg cover x Veg height x NPP coefficient)1/3 + (% hydric soils x % organic matter)1/2/2 |
| Vegetation structure, habitat diversity and substrate properties | Maintain adequate buffer and green space | Property value protection | Provides resilient buffer and protection of property and infrastructure | (Veg cover x Veg height x Width)1/3 |

| Influential Structure and Components | Processes and Functions | Ecosystem Goods and Services | Benefits | Performance Metric |
|---|---|---|---|---|
| Vegetation structure and substrate properties | High soil porosity and surface/groundwater exchange | Provision and storage of groundwater supply | Enhancement of surface/groundwater exchange | n/a |
| Vegetation structure, habitat diversity and substrate properties | Mosaic of drainage patterns, detrital storage, and incipient flooding; carbon export | Recreation–opportunities for tourism and recreational activities | Environmentally sustainable and potentially profitable availability of private and public use areas | (Public beach, park, or open space [0.1 or 1] x Veg cover x Veg height x Pop density in Plan Reach)1/4 |
| Structural diversity, rooted vegetation, macrotopographic complexity, soil stability | Biogeochemical processes and contact time; semidiurnal tides | Reduce hazardous or toxic materials in water or landscape | Reduces uptake of toxic substances into the food web | ((Veg cover x Veg height x NPP coefficient)1/3 + (% hydric soils x % organic matter)1/2/2 |
| Vegetation structure, habitat diversity and substrate properties | High vegetation density/Manning's n and flat topography | Reduce storm surge and related flooding | Reduced storm-surge related flooding risk/damages | (Veg cover x Veg height x Width)1/3 |
| Vegetation structure and substrate properties | High vegetation density/Manning's n and flat topography | Reduce the peak flood height and lengthen the time to peak flood | Reduction in flood risk | n/a |
| Structural diversity, rooted vegetation, macrotopographic complexity, soil stability | High vegetation density/Manning's n and macro- and micro-topographic diversity | Reduce wave attack | Lower wave attack related structural damages | (Veg cover x Veg height x Width)1/3 |
| Habitat diversity | Maintenance of critical habitat and life requisites for TES species | TES species protection | Maintains breeding, resting and feeding habitat for TES species | 1 = listed TES that can use habitat OR its critical habitat in county, 0 = Otherwise |

Table 86. NNBF: Maritime Grassland.

| Influential Structure and Components | Processes and Functions | Ecosystem Goods and Services | Benefits | Performance Metric |
|---|---|---|---|---|
| Vegetation structure (forbs and herbs) | Maintain immense/resilient sustainable vegetation | Aesthetics–appreciation of natural scenery (other than through deliberate recreational activities); inspiration for culture, art, and design | Scenic beauty, nature-inspired design, art, and culture | (Veg cover x Pop density in Plan Reach)1/2 |
| Vegetation structure (forbs and herbs) | Maintain endemic forbs and herbs | Biological diversity (biodiversity) | Self-sustaining diverse ecosystem biota | (Veg cover x Prop native x MSPA factor)1/3 |
| Dense vegetation structure | P/R ≥ 1; net primary productivity high | Carbon sequestration | Maintain carbon compartment and balance with atmospheric carbon | ((Veg cover x NPP coefficient)1/2 + (% hydric soils x % organic matter)1/2/2 |
| Vegetation structure and soil properties | Biogeochemical processes and contact time; semidiurnal tides | Clean water provisioning (sediment, nutrients, pathogens, salinity, other pollutants) | Sequestration and transformation of pollutants; water quality enhancement; phosphorus storage | n/a |
| Vegetation structure (forbs and herbs) | Maintain immense/resilient sustainable vegetation | Cultural heritage and identity–sense of place and belonging; spiritual and religious inspiration | Culture and spirituality tied to nature; religion that supports nature | (Veg cover x Pop density in Plan Reach)1/2 |
| Vegetation structure (forbs and herbs) | Sustainability of diverse emergent flora and characteristic fauna | Education and scientific opportunities (for training and education) | Educated constituency, environmental stewardship | (Veg cover x (Pop density in Plan Reach + enrolled students in Plan Reach)/2)1/2 |
| Dense vegetation structure and topographic complexity | Resilient rooted emergent vegetation | Erosion protection and control (water and wind, any source) | Prevents erosion from high spring tides or flood tides and wind erosion | Veg cover |
| Dense vegetation structure and topographic complexity | Mosaic of drainage patterns; carbon export | Habitat for fish and wildlife provisioning (e.g., nursery, refugium, food sources) | Provided habitat for breeding, resting and feeding | (Veg cover x Prop native x MSPA factor x NPP coefficient)1/4 |

| Influential Structure and Components | Processes and Functions | Ecosystem Goods and Services | Benefits | Performance Metric |
|---|---|---|---|---|
| Dense vegetation structure, soil properties and topographic complexity | Sediment vertical accretion and stability | Increase or maintain land elevation, land-building, sediment source reduction | Land building processes; offsets loss of habitat due to sea level rise | n/a |
| Dense vegetation structure, soil properties and topographic complexity | Sediment vertical accretion and stability | Maintain background suspended sediment in surface waters | Water clarity; maintains community metabolism and primary production of SAVs | Veg cover |
| Dense vegetation structure, soil properties and topographic complexity | Biogeochemical processes and contact time | Nutrient sequestration or conversion | Reduced nutrient pollution and maintain nutrient exchange | ((Veg cover x NPP coefficient)1/2 + (% hydric soils x % organic matter)1/2/2 |
| Dense vegetation structure and topographic complexity | Maintain adequate buffer and green space | Property value protection | Provides resilient buffer and protection of property and infrastructure | n/a |
| Soil/sediment properties | High soil porosity and surface/groundwater exchange | Provision and storage of groundwater supply | Enhancement of surface/groundwater exchange | Soil infiltration rate |
| Dense Vegetation Structure and Topographic Complexity | Maintain habitat diversity, ecotone and complexity | Recreation–opportunities for tourism and recreational activities | Environmentally sustainable and potentially profitable availability of private and public use areas | (Public beach, park, or open space [0.1 or 1] x Veg cover x Pop density in Plan Reach)1/3 |
| Dense vegetation structure, soil properties and topographic complexity | Biogeochemical processes and contact time; semidiurnal tides | Reduce hazardous or toxic materials in water or landscape | Reduces uptake of toxic substances into the food web | ((Veg cover x NPP coefficient)1/2 + (% hydric soils x % organic matter)1/2/2 |
| Dense vegetation structure, soil properties and topographic complexity | High vegetation density/Manning's n and geomorphologic diversity | Reduce storm surge and related flooding | Reduced storm-surge related flooding risk/damages | n/a |

| Influential Structure and Components | Processes and Functions | Ecosystem Goods and Services | Benefits | Performance Metric |
|---|---|---|---|---|
| Dense vegetation structure and topographic complexity | High vegetation density/Manning's n and geomorphologic diversity | Reduce the peak flood height and lengthen the time to peak flood | Reduction in flood risk | |
| Dense vegetation structure, soil properties and topographic complexity | High vegetation density/Manning's n and macro- and micro-topographic diversity | Reduce wave attack | Lower wave attack related structural damages | n/a |
| Vegetation structure and diversity | Maintenance of critical habitat and life requisites for TES species | TES species protection | Maintains breeding, resting and feeding habitat for TES species | 1 = listed TES that can use habitat OR its critical habitat in county, 0 = Otherwise |

Table 87. NNBF: Maritime Shrubland.

| Influential Structure and Components | Processes and Functions | Ecosystem Goods and Services | Benefits | Performance Metric |
|---|---|---|---|---|
| Vegetation structure (shrub/scrub) | Maintain immense/resilient sustainable vegetation | Aesthetics–appreciation of natural scenery (other than through deliberate recreational activities); inspiration for culture, art, and design | Scenic beauty, nature-inspired design, art, and culture | (Veg cover x Veg height x Pop density in Plan Reach)1/3 |
| Vegetation structure (shrub/scrub) | Maintain endemic shrub/scrub communities | Biological diversity (biodiversity) | Self-sustaining diverse ecosystem biota | (Veg cover x Veg height x Prop native x MSPA factor)1/4 |
| Dense vegetation structure | P/R ≥ 1; net primary productivity high | Carbon sequestration | Maintain carbon compartment and balance with atmospheric carbon | ((Veg cover x Veg height x NPP coefficient)1/3 + (% hydric soils x % organic matter)1/2/2 |

| Influential Structure and Components | Processes and Functions | Ecosystem Goods and Services | Benefits | Performance Metric |
|---|---|---|---|---|
| Vegetation structure and soil properties | Biogeochemical processes and contact time; semidiurnal tides | Clean water provisioning (sediment, nutrients, pathogens, salinity, other pollutants) | Sequestration and transformation of pollutants; water quality enhancement; phosphorus storage | n/a |
| Vegetation structure | Maintain immense/resilient sustainable vegetation | Cultural heritage and identity–sense of place and belonging; spiritual and religious inspiration | Culture and spirituality tied to nature; religion that supports nature | (Veg cover x Veg height x Pop density in Plan Reach)1/3 |
| Vegetation structure | Sustainability of diverse emergent flora and characteristic fauna | Education and scientific opportunities (for training and education) | Educated constituency, environmental stewardship | (Veg cover x Veg height x (Pop density in Plan Reach + enrolled students in Plan Reach)/2)1/3 |
| Dense vegetation structure and topographic complexity | Resilient rooted emergent vegetation | Erosion protection and control (water and wind, any source) | Prevents erosion from high spring tides or flood tides and wind erosion | (Veg cover x Veg height)1/2 |
| Dense vegetation structure and topographic complexity | Mosaic of drainage patterns; carbon export | Habitat for fish and wildlife provisioning (e.g., nursery, refugium, food sources) | Provided habitat for breeding, resting and feeding | (Veg cover x Veg height x Prop native x MSPA factor x NPP coefficient)1/5 |
| Dense vegetation structure, soil properties and topographic complexity | Sediment vertical accretion and stability | Increase or maintain land elevation, land-building, sediment source reduction | Land building processes; offsets loss of habitat due to sea level rise | n/a |
| Dense vegetation structure, soil properties and topographic complexity | Sediment vertical accretion and stability | Maintain background suspended sediment in surface waters | Water clarity; maintains community metabolism and primary production of SAVs | (Veg cover x Veg height)1/2 |
| Dense vegetation structure, soil properties and topographic complexity | Biogeochemical processes and contact time | Nutrient sequestration or conversion | Reduced nutrient pollution and maintain nutrient exchange | ((Veg cover x Veg height x NPP coefficient)1/3 + (% hydric soils x % organic matter)1/2/2 |

| Influential Structure and Components | Processes and Functions | Ecosystem Goods and Services | Benefits | Performance Metric |
|---|---|---|---|---|
| Dense vegetation structure and topographic complexity | Maintain adequate buffer and green space | Property value protection | Provides resilient buffer and protection of property and infrastructure | n/a |
| Soil/sediment properties | High soil porosity and surface/groundwater exchange | Provision and storage of groundwater supply | Enhancement of surface/groundwater exchange | Soil infiltration rate |
| Dense vegetation structure and topographic complexity | Maintain habitat diversity, ecotone and complexity | Recreation–opportunities for tourism and recreational activities | Environmentally sustainable and potentially profitable availability of private and public use areas | (Public beach, park, or open space [0.1 or 1] x Veg cover x Veg height x Pop density in Plan Reach)1/4 |
| Dense vegetation structure, soil properties and topographic complexity | Biogeochemical processes and contact time; semidiurnal tides | Reduce hazardous or toxic materials in water or landscape | Reduces uptake of toxic substances into the food web | ((Veg cover x Veg height x NPP coefficient)1/3 + (% hydric soils x % organic matter)1/2/2 |
| Dense vegetation structure, soil properties and topographic complexity | High vegetation density/Manning's n and geomorphologic diversity | Reduce storm surge and related flooding | Reduced storm-surge related flooding risk/damages | n/a |
| Dense vegetation structure and topographic complexity | High vegetation density/Manning's n and geomorphologic diversity | Reduce the peak flood height and lengthen the time to peak flood | Reduction in flood risk | |
| Dense vegetation structure, soil properties and topographic complexity | High vegetation density/Manning's n and macro- and micro-topographic diversity | Reduce wave attack | Lower wave attack related structural damages | n/a |
| Vegetation structure and diversity | Maintenance of critical habitat and life requisites for TES species | TES species protection | Maintains breeding, resting and feeding habitat for TES species | 1 = listed TES that can use habitat OR its critical habitat in county, 0 = Otherwise |

Table 88. NNBF: Maritime Forest.

| Influential Structure and Components | Processes and Functions | Ecosystem Goods and Services | Benefits | Performance Metric |
|---|---|---|---|---|
| Vegetation structure (trees) | Maintain immense/resilient sustainable marsh vegetation | Aesthetics–appreciation of natural scenery (other than through deliberate recreational activities); inspiration for culture, art, and design | Scenic beauty, nature-inspired design, art, and culture | (Veg cover x Veg height x Pop density in Plan Reach)1/3 |
| Vegetation structure (trees) | Maintain endemic trees including vertical diversity | Biological diversity (biodiversity) | Self-sustaining diverse ecosystem biota | (Veg cover x Veg height x Prop native x MSPA factor)1/4 |
| Dense vegetation structure and vertical complexity | P/r ≥ 1; net primary productivity high | Carbon sequestration | Maintain carbon compartment and balance with atmospheric carbon | ((Veg cover x Veg height x NPP coefficient)1/3 + (% hydric soils x % organic matter)1/2/2 |
| Vegetation structure and soil properties | Biogeochemical processes and contact time; semidiurnal tides | Clean water provisioning (sediment, nutrients, pathogens, salinity, other pollutants) | Sequestration and transformation of pollutants; water quality enhancement; phosphorus storage | n/a |
| Vegetation structure and diversity | Maintain immense/resilient sustainable vegetation | Cultural heritage and identity–sense of place and belonging; spiritual and religious inspiration | Culture and spirituality tied to nature; religion that supports nature | (Veg cover x Veg height x Pop density in Plan Reach)1/3 |
| Vegetation structure and diversity | Sustainability of diverse emergent flora and characteristic fauna | Education and scientific opportunities (for training and education) | Educated constituency, environmental stewardship | (Veg cover x Veg height x (Pop density in Plan Reach + enrolled students in Plan Reach)/2)1/3 |
| Dense vegetation structure and topographic complexity | Resilient rooted emergent vegetation | Erosion protection and control (water and wind, any source) | Prevents erosion from high spring tides or flood tides and wind erosion | (Veg cover x Veg height)1/2 |
| Dense vegetation structure and topographic complexity | Mosaic of drainage patterns; carbon export | Habitat for fish and wildlife provisioning (e.g., nursery, refugium, food sources) | Provided habitat for breeding, resting and feeding | (Veg cover x Veg height x Prop native x MSPA factor x NPP coefficient)1/5 |

| Influential Structure and Components | Processes and Functions | Ecosystem Goods and Services | Benefits | Performance Metric |
|---|---|---|---|---|
| Dense vegetation structure, soil properties and topographic complexity | Sediment vertical accretion and stability | Increase or maintain land elevation, land-building, sediment source reduction | Land building processes; offsets loss of habitat due to sea level rise | n/a |
| Dense vegetation structure, soil properties and topographic complexity | Sediment vertical accretion and stability | Maintain background suspended sediment in surface waters | Water clarity; maintains community metabolism and primary production of SAVs | (Veg cover x Veg height)1/2 |
| Dense vegetation structure, soil properties and topographic complexity | Biogeochemical processes and contact time | Nutrient sequestration or conversion | Reduced nutrient pollution and maintain nutrient exchange | ((Veg cover x Veg height x NPP coefficient)1/3 + (% hydric soils x % organic matter)1/2/2 |
| Dense vegetation structure and topographic complexity | Maintain adequate buffer and green space | Property value protection | Provides resilient buffer and protection of property and infrastructure | n/a |
| Soil/sediment properties | High soil porosity and surface/groundwater exchange | Provision and storage of groundwater supply | Enhancement of surface/groundwater exchange | Soil infiltration rate |
| Dense vegetation structure and topographic complexity | Maintain habitat diversity, ecotone and complexity | Recreation–opportunities for tourism and recreational activities | Environmentally sustainable and potentially profitable availability of private and public use areas | (Public beach, park, or open space [0.1 or 1] x Veg cover x Veg height x Pop density in Plan Reach)1/4 |
| Dense vegetation structure, soil properties and topographic complexity | Biogeochemical processes and contact time; semidiurnal tides | Reduce hazardous or toxic materials in water or landscape | Reduces uptake of toxic substances into the food web | ((Veg cover x Veg height x NPP coefficient)1/3 + (% hydric soils x % organic matter)1/2/2 |
| Dense vegetation structure, soil properties and topographic complexity | High vegetation density/Manning's n and geomorphologic diversity | Reduce storm surge and related flooding | Reduced storm-surge related flooding risk/damages | n/a |

| Influential Structure and Components | Processes and Functions | Ecosystem Goods and Services | Benefits | Performance Metric |
|---|---|---|---|---|
| Dense vegetation structure and topographic complexity | High vegetation density/Manning's n and geomorphologic diversity | Reduce the peak flood height and lengthen the time to peak flood | Reduction in flood risk | |
| Dense vegetation structure, soil properties and topographic complexity | High vegetation density/Manning's n and macro- and micro-topographic diversity | Reduce wave attack | Lower wave attack related structural damages | n/a |
| Vegetation structure and diversity | Maintenance of critical habitat and life requisites for TES species | TES species protection | Maintains breeding, resting and feeding habitat for TES species | 1 = listed TES that can use habitat OR its critical habitat in county, 0 = Otherwise |

Table 89. NNBF: Submerged Aquatic Vegetation or Aquatic vegetation Bed (seagrass, other - fresh or saline).

| Influential Structure and Components | Processes and Functions | Ecosystem Goods and Services | Benefits | Performance Metric |
|---|---|---|---|---|
| Diverse SAV with associated periphyton and macroalgae | Maintain Resilient and Sustainable Aquatic Vegetation | Aesthetics–appreciation of natural scenery (other than through deliberate recreational activities); inspiration for culture, art, and design | Scenic beauty, nature-inspired design, art, and culture | (Veg cover x Pop density in Plan Reach)1/2 |
| Diverse SAV with associated periphyton and macroalgae | Maintain semidiurnal tidal exchange; maintain endemic sav and associated benthic and epiphytic algae | Biological diversity (biodiversity) | Self-sustaining diverse ecosystem biota | Veg cover x ((25 - % imp cover in 100 m radius)/15 + (50 - % ag cover in 100 m radius)/25)/2 |
| Diverse SAV with associated periphyton and macroalgae | P/R ≥ 1; net primary productivity high | Carbon sequestration | Maintain carbon compartment and balance with atmospheric carbon | (Veg cover x NPP coefficienticient)1/2 |
| Diverse SAV with associated periphyton and macroalgae and sediment properties | Maintain adequate light transparency, nutrient cycling and exchange and detrital processes | Clean water provisioning (sediment, nutrients, pathogens, salinity, other pollutants) | Sequestration and transformation of pollutants; water quality enhancement | n/a |

| Influential Structure and Components | Processes and Functions | Ecosystem Goods and Services | Benefits | Performance Metric |
|---|---|---|---|---|
| Diverse SAV with associated periphyton and macroalgae | Sustainability of diverse SAV flora and associated fauna; maintain interface with other aquatic ecosystems | Cultural heritage and identity–sense of place and belonging; spiritual and religious inspiration | Culture and spirituality tied to nature; religion that supports nature | (Veg cover x Pop density in Plan Reach)1/2 |
| Diverse SAV with associated periphyton and macroalgae | Sustainability of diverse SAV flora and associated fauna; maintain interface with other aquatic ecosystems | Education and scientific opportunities (for training and education) | Educated constituency, environmental stewardship | (Veg cover x (Pop density in Plan Reach + enrolled students in Plan Reach)/2)1/2 |
| Diverse SAV with associated periphyton and macroalgae | Maintain healthy and diverse SAV communities; carbon export | Habitat for fish and wildlife provisioning (e.g., nursery, refugium, food sources) | Healthy fish and wildlife Pops | (Veg cover x NPP coefficient)1/2 x ((25 - % imp cover in 100 m radius)/15 + (50 - % ag cover in 100 m radius)/25)/2 |
| Diverse SAV with associated periphyton and macroalgae and sediment properties | Sediment vertical accretion and stability | Increase or maintain land elevation, land-building, sediment source reduction | Land building processes; offsets loss of habitat due to sea level rise | (Veg cover x NPP coefficienticient)1/2 |
| Diverse SAV with associated periphyton and macroalgae and sediment properties | Sediment vertical accretion and stability | Maintain background suspended sediment in surface waters | Water clarity; maintains community metabolism and primary production of SAVs | Veg cover |
| Diverse SAV with associated periphyton and macroalgae and sediment properties | Biogeochemical processes and contact time; semidiurnal tides | Nutrient sequestration or conversion | Reduced nutrient pollution and maintain nutrient exchange | (Veg cover x NPP coefficient)1/2 |
| Diverse SAV with associated periphyton and macroalgae and water clarity | Natural submerged SAV community | Property value protection | Provides resilient buffer and Sediment Stability | n/a |

| Influential Structure and Components | Processes and Functions | Ecosystem Goods and Services | Benefits | Performance Metric |
|---|---|---|---|---|
| Diverse SAV with associated periphyton and macroalgae and water clarity | Maintain healthy and diverse SAV communities | Recreation–opportunities for tourism and recreational activities | Environmentally sustainable and potentially profitable availability of private and public use areas | (Public beach [0.1 or 1] x Veg cover x Pop density in planning reach)1/3 |
| Diverse SAV with associated periphyton and macroalgae and sediment properties | Biogeochemical processes and contact time; semidiurnal tides | Reduce hazardous or toxic materials in water or landscape | Reduces uptake of toxic substances into the food web | (Veg cover x NPP coefficient)1/2 |
| Diverse SAV with associated periphyton and macroalgae and habitat diversity | Maintenance of critical habitat and life requisites for TES species | TES species protection | Maintains breeding, resting and feeding habitat for TES species | 1 = listed TES that can use habitat OR its critical habitat in county, 0 = Otherwise |

Table 90. NNBF: Riparian Buffer.

| Influential Structure and Components | Processes and Functions | Ecosystem Goods and Services | Benefits | Performance Metric |
|---|---|---|---|---|
| Vegetation structure | Maintain immense/resilient sustainable plant community | Aesthetics–appreciation of natural scenery (other than through deliberate recreational activities); inspiration for culture, art, and design | Scenic beauty, nature-inspired design, art, and culture | (Veg cover x Veg height x Pop density in Plan Reach)1/3 |
| Diverse vegetation associated with landscape position | Maintain endemic trees on levees and back swamps | Biological diversity (biodiversity) | Self-sustaining diverse ecosystem biota | (Veg cover x Veg height x Prop native x MSPA factor)1/4 |
| Structural diversity, rooted vegetation, macrotopographic complexity, soil stability | P/R ≥ 1; net primary productivity high | Carbon sequestration | Maintain carbon compartment and balance with atmospheric carbon | (Veg cover x Veg height x NPP coefficient)1/3 |
| Structural diversity, rooted vegetation, macrotopographic complexity, soil stability | Biogeochemical processes and contact time | Clean water provisioning (sediment, nutrients, pathogens, salinity, other pollutants) | Sequestration and transformation of pollutants; water quality enhancement; phosphorus storage | n/a |

| Influential Structure and Components | Processes and Functions | Ecosystem Goods and Services | Benefits | Performance Metric |
|---|---|---|---|---|
| Diverse vegetation associated with landscape position | Maintain immense/resilient sustainable vegetation | Cultural heritage and identity–sense of place and belonging; spiritual and religious inspiration | Culture and spirituality tied to nature; religion that supports nature | (Veg cover x Veg height x Pop density in Plan Reach)1/3 |
| Vegetation structure and substrate properties | Sustainability of diverse emergent flora and characteristic fauna | Education and scientific opportunities (for training and education) | Educated constituency, environmental stewardship | (Veg cover x Veg height x (Pop density in Plan Reach + enrolled students in Plan Reach)/2)1/3 |
| Vegetation structure and substrate properties | Maintain stream channel stability and shading | Erosion protection and control (water and wind, any source) | Reduced accelerated erosional rates | (Veg cover x Veg height)1/2 |
| Structural diversity, rooted vegetation, macrotopographic complexity, soil stability | Maintain in-channel habitat diversity (undercut banks, root zones, bedform maintenance, shading) | Habitat for fish and wildlife provisioning (e.g., nursery, refugium, food sources) | Provided habitat for breeding, resting and feeding | (Veg cover x Veg height x Prop native x MSPA factor x NPP coefficient)1/5 |
| Structural diversity, rooted vegetation, macrotopographic complexity, soil stability | Sediment vertical accretion and stability | Increase or maintain land elevation, land-building, sediment source reduction | Land building processes; offsets loss of habitat due to sea level rise | Feature size x Veg Height x NLCD tree cover x NPP |
| Structural diversity, rooted vegetation, macrotopographic complexity, soil stability | Sediment vertical accretion and stability | Maintain background suspended sediment in surface waters | Water clarity; maintains community metabolism and primary production of SAVs | (Veg cover x Veg height)1/2 |
| Structural diversity, rooted vegetation, macrotopographic complexity, soil stability | Biogeochemical processes and contact time | Nutrient sequestration or conversion | Reduced nutrient pollution and maintain nutrient exchange | ((Veg cover x Veg height x NPP coefficient)1/3 + (% hydric soils x % organic matter)1/2/2 |
| Vegetation structure, habitat diversity and substrate properties | Maintain adequate buffer and green space | Property value protection | Provides resilient buffer and protection of property and infrastructure | (Veg cover x Veg height x Width)1/3 |

| Influential Structure and Components | Processes and Functions | Ecosystem Goods and Services | Benefits | Performance Metric |
|---|---|---|---|---|
| Vegetation structure and substrate properties | High soil porosity and surface/groundwater exchange and bank storage | Provision and storage of groundwater supply | Enhancement of surface/groundwater exchange; baseflow augmentation | Soil infiltration rate |
| Vegetation structure and type | Maintain mature forest production | Raw materials production (e.g., timber, fiber and fuel.) | Provides wood materials | (Veg cover x Veg height x NPP coefficienticient)1/3 |
| Vegetation structure, habitat diversity and substrate properties | Maintain habitat diversity, ecotone and complexity | Recreation–opportunities for tourism and recreational activities | Environmentally sustainable and potentially profitable availability of private and public use areas | (Public beach, park, or open space [0.1 or 1] x Veg cover x Veg height x Pop density in Plan Reach)1/4 |
| Habitat diversity | Biogeochemical processes and contact time | Reduce hazardous or toxic materials in water or landscape | Reduces uptake of toxic substances into the food web | ((Veg cover x Veg height x NPP coefficient)1/3 + (% hydric soils x % organic matter)1/2/2 |
| Structural diversity, rooted vegetation, macrotopographic complexity, soil stability | High vegetation density/Manning's n and channel bank protection | Reduce storm surge and related flooding | Reduced storm-surge related flooding risk/damages | (Veg cover x Veg height x Width)1/3 |
| Structural diversity, rooted vegetation, macrotopographic complexity, soil stability | High vegetation density/Manning's n and geomorphologic diversity | Reduce the peak flood height and lengthen the time to peak flood | Reduction in flood risk | Feature size / Floodplain size |
| Habitat diversity | Maintenance of critical habitat and life requisites for TES species | TES species protection | Maintains breeding, resting and feeding habitat for TES species | 1 = listed TES that can use habitat OR its critical habitat in county, 0 = Otherwise |

Table 91. NNBF: Emergent Herbaceous Marsh / Wetland (fresh).

| Influential Structure and Components | Processes and Functions | Ecosystem Goods and Services | Benefits | Performance Metric |
|---|---|---|---|---|
| Vegetation structure (forbs and herbs) | Maintain immense/resilient sustainable plant community | Aesthetics–appreciation of natural scenery (other than through deliberate recreational activities); inspiration for culture, art, and design | Scenic beauty, nature-inspired design, art, and culture | (Veg cover x Pop density in Plan Reach)1/2 |
| Diverse vegetation and surface water connection | Maintain emergent vegetation adapted to hydric conditions | Biological diversity (biodiversity) | Self-sustaining diverse ecosystem biota | (Veg cover x Prop Native x Tree cover in 100 m radius x Cover of open water and wetlands in 1 km radius)1/4 x Ditch density |
| Dense vegetation structure | P/R ≥ 1; net primary productivity high | Carbon sequestration | Maintain carbon compartment and balance with atmospheric carbon | (Veg cover x NPP coefficient)1/2 |
| Dense vegetation structure and substrate properties | Biogeochemical processes and contact time | Clean water provisioning (sediment, nutrients, pathogens, salinity, other pollutants) | Sequestration and transformation of pollutants; water quality enhancement | n/a |
| Dense vegetation structure and substrate properties | Maintain immense/resilient sustainable vegetation | Cultural heritage and identity–sense of place and belonging; spiritual and religious inspiration | Culture and spirituality tied to nature; religion that supports nature | (Veg cover x Pop density in Plan Reach)1/2 |
| Dense vegetation structure and substrate properties | Sustainability of diverse emergent flora and characteristic fauna | Education and scientific opportunities (for training and education) | Educated constituency, environmental stewardship | (Veg cover x (Pop density in Plan Reach + enrolled students in Plan Reach)/2)1/2 |
| Dense vegetation structure and substrate properties | Resilient rooted marsh vegetation | Erosion protection and control (water and wind, any source) | Decreased erosion, sediment transport to open water | Veg cover |

| Influential Structure and Components | Processes and Functions | Ecosystem Goods and Services | Benefits | Performance Metric |
|---|---|---|---|---|
| Dense vegetation structure, habitat diversity and substrate properties | Maintain vegetation, geomorphologic diversity and drainage patterns | Habitat for fish and wildlife provisioning (e.g., nursery, refugium, food sources) | Provided habitat for breeding, resting and feeding | (Veg cover x Prop Native x Tree cover in 100 m radius x Cover of open water and wetlands in 1 km radius x NPP coefficient)1/5 x Ditch density |
| Structural diversity, rooted vegetation, macrotopographic complexity, soil stability | Sediment vertical accretion and stability | Increase or maintain land elevation, land-building, sediment source reduction | Land building processes; offsets loss of habitat due to sea level rise | Feature size x Veg Height x Veg cover x NPP |
| Structural diversity, rooted vegetation, macrotopographic complexity, soil stability | Sediment vertical accretion and stability | Maintain background suspended sediment in surface waters | Water clarity; maintains community metabolism and primary production of SAVs | Veg cover |
| Dense vegetation structure, habitat diversity and substrate properties | Biogeochemical processes and contact time | Nutrient sequestration or conversion | Reduced nutrient pollution and maintain nutrient exchange | ((Veg cover x NPP coefficient)1/2 + (% hydric soils x % organic matter)1/2/2 |
| Dense vegetation structure, habitat diversity and substrate properties | Maintain adequate buffer and green space | Property value protection | Provides resilient buffer and protection of property and infrastructure | (Veg cover x Width)1/2 |
| Dense vegetation structure and substrate properties | High soil porosity and surface/groundwater exchange and bank storage | Provision and storage of groundwater supply | Enhancement of surface/groundwater exchange; baseflow augmentation | Soil infiltration rate |
| Dense vegetation structure, habitat diversity and substrate properties | Maintain habitat diversity, ecotone and complexity | Recreation–opportunities for tourism and recreational activities | Environmentally sustainable and potentially profitable availability of private and public use areas | (Public beach, park, or open space [0.1 or 1] x Veg cover x Pop density in Plan Reach)1/3 |
| Structural diversity, rooted vegetation, macrotopographic complexity, soil stability | Biogeochemical processes and contact time | Reduce hazardous or toxic materials in water or landscape | Reduces uptake of toxic substances into the food web | ((Veg cover x NPP coefficient)1/2 + (% hydric soils x % organic matter)1/2/2 |

| Influential Structure and Components | Processes and Functions | Ecosystem Goods and Services | Benefits | Performance Metric |
|---|---|---|---|---|
| Dense vegetation structure, habitat diversity and substrate properties | High vegetation density/Manning's n and topographic diversity | Reduce storm surge and related flooding | Reduced storm-surge related flooding risk/damages | (Veg cover x Width)1/2 |
| Dense vegetation structure and substrate properties | High vegetation density/Manning's n and geomorphologic diversity | Reduce the peak flood height and lengthen the time to peak flood | Reduction in flood risk | Feature size / Watershed size |
| Dense vegetation structure, habitat diversity and substrate properties | High vegetation density/Manning's n and topographic diversity | Reduce wave attack | Lower wave attack related structural damages | n/a |
| Diverse vegetation and habitat types | Maintenance of critical habitat and life requisites for TES species | TES species protection | Maintains breeding, resting and feeding habitat for TES species | 1 = listed TES that can use habitat OR its critical habitat in county, 0 = Otherwise |

Table 92. NNBF: Shrub-scrub Wetland (fresh).

| Influential Structure and Components | Processes and Functions | Ecosystem Goods and Services | Benefits | Performance Metric |
|---|---|---|---|---|
| Vegetation structure and diversity | Maintain immense/resilient sustainable plant community | Aesthetics–appreciation of natural scenery (other than through deliberate recreational activities); inspiration for culture, art, and design | Scenic beauty, nature-inspired design, art, and culture | (Veg cover x Veg height x Pop density in Plan Reach)1/3 |
| Diverse vegetation and surface water connection | Maintain emergent vegetation adapted to hydric conditions | Biological diversity (biodiversity) | Self-sustaining diverse ecosystem biota | (Veg cover x Veg height x Prop Native x Tree cover in 100 m radius x Cover of open water and wetlands in 1 km radius)1/5 x Ditch density |
| Vegetation structure and substrate properties | P/R ≥ 1; net primary productivity high | Carbon sequestration | Maintain carbon compartment and balance with atmospheric carbon | (Veg cover x Veg height x NPP coefficient)1/3 |

| Influential Structure and Components | Processes and Functions | Ecosystem Goods and Services | Benefits | Performance Metric |
|---|---|---|---|---|
| Vegetation structure and substrate properties | Biogeochemical processes and contact time | Clean water provisioning (sediment, nutrients, pathogens, salinity, other pollutants) | Sequestration and transformation of pollutants; water quality enhancement | n/a |
| Vegetation structure and substrate properties | Maintain immense/resilient sustainable vegetation | Cultural heritage and identity–sense of place and belonging; spiritual and religious inspiration | Culture and spirituality tied to nature; religion that supports nature | (Veg cover x Veg height x Pop density in Plan Reach)1/3 |
| Vegetation structure and substrate properties | Sustainability of diverse emergent flora and characteristic fauna | Education and scientific opportunities (for training and education) | Educated constituency, environmental stewardship | (Veg cover x Veg height x (Pop density in Plan Reach + enrolled students in Plan Reach)/2)1/3 |
| Vegetation structure and substrate properties | Resilient rooted marsh vegetation | Erosion protection and control (water and wind, any source) | Decreased erosion, sediment transport to open water | (Veg cover x Veg height)1/2 |
| Vegetation structure, habitat diversity and substrate properties | Maintain vegetation, geomorphologic diversity and drainage patterns | Habitat for fish and wildlife provisioning (e.g., nursery, refugium, food sources) | Provided habitat for breeding, resting and feeding | (Veg cover x Veg height x Prop Native x Tree cover in 100 m radius x Cover of open water and wetlands in 1 km radius x NPP coefficient)1/6 x Ditch density |
| Structural diversity, rooted vegetation, macrotopographic complexity, soil stability | Sediment vertical accretion and stability | Increase or maintain land elevation, land-building, sediment source reduction | Land building processes; offsets loss of habitat due to sea level rise | (Veg cover x Veg height x NPP coefficient)1/3 |
| Vegetation structure, habitat diversity and substrate properties | Sediment vertical accretion and stability | Maintain background suspended sediment in surface waters | Water clarity; maintains community metabolism and primary production of SAVs | (Veg cover x Veg height)1/2 |

| Influential Structure and Components | Processes and Functions | Ecosystem Goods and Services | Benefits | Performance Metric |
|---|---|---|---|---|
| Structural diversity, rooted vegetation, macrotopographic complexity, soil stability | Biogeochemical processes and contact time | Nutrient sequestration or conversion | Reduced nutrient pollution and maintain nutrient exchange | ((Veg cover x Veg height x NPP coefficient)1/3 + (% hydric soils x % organic matter)1/2/2 |
| Vegetation structure, habitat diversity and substrate properties | Maintain adequate buffer and green space | Property value protection | Provides resilient buffer and protection of property and infrastructure | (Veg cover x Veg height x Width)1/3 |
| Vegetation structure and substrate properties | High soil porosity and surface/groundwater exchange and bank storage | Provision and storage of groundwater supply | Enhancement of surface/groundwater exchange; baseflow augmentation | Soil infiltration rate |
| Vegetation structure, habitat diversity and substrate properties | Maintain habitat diversity, ecotone and complexity | Recreation–opportunities for tourism and recreational activities | Environmentally sustainable and potentially profitable availability of private and public use areas | (Public beach, park, or open space [0.1 or 1] x Veg cover x Veg height x Pop density in Plan Reach)1/4 |
| Structural diversity, rooted vegetation, macrotopographic complexity, soil stability | Biogeochemical processes and contact time | Reduce hazardous or toxic materials in water or landscape | Reduces uptake of toxic substances into the food web | ((Veg cover x Veg height x NPP coefficient)1/3 + (% hydric soils x % organic matter)1/2/2 |
| Vegetation structure, habitat diversity and substrate properties | High vegetation density/Manning's n and topographic diversity | Reduce storm surge and related flooding | Reduced storm-surge related flooding risk/damages | (Veg cover x Veg height x Width)1/3 |
| Vegetation structure and substrate properties | High vegetation density/Manning's n and geomorphologic diversity | Reduce the peak flood height and lengthen the time to peak flood | Reduction in flood risk | Feature size / Watershed size |
| Vegetation structure, habitat diversity and substrate properties | Maintenance of critical habitat and life requisites for TES species | TES species protection | Maintains breeding, resting and feeding habitat for TES species | 1 = listed TES that can use habitat OR its critical habitat in county, 0 = Otherwise |

Table 93. NNBF: Flooded Swamp Forest (fresh).

| Influential Structure and Components | Processes and Functions | Ecosystem Goods and Services | Benefits | Performance Metric |
|---|---|---|---|---|
| Vegetation structure (trees) | Maintain immense/resilient sustainable plant community | Aesthetics–appreciation of natural scenery (other than through deliberate recreational activities); inspiration for culture, art, and design | Scenic beauty, nature-inspired design, art, and culture | (Veg cover x Veg height x Pop density in Plan Reach)1/3 |
| Diverse vegetation and surface water connection | Maintain endemic trees on levees and back swamps | Biological diversity (biodiversity) | Self-sustaining diverse ecosystem biota | (Veg cover x Veg height x Prop Native x Tree cover in 100-m radius x Cover of open water and wetlands in 1-km radius)1/5 x Ditch density |
| Dense vegetation structure, soil properties and topographic complexity | P/R ≥ 1; net primary productivity high | Carbon sequestration | Maintain carbon compartment and balance with atmospheric carbon | (Veg cover x Veg height x NPP coefficient)1/3 |
| Vegetation structure and soil properties | Biogeochemical processes and contact time | Clean water provisioning (sediment, nutrients, pathogens, salinity, other pollutants) | Sequestration and transformation of pollutants; water quality enhancement; phosphorus storage | n/a |
| Vegetation structure and diversity | Maintain immense/resilient sustainable vegetation | Cultural heritage and identity–sense of place and belonging; spiritual and religious inspiration | Culture and spirituality tied to nature; religion that supports nature | (Veg cover x Veg height x Pop density in Plan Reach)1/3 |
| Vegetation structure and diversity | Sustainability of diverse emergent flora and characteristic fauna | Education and scientific opportunities (for training and education) | Educated constituency, environmental stewardship | (Veg cover x Veg height x (Pop density in Plan Reach + enrolled students in Plan Reach)/2)1/3 |
| Dense vegetation structure and topographic complexity | Maintain stream channel stability and shading | Erosion protection and control (water and wind, any source) | Reduced accelerated erosional rates | (Veg cover x Veg height)1/2 |

| Influential Structure and Components | Processes and Functions | Ecosystem Goods and Services | Benefits | Performance Metric |
|---|---|---|---|---|
| Dense vegetation structure, soil properties and topographic complexity | Maintain in-channel habitat diversity (undercut banks, root zones, bedform maintenance, shading) | Habitat for fish and wildlife provisioning (e.g., nursery, refugium, food sources) | Provided habitat for breeding, resting and feeding | (Veg cover x Veg height x Prop Native x Tree cover in 100 m radius x Cover of open water and wetlands in 1 km radius x NPP coefficient)1/6 x Ditch density |
| Dense vegetation structure, soil properties and topographic complexity | Sediment vertical accretion and stability | Increase or maintain land elevation, land-building, sediment source reduction | Land building processes; offsets loss of habitat due to sea level rise | (Veg cover x Veg height x NPP coefficient)1/3 |
| Dense vegetation structure, soil properties and topographic complexity | Sediment vertical accretion and stability | Maintain background suspended sediment in surface waters | Water clarity; maintains community metabolism and primary production of SAVs | (Veg cover x Veg height)1/2 |
| Dense vegetation structure, soil properties and topographic complexity | Biogeochemical processes and contact time | Nutrient sequestration or conversion | Reduced nutrient pollution and maintain nutrient exchange | ((Veg cover x Veg height x NPP coefficient)1/3 + (% hydric soils x % organic matter)1/2/2 |
| Dense vegetation structure and topographic complexity | Maintain adequate buffer and green space | Property value protection | Provides resilient buffer and protection of property and infrastructure | (Veg cover x Veg height x Width)1/3 |
| Soil/sediment properties | High soil porosity and surface/groundwater exchange and bank storage | Provision and storage of groundwater supply | Enhancement of surface/groundwater exchange; baseflow augmentation | Soil infiltration rate |
| Dense vegetation structure and topographic complexity | Maintain habitat diversity, ecotone and complexity | Recreation–opportunities for tourism and recreational activities | Environmentally sustainable and potentially profitable availability of private and public use areas | (Public beach, park, or open space [0.1 or 1] x Veg cover x Veg height x Pop density in Plan Reach)1/4 |

| Influential Structure and Components | Processes and Functions | Ecosystem Goods and Services | Benefits | Performance Metric |
|---|---|---|---|---|
| Dense vegetation structure, soil properties and topographic complexity | Biogeochemical processes and contact time | Reduce hazardous or toxic materials in water or landscape | Reduces uptake of toxic substances into the food web | ((Veg cover x Veg height x NPP coefficient)1/3 + (% hydric soils x % organic matter)1/2/2 |
| Dense vegetation structure, soil properties and topographic complexity | High vegetation density/Manning's n and channel bank protection | Reduce storm surge and related flooding | Reduced storm-surge related flooding risk/damages | (Veg cover x Veg height x Width)1/3 |
| Dense vegetation structure and topographic complexity | High vegetation density/Manning's n and geomorphologic diversity | Reduce the peak flood height and lengthen the time to peak flood | Reduction in flood risk | Feature size / Watershed size |
| Vegetation structure, habitat diversity and substrate properties | Maintenance of critical habitat and life requisites for TES species | TES species protection | Maintains breeding, resting and feeding habitat for TES species | 1 = listed TES that can use habitat OR its critical habitat in county, 0 = Otherwise |

Table 94. NNBF: Pond.

| Influential Structure and Components | Processes and Functions | Ecosystem Goods and Services | Benefits | Performance Metric |
|---|---|---|---|---|
| SAV and fringe vegetation diversity | Maintain water quality including water clarity | Aesthetics–appreciation of natural scenery (other than through deliberate recreational activities); inspiration for culture, art, and design | Scenic beauty, nature-inspired design, art, and culture | (Veg cover in 100-m buffer x Pop density in Plan Reach)1/2 |
| SAV and fringe vegetation diversity and endemic fish and macroinvertebrates | Maintain endemic SAV, fringe vegetation and associated phytoplankton and periplankton | Biological diversity (biodiversity) | Self-sustaining diverse ecosystem biota | (Tree cover in 100 m radius x Cover of open water and wetlands in 1 km radius)1/2 |

| Influential Structure and Components | Processes and Functions | Ecosystem Goods and Services | Benefits | Performance Metric |
|---|---|---|---|---|
| SAV and fringe vegetation diversity and substrate properties | Maintain adequate light transparency, nutrient cycling and exchange and detrital processes | Clean water provisioning (sediment, nutrients, pathogens, salinity, other pollutants) | Sequestration and transformation of pollutants; water quality enhancement | n/a |
| Suitable habitat and niche for edible fish | Supports life stage(s) of edible species of fish, mussels and crustaceans | Commercial harvestable fish and wildlife production | Socio-economic enhancement | n/a |
| SAV and fringe vegetation diversity and endemic fish and macroinvertebrates | Sustainability of diverse SAV and fringe vegetation associated fauna; maintain interface with other aquatic ecosystems | Cultural heritage and identity–sense of place and belonging; spiritual and religious inspiration | Culture and spirituality tied to nature; religion that supports nature | (Veg cover in 100 m buffer x Pop density in Plan Reach)1/2 |
| SAV and fringe vegetation diversity and endemic fish and macroinvertebrates | Sustainability of diverse SAV and fringe vegetation associated fauna; maintain interface with other aquatic ecosystems | Education and scientific opportunities (for training and education) | Educated constituency, environmental stewardship | (Veg cover in 100 m buffer x (Pop density in Plan Reach + enrolled students in Plan Reach)/2)1/2 |
| Diverse SAV with associated periphyton and phytoplankton and sediment properties | Maintain open water and littoral zone habitat diversity | Habitat for fish and wildlife provisioning (e.g., nursery, refugium, food sources) | Provided habitat for breeding, resting and feeding | (Veg cover in 100 m radius x Cover of open water and wetlands in 1 km radius x NPP coefficient)1/3 |
| SAV and fringe vegetation diversity and substrate properties | Maintain bank stability | Maintain background suspended sediment in surface waters | Water clarity; maintains community metabolism and primary production of SAVs | Feature size / Watershed size |
| Diverse SAV with associated periphyton and phytoplankton and sediment properties | Biogeochemical processes and contact time | Nutrient sequestration or conversion | reduced nutrient pollution and maintain nutrient exchange | NPP coefficient |
| Diverse SAV with associated periphyton and macroalgae and sediment properties | Maintain adequate buffer and green space | Property value protection | Provides resilient buffer and protection of property and infrastructure | Feature size / Watershed size |

| Influential Structure and Components | Processes and Functions | Ecosystem Goods and Services | Benefits | Performance Metric |
|---|---|---|---|---|
| Substrate properties | High soil/sediment porosity, hydraulic conductivity, surface/groundwater exchange and bank storage | Provision and storage of groundwater supply | Enhancement of surface/groundwater exchange; baseflow augmentation | Soil infiltration rate |
| SAV and fringe vegetation diversity; habitat and niche for sport fish | Maintain habitat diversity, ecotone and complexity | Recreation–opportunities for tourism and recreational activities | Environmentally sustainable and potentially profitable availability of private and public use areas | (Public beach, park, or open space [0.1 or 1] x Veg cover in 100 m buffer x Pop density in Plan Reach)1/3 |
| SAV and fringe vegetation diversity and substrate properties | High vegetation density/Manning's n and pond bank protection | Reduce storm surge and related flooding | Reduced storm-surge related flooding risk/damages | n/a |
| SAV and fringe vegetation diversity and endemic fish and macroinvertebrates; water storage | Maintain adequate short- and long-term water storage and roughness (fringe vegetation) | Reduce the peak flood height and lengthen the time to peak flood | Reduction in flood risk | Feature size / Watershed size |
| Vegetation structure, habitat diversity including open water and substrate properties | Maintenance of critical habitat and life requisites for TES species | TES species protection | Maintains breeding, resting and feeding habitat for TES species | 1 = listed TES that can use habitat OR its critical habitat in county, 0 = Otherwise |

Table 95. NNBF: Terrestrial Grassland.

| Influential Structure and Components | Processes and Functions | Ecosystem Goods and Services | Benefits | Performance Metric |
|---|---|---|---|---|
| Vegetation structure (forbs and herbs) | Maintain immense/resilient sustainable plant community | Aesthetics–appreciation of natural scenery (other than through deliberate recreational activities); inspiration for culture, art, and design | Scenic beauty, nature-inspired design, art, and culture | (Veg cover x Pop density in Plan Reach)1/2 |
| Vegetation structure (forbs and herbs) | Maintain emergent vegetation adapted to hydric conditions | Biological diversity (biodiversity) | Self-sustaining diverse ecosystem biota | (Veg cover x Prop native x MSPA factor)1/3 |

| Influential Structure and Components | Processes and Functions | Ecosystem Goods and Services | Benefits | Performance Metric |
|---|---|---|---|---|
| Dense vegetation structure | $P/R \geq 1$; net primary productivity high | Carbon sequestration | Maintain carbon compartment and balance with atmospheric carbon | (Veg cover x NPP coefficient)1/2 |
| Vegetation structure and soil properties | Biogeochemical processes, buffer strip and contact time | Clean water provisioning (sediment, nutrients, pathogens, salinity, other pollutants) | Sequestration and transformation of pollutants; water quality enhancement | n/a |
| Vegetation structure (forbs and herbs) | Maintain immense/resilient sustainable vegetation | Cultural heritage and identity–sense of place and belonging; spiritual and religious inspiration | Culture and spirituality tied to nature; religion that supports nature | (Veg cover x Pop density in Plan Reach)1/2 |
| Vegetation structure (forbs and herbs) | Sustainability of diverse emergent flora and characteristic fauna | Education and scientific opportunities (for training and education) | Educated constituency, environmental stewardship | (Veg cover x (Pop density in Plan Reach + enrolled students in Plan Reach)/2)1/2 |
| Dense vegetation structure and topographic complexity | Resilient rooted marsh vegetation | Erosion protection and control (water and wind, any source) | Decreased erosion, sediment transport to open water | Veg cover |
| Dense vegetation structure and topographic complexity | Maintain vegetation, geomorphologic diversity and drainage patterns | Habitat for fish and wildlife provisioning (e.g., nursery, refugium, food sources) | Provided habitat for breeding, resting and feeding | (Veg cover x Prop native x MSPA factor x NPP coefficient)1/4 |
| Dense vegetation structure, soil properties and topographic complexity | Sediment vertical accretion and stability | Increase or maintain land elevation, land-building, sediment source reduction | Land building processes; offsets loss of habitat due to sea level rise | n/a |
| Dense vegetation structure, soil properties and topographic complexity | Sediment vertical accretion and stability | Maintain background suspended sediment in surface waters | Water clarity; maintains community metabolism and primary production of SAVs | Veg cover |

| Influential Structure and Components | Processes and Functions | Ecosystem Goods and Services | Benefits | Performance Metric |
|---|---|---|---|---|
| Dense vegetation structure, soil properties and topographic complexity | Maintain characteristic soil properties associated with biogeochemical processes (soil horizons and ultrasol) | Nutrient sequestration or conversion | Improves surface and ground water quality (buffer strip phenomenon) | ((Veg cover x NPP coefficient)1/2 + (% hydric soils x % organic matter)1/2/2 |
| Dense vegetation structure and topographic complexity | Maintain adequate buffer and green space | Property value protection | Provides resilient buffer and protection of property and infrastructure | n/a |
| Soil/sediment properties | High soil porosity and surface/groundwater exchange and bank storage | Provision and storage of groundwater supply | Enhancement of surface/groundwater exchange; baseflow augmentation | Soil infiltration rate |
| Dense vegetation structure and topographic complexity | Maintain habitat diversity, ecotone and complexity | Recreation–opportunities for tourism and recreational activities | Environmentally sustainable and potentially profitable availability of private and public use areas | (Public beach, park, or open space [0.1 or 1] x Veg cover x Pop density in Plan Reach)1/3 |
| Dense vegetation structure, soil properties and topographic complexity | Biogeochemical processes and contact time | Reduce hazardous or toxic materials in water or landscape | Reduces uptake of toxic substances into the food web | ((Veg cover x NPP coefficient)1/2 + (% hydric soils x % organic matter)1/2/2 |

Table 96. NNBF: Terrestrial Shrubland.

| Influential Structure and Components | Processes and Functions | Ecosystem Goods and Services | Benefits | Performance Metric |
|---|---|---|---|---|
| Vegetation structure (shrub/scrub) | Maintain immense/resilient sustainable plant community | Aesthetics–appreciation of natural scenery (other than through deliberate recreational activities); inspiration for culture, art, and design | Scenic beauty, nature-inspired design, art, and culture | (Veg cover x Veg height x Pop density in Plan Reach)1/3 |
| Vegetation structure (shrub/scrub) | Maintain emergent vegetation adapted to hydric conditions | Biological diversity (biodiversity) | Self-sustaining diverse ecosystem biota | (Veg cover x Veg height x Prop native x MSPA factor)1/4 |

| Influential Structure and Components | Processes and Functions | Ecosystem Goods and Services | Benefits | Performance Metric |
|---|---|---|---|---|
| Dense vegetation structure | P/R ≥ 1; net primary productivity high | Carbon sequestration | Maintain carbon compartment and balance with atmospheric carbon | ((Veg cover x Veg height x NPP coefficient)1/3 + (% hydric soils x % organic matter)1/2/2 |
| Vegetation structure and soil properties | Biogeochemical processes and contact time | Clean water provisioning (sediment, nutrients, pathogens, salinity, other pollutants) | Sequestration and transformation of pollutants; water quality enhancement | n/a |
| Vegetation structure | Maintain immense/resilient sustainable vegetation | Cultural heritage and identity–sense of place and belonging; spiritual and religious inspiration | Culture and spirituality tied to nature; religion that supports nature | (Veg cover x Veg height x Pop density in Plan Reach)1/3 |
| Vegetation structure | Sustainability of diverse emergent flora and characteristic fauna | Education and scientific opportunities (for training and education) | Educated constituency, environmental stewardship | (Veg cover x Veg height x (Pop density in Plan Reach + enrolled students in Plan Reach)/2)1/3 |
| Dense vegetation structure and topographic complexity | Resilient rooted marsh vegetation | Erosion protection and control (water and wind, any source) | Decreased erosion, sediment transport to open water | (Veg cover x Veg height)1/2 |
| Dense vegetation structure and topographic complexity | Maintain vegetation, geomorphologic diversity and drainage patterns | Habitat for fish and wildlife provisioning (e.g., nursery, refugium, food sources) | Provided habitat for breeding, resting and feeding | (Veg cover x Veg height x Prop native x MSPA factor x NPP coefficient)1/5 |
| Dense vegetation structure, soil properties and topographic complexity | Sediment vertical accretion and stability | Increase or maintain land elevation, land-building, sediment source reduction | Land building processes; offsets loss of habitat due to sea level rise | n/a |
| Dense vegetation structure, soil properties and topographic complexity | Sediment vertical accretion and stability | Maintain background suspended sediment in surface waters | Water clarity; maintains community metabolism and primary production of SAVs | (Veg cover x Veg height)1/2 |

| Influential Structure and Components | Processes and Functions | Ecosystem Goods and Services | Benefits | Performance Metric |
|---|---|---|---|---|
| Dense vegetation structure, soil properties and topographic complexity | Biogeochemical processes and contact time | Nutrient sequestration or conversion | reduced nutrient pollution and maintain nutrient exchange | ((Veg cover x Veg height x NPP coefficient)1/3 + (% hydric soils x % organic matter)1/2/2 |
| Dense vegetation structure and topographic complexity | Maintain adequate buffer and green space | Property value protection | Provides resilient buffer and protection of property and infrastructure | n/a |
| Soil/sediment properties | High soil porosity and surface/groundwater exchange and bank storage | Provision and storage of groundwater supply | Enhancement of surface/groundwater exchange; baseflow augmentation | Soil infiltration rate |
| Dense vegetation structure and topographic complexity | Maintain habitat diversity, ecotone and complexity | Recreation–opportunities for tourism and recreational activities | Environmentally sustainable and potentially profitable availability of private and public use areas | (Public beach, park, or open space [0.1 or 1] x Veg cover x Veg height x Pop density in Plan Reach)1/4 |
| Dense vegetation structure, soil properties and topographic complexity | Biogeochemical processes and contact time | Reduce hazardous or toxic materials in water or landscape | Reduces uptake of toxic substances into the food web | ((Veg cover x Veg height x NPP coefficient)1/3 + (% hydric soils x % organic matter)1/2/2 |
| Dense vegetation structure, soil properties and topographic complexity | High vegetation density/Manning's n and topographic diversity | Reduce storm surge and related flooding | Reduced storm-surge related flooding risk/damages | n/a |
| Dense vegetation structure and topographic complexity | High vegetation density/Manning's n and geomorphologic diversity | Reduce the peak flood height and lengthen the time to peak flood | Reduction in flood risk | Feature size / Watershed size |
| Vegetation structure and diversity | Maintenance of critical habitat and life requisites for TES species | TES species protection | Maintains breeding, resting and feeding habitat for TES species | 1 = listed TES that can use habitat OR its critical habitat in county, 0 = Otherwise |

Table 97. NNBF: Terrestrial Forest.

| Influential Structure and Components | Processes and Functions | Ecosystem Goods and Services | Benefits | Performance Metric |
|---|---|---|---|---|
| Vegetation structure (trees) | Maintain immense/resilient sustainable plant community | Aesthetics–appreciation of natural scenery (other than through deliberate recreational activities); inspiration for culture, art, and design | Scenic beauty, nature-inspired design, art, and culture | (Veg cover x Veg height x Pop density in Plan Reach)1/3 |
| Vegetation structure (trees) | Maintain endemic trees on levees and back swamps | Biological diversity (biodiversity) | Self-sustaining diverse ecosystem biota | (Veg cover x Veg height x Prop native x MSPA factor)1/4 |
| Dense vegetation structure and vertical complexity | P/R ≥ 1; net primary productivity high | Carbon sequestration | Maintain carbon compartment and balance with atmospheric carbon | ((Veg cover x Veg height x NPP coefficient)1/3 + (% hydric soils x % organic matter)1/2/2 |
| Vegetation structure and soil properties | Biogeochemical processes and contact time | Clean water provisioning (sediment, nutrients, pathogens, salinity, other pollutants) | Sequestration and transformation of pollutants; water quality enhancement; phosphorus storage | n/a |
| Vegetation structure and diversity | Maintain immense/resilient sustainable vegetation | Cultural heritage and identity–sense of place and belonging; spiritual and religious inspiration | Culture and spirituality tied to nature; religion that supports nature | (Veg cover x Veg height x Pop density in Plan Reach)1/3 |
| Vegetation structure and diversity | Sustainability of diverse emergent flora and characteristic fauna | Education and scientific opportunities (for training and education) | Educated constituency, environmental stewardship | (Veg cover x Veg height x (Pop density in Plan Reach + enrolled students in Plan Reach)/2)1/3 |
| Dense vegetation structure and topographic complexity | Maintain soil stability and shading | Erosion protection and control (water and wind, any source) | Reduced accelerated erosional rates | (Veg cover x Veg height)1/2 |
| Dense vegetation structure and topographic complexity | Maintain habitat diversity and ecotone | Habitat for fish and wildlife provisioning (e.g., nursery, refugium, food sources) | Provided habitat for breeding, resting and feeding | (Veg cover x Veg height x Prop native x MSPA factor x NPP coefficient)1/5 |

| Influential Structure and Components | Processes and Functions | Ecosystem Goods and Services | Benefits | Performance Metric |
|---|---|---|---|---|
| Dense vegetation structure, soil properties and topographic complexity | Sediment vertical accretion and stability | Increase or maintain land elevation, land-building, sediment source reduction | Land building processes; offsets loss of habitat due to sea level rise | n/a |
| Dense vegetation structure, soil properties and topographic complexity | Sediment vertical accretion and stability | Maintain background suspended sediment in surface waters | Water clarity; maintains community metabolism and primary production of SAVs | (Veg cover x Veg height)1/2 |
| Dense vegetation structure, soil properties and topographic complexity | Biogeochemical processes and contact time | Nutrient sequestration or conversion | Reduced nutrient pollution and maintain nutrient exchange | ((Veg cover x Veg height x NPP coefficient)1/3 + (% hydric soils x % organic matter)1/2/2 |
| Dense vegetation structure and topographic complexity | Maintain adequate buffer and green space | Property value protection | Provides resilient buffer and protection of property and infrastructure | n/a |
| Soil/sediment properties | High soil porosity and surface/groundwater exchange and bank storage | Provision and storage of groundwater supply | Enhancement of surface/groundwater exchange; baseflow augmentation | Soil infiltration rate |
| Dense vegetation structure and topographic complexity | Maintain mature forest production | Raw materials production (e.g., timber, fiber and fuel) | Provides Wood Materials | (Veg cover x Veg height x NPP coefficienticient)1/3 |
| Dense vegetation structure, soil properties and topographic complexity | Maintain habitat diversity, ecotone and complexity | Recreation–opportunities for tourism and recreational activities | Environmentally sustainable and potentially profitable availability of private and public use areas | (Public beach, park, or open space [0.1 or 1] x Veg cover x Veg height x Pop density in Plan Reach)1/4 |
| Dense vegetation structure, soil properties and topographic complexity | Biogeochemical processes and contact time | Reduce hazardous or toxic materials in water or landscape | Reduces uptake of toxic substances into the food web | ((Veg cover x Veg height x NPP coefficient)1/3 + (% hydric soils x % organic matter)1/2/2 |

| Influential Structure and Components | Processes and Functions | Ecosystem Goods and Services | Benefits | Performance Metric |
|---|---|---|---|---|
| Dense vegetation structure and topographic complexity | High vegetation density/Manning's n and geomorphologic diversity | Reduce the peak flood height and lengthen the time to peak flood | Reduction in flood risk | Feature size / Watershed size |
| Vegetation structure and diversity | Maintenance of critical habitat and life requisites for TES species | TES species protection | Maintains breeding, resting and feeding habitat for TES species | 1 = listed TES that can use habitat OR its critical habitat in county, 0 = Otherwise |

Table 98. NNBF and structural feature complexes: Reef or Mollusk reef, Intertidal or Submerged (also see Breakwater).

| Influential Structure and Components | Processes and Functions | Ecosystem Goods and Services | Benefits | Performance Metric |
|---|---|---|---|---|
| Diverse benthic organisms with associated fish | Maintain immense/resilient sustainable reef communities including macroalgae | Aesthetics–appreciation of natural scenery (other than through deliberate recreational activities); inspiration for culture, art, and design | Scenic beauty, nature-inspired design, art, and culture | (1/(distance to mainland in km) x pop density in plan reach)1/2 |
| Suitable substrate for attachment of benthic organisms with associated fish | Maintain fish and benthic communities | Biological diversity (biodiversity) | self-sustaining diverse ecosystem biota | ((25 - % imp cover in 100 m radius)/15 + (50 - % ag cover in 100 m radius)/25)/2 |
| Suitable substrate for attachment of benthic organisms with associated fish | Maintain adequate light transparency, nutrient cycling and exchange | Clean water provisioning (sediment, nutrients, pathogens, salinity, other pollutants) | Sequestration and transformation of pollutants; water quality enhancement | n/a |
| Suitable substrate for attachment of benthic organisms with associated edible fish and shell fish | Supports life stage(s) of edible species of fish, mussels and crustaceans | Commercial harvestable fish and wildlife production | Socio-economic enhancement | Same as Habitat Provisioning |

| Influential Structure and Components | Processes and Functions | Ecosystem Goods and Services | Benefits | Performance Metric |
|---|---|---|---|---|
| Diverse benthic organisms with associated fish | Sustainability of diverse fisheries and benthic communities; maintain interface with other aquatic ecosystems | Cultural heritage and identity–sense of place and belonging; spiritual and religious inspiration | Culture and spirituality tied to nature; religion that supports nature | (1/(distance to mainland in km) x pop density in plan reach)1/2 |
| Diverse benthic organisms with associated fish | Sustainability of diverse fisheries and benthic communities; maintain interface with other aquatic ecosystems | Education and scientific opportunities (for training and education) | Educated constituency, environmental stewardship | (1/(distance to mainland in km) x Pop density in Plan Reach + Enrolled students in High School and Universities in Plan Reach)/2)1/2 |
| Suitable substrate for attachment of stable benthic organisms | Maintain benthic community and appropriate substrate type | Erosion protection and control (water and wind, any source) | Decreased erosion, sediment transport to open water and to inland waters | Height - MSL + 1 |
| Suitable substrate for attachment of benthic organisms with associated fish | Sustainability of diverse fisheries and benthic communities; maintain interface with other aquatic ecosystems | Habitat for fish and wildlife provisioning (e.g., nursery, refugium, food sources) | Provided habitat for breeding, resting and feeding | NPP coefficient x ((25 - % imp cover in 100 m radius)/15 + (50 - % ag cover in 100 m radius)/25)/2 |
| Suitable substrate for attachment of stable benthic organisms | Maintain reef stability and substrate type | Maintain background suspended sediment in surface waters | Water clarity; maintains community metabolism and primary production of SAVs | n/a |
| Suitable substrate for attachment of benthic organisms | Biogeochemical processes and contact time | Nutrient sequestration or conversion | Reduced nutrient pollution and maintain nutrient exchange | n/a |
| Suitable substrate for attachment of benthic organisms with associated fish | Maintain reef ecosystem | Property value protection | Provides resilient buffer and protection of property and infrastructure | n/a |

| Influential Structure and Components | Processes and Functions | Ecosystem Goods and Services | Benefits | Performance Metric |
|---|---|---|---|---|
| Suitable substrate for attachment of benthic organisms with associated fish | Maintain habitat diversity, ecotone and complexity | Recreation–opportunities for tourism and recreational activities | Environmentally sustainable and potentially profitable availability of private and public use areas | (Public beach, park, or open space [0.1 or 1] x (1/(distance to mainland in km) x Pop density in planning reach)1/3 |
| Suitable substrate for attachment of stable benthic organisms | Biogeochemical processes and contact time | Reduce hazardous or toxic materials in water or landscape | Reduces uptake of toxic substances into the food web | n/a |
| Suitable substrate for attachment of stable benthic organisms | Maintain benthic community and appropriate substrate type | Reduce storm surge and related flooding | Reduced storm-surge related flooding risk/damages | n/a |
| Suitable substrate for attachment of stable benthic organisms | Maintain benthic community and appropriate substrate type | Reduce wave attack | Lower wave attack related structural damages | Relative height |
| Diverse benthic habitat | Maintenance of critical habitat and life requisites for TES species | TES species protection | Maintains breeding, resting and feeding habitat for TES species | 1 = listed TES that can use habitat OR its critical habitat in county, 0 = Otherwise |

Table 99. NNBF and structural feature complexes: Living Shoreline (e.g., vegetation w/ sills, benches, breakwaters).

| Influential Structure and Components | Processes and Functions | Ecosystem Goods and Services | Benefits | Performance Metric |
|---|---|---|---|---|
| Diverse vegetation structure and natural substrate properties | Maintain immense/resilient sustainable shoreline vegetation | Aesthetics–appreciation of natural scenery (other than through deliberate recreational activities); inspiration for culture, art, and design | Scenic beauty, nature-inspired design, art, and culture | Pop density in Plan Reach |
| Diverse vegetation structure, natural substrate properties and mesohabitats | Lunar semidiurnal tides | Biological diversity (biodiversity) | Self-sustaining diverse ecosystem biota | log(Feature Size) x ((25 - % imp cover in 100 m radius)/15 [max = 1, min = 0]) |

| Influential Structure and Components | Processes and Functions | Ecosystem Goods and Services | Benefits | Performance Metric |
|---|---|---|---|---|
| Structural diversity, rooted vegetation, macrotopographic complexity, soil stability | P/R ≥ 1; net primary productivity high | Carbon sequestration | Maintain carbon compartment and balance with atmospheric carbon | |
| Structural diversity, rooted vegetation, macrotopographic complexity, soil stability | Biogeochemical processes and contact time; semidiurnal tides | Clean water provisioning (sediment, nutrients, pathogens, salinity, other pollutants) | Sequestration and transformation of pollutants; water quality enhancement | n/a |
| Structural diversity, rooted vegetation, macrotopographic complexity, soil stability | Sustainability of diverse shoreline flora and fauna | Education and scientific opportunities (for training and education) | Educated constituency, environmental stewardship | log(Feature Size) x (Pop density in Plan Reach + # schools in 10 km radius)/2 |
| Structural diversity, rooted vegetation, macrotopographic complexity, soil stability | Resilient rooted shoreline vegetation and substrate | Erosion protection and control (water and wind, any source) | Decreased erosion, sediment transport to open water | Feature size x Veg cover x Veg Height |
| Structural diversity, rooted vegetation, macrotopographic complexity, soil stability | Emergent and shrub/scrub shoreline vegetation | Habitat for fish and wildlife provisioning (e.g., nursery, refugium, food sources) | Healthy fish and wildlife Pops | biological diversity x NPP coefficienticient |
| Structural diversity, rooted vegetation, macrotopographic complexity, soil stability | Sediment vertical accretion and stability | Increase or maintain land elevation, land-building, sediment source reduction | Land building processes; offsets loss of habitat due to sea level rise | n/a |
| Structural diversity, rooted vegetation, macrotopographic complexity, soil stability | Sediment vertical accretion and stability | Maintain background suspended sediment in surface waters | Water clarity; maintains community metabolism and primary production of SAVs | Feature size x Veg cover x Veg Height |
| Dense vegetation structure, habitat diversity and substrate properties | Biogeochemical processes and contact time | Nutrient sequestration or conversion | reduced nutrient pollution and maintain nutrient exchange | Feature size x NPP coefficienticient |
| Structural diversity, rooted vegetation, macrotopographic complexity, soil stability | Natural shoreline features | Property value protection | Provides resilient buffer and protection of property and infrastructure | Feature size x Veg cover x Veg Height |

| Influential Structure and Components | Processes and Functions | Ecosystem Goods and Services | Benefits | Performance Metric |
|---|---|---|---|---|
| Dense vegetation structure, soil properties and topographic complexity | Biogeochemical processes and contact time; semidiurnal tides | Reduce hazardous or toxic materials in water or landscape | Reduces uptake of toxic substances into the food web | Feature size x NPP coefficienticient |
| Structural diversity, rooted vegetation, macrotopographic complexity, soil stability | High vegetation density/Manning's n and topography relief | Reduce storm surge and related flooding | Reduced storm-surge related flooding risk/damages | n/a |
| Structural diversity, rooted vegetation, macrotopographic complexity, soil stability | High vegetation density/Manning's n and topography relief | Reduce wave attack | Lower wave attack related structural damages | Feature size x Veg cover x Veg Height |
| Suitable habitat and niche for TES species | Maintenance of critical habitat and life requisites for TES species | TES species protection | Maintains breeding, resting and feeding habitat for TES species | 1 = listed TES that can use habitat OR its critical habitat in county, 0 = Otherwise |

Table 100. Structural features: Levee.

| Influential Structure and Components | Processes and Functions | Ecosystem Goods and Services | Benefits | Performance Metric |
|---|---|---|---|---|
| Structure as a barrier | Maintain barrier | Aesthetics–appreciation of natural scenery (other than through deliberate recreational activities); inspiration for culture, art, and design | Architectural beauty, nature-inspired design, art and culture, locally iconic feature | Structural Integrity |
| Structure as a barrier | Maintain barrier | Cultural heritage and identity–sense of place and belonging; spiritual and religious inspiration | Iconic in villages, provides resilient buffer and protection of property and infrastructure | log(Feature Size) x Pop density in Plan Reach, Structural Integrity |
| Structure as a barrier | The presence of the structure, provides the opportunity of training and education | Education and scientific opportunities (for training and education) | Improved understanding of vulnerability and risk of the coastal setting, function of levees | Structural Integrity |

| Influential Structure and Components | Processes and Functions | Ecosystem Goods and Services | Benefits | Performance Metric |
|---|---|---|---|---|
| Crest elevation, structure footprint, cross-sectional volume. | Provides a physical barrier to erosion, provides source of material to absorb erosion forces. | Erosion protection and control (water and wind, any source) | Limits erosion losses to properties landward of structure | Levee crest elevation, volume of material in levee cross-section, footprint of levee. |
| Crest elevation. | Provides physical barrier to the introduction of sediments from the coast to upland areas. | Increase or maintain land elevation, land-building, sediment source reduction | Prevents overwash of coastal sediments. | Levee crest elevation; Probability of failure x Value of property being protected |
| Crest elevation, structure footprint, cross-sectional volume. | Provide a physical barrier to erosion processes and flood waters | Property value protection | Protects properties landward of structure from erosion and inundation losses. | Probability of failure x Value of property being protected |
| Crest elevation. | Provides a physical barrier to flood waters | Reduce storm surge and related flooding | Protects properties landward of structure from inundation losses. | Levee crest elevation; Probability of failure x Value of property being protected |
| Crest elevation. | Provides a physical barrier to flood waters | Reduce the peak flood height and lengthen the time to peak flood | Protects properties landward of structure from inundation losses. | Levee crest elevation; Probability of failure x Value of property being protected |
| Crest elevation/width, cross-sectional volume. Seaward slope; surface coverage | Absorbs wave energy | Reduce wave attack | Protects properties landward of structure from direct wave impacts. | Levee crest elevation/width. Seaward slope; Surface coverage; Probability of failure x Value of property being protected |

Table 101. Structural features: Storm Surge Barrier.

| Influential Structure and Components | Processes and Functions | Ecosystem Goods and Services | Benefits | Performance Metric |
|---|---|---|---|---|
| Structure as a barrier | Maintain barrier | Aesthetics–appreciation of natural scenery (other than through deliberate recreational activities); inspiration for culture, art, and design | Scenic beauty, nature-inspired design, art, and culture | Structure Integrity |
| Suitable substrate for attachment of diverse benthic organisms with associated fish | Maintain fish and benthic communities | Biological diversity (biodiversity) | Self-sustaining diverse ecosystem biota | log(Feature Size) x ((25 - % imp cover in 100 m radius)/15 [max = 1, min = 0]) |
| Structure as a barrier | Sediment/oil spill barrier | Clean water provisioning (Limit sediment and pollutant transport into estuaries) | Limit sediment and pollutant transport into estuaries | Structure Integrity, porosity |
| Suitable substrate for attachment of benthic organisms with associated fish, structure as a barrier | Sustainability of diverse fisheries and benthic communities; maintain interface with other aquatic ecosystems | Cultural heritage and identity–sense of place and belonging; spiritual and religious inspiration | Iconic in villages, provides resilient buffer and protection of property and infrastructure | log(Feature Size) x Pop density in Plan Reach; Structure Integrity |
| Suitable substrate for attachment of benthic organisms with associated fish, structure as a barrier | The presence of the structure, provides the opportunity for training and education | Education and scientific opportunities (for training and education) | Improved understanding of vulnerability and risk of the coastal setting, function of surge barriers | log(Feature Size) x (Pop density in Plan Reach + # schools in 10 km radius)/2; Structure Integrity |
| Suitable substrate for attachment of benthic organisms with associated fish | Maintain benthic community and appropriate substrate type | Erosion protection and control (water and wind, any source) | Decreased erosion, sediment transport to open water and to inland waters | Feature size x Mean height x Prop of Leeward shoreline in BW shadow |
| Structure as a barrier | Breakwaters protect harbors and maintain channels, shelter estuaries | Commercial harvestable fish and wildlife production | Maintain commercial fishery by protecting fleet and fleet services | biological diversity x NPP coefficienticient x Living Resources GDP/aquatic resource area of County; Structure Integrity |

| Influential Structure and Components | Processes and Functions | Ecosystem Goods and Services | Benefits | Performance Metric |
|---|---|---|---|---|
| Structure as a barrier | Maintain barrier | Property value protection | Provides buffer and protection of property and infrastructure | Feature size x Mean height x Prop of Leeward shoreline in BW shadow; Structure Integrity |
| Structure as a barrier | Maintain barrier | Reduce storm surge and related flooding | Provides buffer and protection of property and infrastructure | Feature size x Mean height x Prop of Leeward shoreline in BW shadow, Structure Integrity |
| Structure as a barrier | Maintain barrier | Reduce wave attack | Provides buffer and protection of property and infrastructure | Feature size x Mean height x Prop of Leeward shoreline in BW shadow, Structure Integrity |
| Structure as a barrier | Maintain barrier | Keep unwanted sediments out of storm waters | Decreased erosion, sediment transport to open water and to inland waters | Structure Integrity |
| Structure as a barrier | Maintain barrier | Increase or maintain land elevation, land-building, sediment source reduction | Decreased erosion, sediment transport to open water and to inland waters | Structure Integrity |
| Structure as a barrier | Maintain barrier | TES species protection | Protect habitat in sheltered sensitive areas, decreased erosion, sediment transport to inland waters/estuaries | 1 = listed TES that can use habitat OR its critical habitat in county , 0 = Otherwise |
| Structure as a barrier | Maintain barrier | Reduce hazardous or toxic materials in water or landscape | Limit pollutant transport into estuaries | Structure Integrity |

Table 102. Structural features: Seawall / Revetment / Bulkhead.

| Influential Structure and Components | Processes and Functions | Ecosystem Goods and Services | Benefits | Performance Metric |
|---|---|---|---|---|
| Structure as a barrier | Maintain barrier | Aesthetics–appreciation of natural scenery (other than through deliberate recreational activities); inspiration for culture, art, and design | Architectural beauty, nature-inspired design, art and culture, locally iconic feature, sense of community | log(Feature Size) x Pop density in Plan Reach, Structure Integrity |
| Structure as a barrier | Maintain barrier | Cultural heritage and identity–sense of place and belonging; spiritual and religious inspiration | Iconic in region, provides resilient buffer and protection of property and infrastructure | log(Feature Size) x Pop density in Plan Reach, Structure Integrity |
| Structure as a barrier | The presence of the structure, provides the opportunity for training and education | Education and scientific opportunities (for training and education) | Improved understanding of vulnerability and risk of the coastal setting, function of seawalls | Structure Integrity |
| Structure as a barrier | Sequesters material (soil) landward of the seawall from erosive forces. | Erosion protection and control (water and wind, any source) | Prevents loss of sediments and provides erosion protection to upland infrastructure. | Structure Integrity; observed shoreline change from GIS |
| Structure as a barrier | Sequesters material (soil) landward of the seawall from erosive forces. | Increase or maintain land elevation, land-building, sediment source reduction | Prevents loss of sediments behind seawall to erosion forces | Structure Integrity; observed shoreline change from GIS |
| Structure as a barrier | Sequesters material (soil) landward of the seawall from erosive forces. | Property value protection | Prevents wave attack on property, erosion losses | Structure Integrity; observed shoreline change from GIS |
| Structure as a barrier | Physical barrier to flood waters (provided the structure is not overtopped) | Reduce storm surge and related flooding | Prevents inundation losses (provided structure is not overtopped) | Structure Integrity; crest elevation |

| Influential Structure and Components | Processes and Functions | Ecosystem Goods and Services | Benefits | Performance Metric |
|---|---|---|---|---|
| Structure as a barrier | Physical barrier to flood waters (provided the structure is not overtopped) | Reduce the peak flood height and lengthen the time to peak flood | Prevents inundation losses (provided structure is not overtopped) | Structure Integrity; crest elevation |
| Structure as a barrier | Provides physical barrier to direct wave impacts (provided structure is not overtopped). | Reduce wave attack | prevents loss of sediments and provides erosion protection to upland infrastructure by blocking wave energy. | Structure Integrity; crest elevation |

Table 103. Structural features: Groin.

| Influential Structure and Components | Processes and Functions | Ecosystem Goods and Services | Benefits | Performance Metric |
|---|---|---|---|---|
| Diverse benthic organisms with associated fish | Maintain resilient sustainable barrier communities including periphyton | Aesthetics–appreciation of natural scenery (other than through deliberate recreational activities); inspiration for culture, art, and design | Architectural beauty, nature-inspired design, art and culture | Structure Integrity |
| Suitable substrate for attachment of diverse benthic organisms with associated fish | Maintain fish and benthic communities | Biological diversity (biodiversity) | Self-sustaining diverse ecosystem biota | log(Feature Size) x ((25 - % imp cover in 100 m radius)/15 [max = 1,<br>min = 0]) |
| Suitable substrate for attachment of benthic organisms with associated fish | Sustainability of diverse fisheries and benthic communities; maintain interface with other aquatic ecosystems | Cultural heritage and identity–sense of place and belonging; spiritual and religious inspiration | Iconic in villages, provides resilient sediment barrier and indirect protection of property and infrastructure | log(Feature Size) x 1/(1+log(1+distance to shore in km)); ; observed shoreline change from GIS |

| Influential Structure and Components | Processes and Functions | Ecosystem Goods and Services | Benefits | Performance Metric |
|---|---|---|---|---|
| Suitable substrate for attachment of benthic organisms with associated fish | Sustainability of diverse fisheries and benthic communities; often easily accessible | Education and scientific opportunities (for training and education) | Numerous education opportunities both above water and below with easy access to deeper water habitat, understanding risk | log(Feature Size) x (Pop density in Plan Reach + # schools in 10 km radius)/2, Structural Integrity |
| Suitable substrate for attachment of benthic organisms with associated fish | Maintain benthic community and appropriate substrate type | Erosion protection and control (water and wind, any source) | Decreased erosion, sediment transport to open water and to inland waters | Feature size x Mean height x Prop of Leeward shoreline in BW shadow; observed shoreline change from GIS |
| Suitable substrate for attachment of benthic organisms with associated fish | Sustainability of diverse fisheries and benthic communities; often easily accessible | Habitat for fish and wildlife provisioning (e.g., nursery, refugium, food sources) | Provided habitat for breeding, resting and feeding | biological diversity x NPP coefficienticient |
| Suitable substrate for attachment of benthic organisms | Biogeochemical processes and contact time | Nutrient sequestration or conversion | Reduced nutrient pollution and maintain nutrient exchange | 3 g/(m2*y) |
| Suitable substrate for attachment of benthic organisms with associated fish | Maintain habitat diversity, ecotone and complexity | Recreation–opportunities for tourism and recreational activities | Provided habitat for breeding, resting and feeding | public beach, park, or open space [0.1 or 1] x log(area) x pop density in planning reach; observed shoreline change from GIS |
| Structure as a barrier | Maintain barrier | Increase or maintain land elevation, land-building, sediment source reduction | Decreased erosion, sediment transport to open water and to inland waters | Observed shoreline change from GIS |

Table 104. Structural features: Breakwater.

| Influential Structure and Components | Processes and Functions | Ecosystem Goods and Services | Benefits | Performance Metric |
|---|---|---|---|---|
| Structure as a barrier | Maintain resilient sustainable barrier | Aesthetics–appreciation of natural scenery (other than through deliberate recreational activities); inspiration for culture, art, and design | Architectural beauty, nature-inspired design, art and culture, locally iconic feature | Structure Integrity |
| Suitable substrate for attachment of diverse benthic organisms with associated fish | Maintain fish and benthic communities | Biological diversity (biodiversity) | Self-sustaining diverse ecosystem biota | log(Feature Size) x ((25 - % imp cover in 100 m radius)/ 15 [max = 1, min = 0]) |
| Structure as a barrier | Sediment/oil spill barrier | Clean water provisioning (Limit sediment and pollutant transport into estuaries) | Limit sediment and pollutant transport into estuaries | Structure Integrity |
| Suitable substrate for attachment of benthic organisms with associated fish, structure as a barrier | Sustainability of diverse fisheries and benthic communities; maintain interface with other aquatic ecosystems | Cultural heritage and identity–sense of place and belonging; spiritual and religious inspiration | Iconic in villages, provides resilient buffer and protection of property and infrastructure | log(Feature Size) x Pop density in Plan Reach, Structure Integrity |
| Suitable substrate for attachment of benthic organisms with associated fish, structure as a barrier | Sustainability of diverse fisheries and benthic communities; often easily accessible | Education and scientific opportunities (for training and education) | Numerous education opportunities both above water and below with easy access to deeper water habitat, understanding risk | log(Feature Size) x (Pop density in Plan Reach + # schools in 10 km radius)/2, Structure Integrity |
| Suitable substrate for attachment of benthic organisms with associated fish | Maintain benthic community and appropriate substrate type | Erosion protection and control (water and wind, any source) | Decreased erosion, sediment transport to open water and to inland waters | Feature size x Mean height x Prop of Leeward shoreline in BW shadow |
| Suitable substrate for attachment of benthic organisms with associated fish | Sustainability of diverse fisheries and benthic communities; often easily accessible | Habitat for fish and wildlife provisioning (e.g., nursery, refugium, food sources) | Provided habitat for breeding, resting and feeding | Structure Porosity, biological diversity x NPP coefficienticient |

| Influential Structure and Components | Processes and Functions | Ecosystem Goods and Services | Benefits | Performance Metric |
|---|---|---|---|---|
| Structure as a barrier | Breakwaters protect harbors and maintain channels, shelter estuaries | Commercial harvestable fish and wildlife production | Maintain commercial fishery by protecting fleet and fleet services | biological diversity x NPP coefficienticient x Living Resources GDP/aquatic resource area of County |
| Suitable substrate for attachment of benthic organisms | Biogeochemical processes and contact time | Nutrient sequestration or conversion | Reduced nutrient pollution and maintain nutrient exchange | function of Structure Porosity |
| Structure as a barrier | Maintain barrier | Property value protection | Provides resilient buffer and protection of property and infrastructure | Probability of failure x Value of property being protected |
| Suitable substrate for attachment of benthic organisms with associated fish | Maintain habitat diversity, ecotone and complexity | Recreation–opportunities for tourism and recreational activities | Provided habitat for breeding, resting and feeding | public beach, park, or open space [0.1 or 1] x log(area) x pop density in planning reach |
| Structure as a barrier | Maintain barrier | Reduce storm surge and related flooding | Provides resilient buffer and protection of property and infrastructure | Probability of failure x Value of property being protected |
| Structure as a barrier | Maintain barrier | Reduce wave attack | Provides resilient buffer and protection of property and infrastructure | Probability of failure x Value of property being protected |
| Structure as a barrier | Maintain barrier | Keep unwanted sediments out of storm waters | Decreased erosion, sediment transport to open water and to inland waters | n/a |
| Structure as a barrier | Maintain barrier | Increase or maintain land elevation, land-building, sediment source reduction | Decreased erosion, sediment transport to open water and to inland waters | n/a |
| Structure as a barrier | Maintain barrier | TES species protection | Protect habitat in sheltered sensitive areas, decreased erosion, sediment transport to inland waters/estuaries | 1 = listed TES that can use habitat OR its critical habitat in county , 0 = Otherwise |
| Structure as a barrier | Maintain barrier | Reduce hazardous or toxic materials in water or landscape | Limit pollutant transport into estuaries | n/a |

# Appendix I: Causal Maps

A series of three causal maps were developed for this study to capture the pathway to providing benefits using structural features (Figure 81) versus NNBF (Figure 82 and Figure 83). The causal maps developed for this study identified over 400 causal relationships. Since it would be too cumbersome to describe all of those relationships, this appendix offers a few examples from both structural and NNBF to highlight how qualitative causal mapping is used in the analysis.

The analysis of structural features identified ten benefits and ten services across six features. Figure 81 illustrates how the causal map can be used to identify potential leverage points in the system. The example shows how features may converge to support a given benefit. An important service that reaches across both structural and NNBF is reduce storm surge and related flooding. The benefit of this service is to protect properties from inundation losses and damages from flooding. For structural features, there is one function that supports this service: provide a physical barrier to flood waters. The causal map shows three primary features provide the physical barrier: levees, seawalls, and surge barriers. In terms of performance, the functions for those features establish metrics for the analysis: crest elevation, structural integrity of seawall, and structure elevation, respectively. The example shows how three features converge to support one benefit. In addition, the causal map shows how features diverge to support multiple benefits from a given feature. The features which provide physical barriers to flood waters and reduce storm surge promote other services and benefits. For example, levees have another function to provide a physical barrier to erosion for the service of erosion protection and control that supports the benefit to limit erosion losses. In addition, levees have a third function to absorb wave energy for the service to reduce wave attack that supports a benefit to reduce wave energy. Therefore, the implementation of a policy to improve one feature to reduce storm surge and related flooding could have multiple benefits. The causal map of structural features shows approximately 75 causal links in the conceptual model. The examples mentioned represent just a small fraction of analyses that may be explored using this approach.

Figure 81. Causal map for structural features alone.

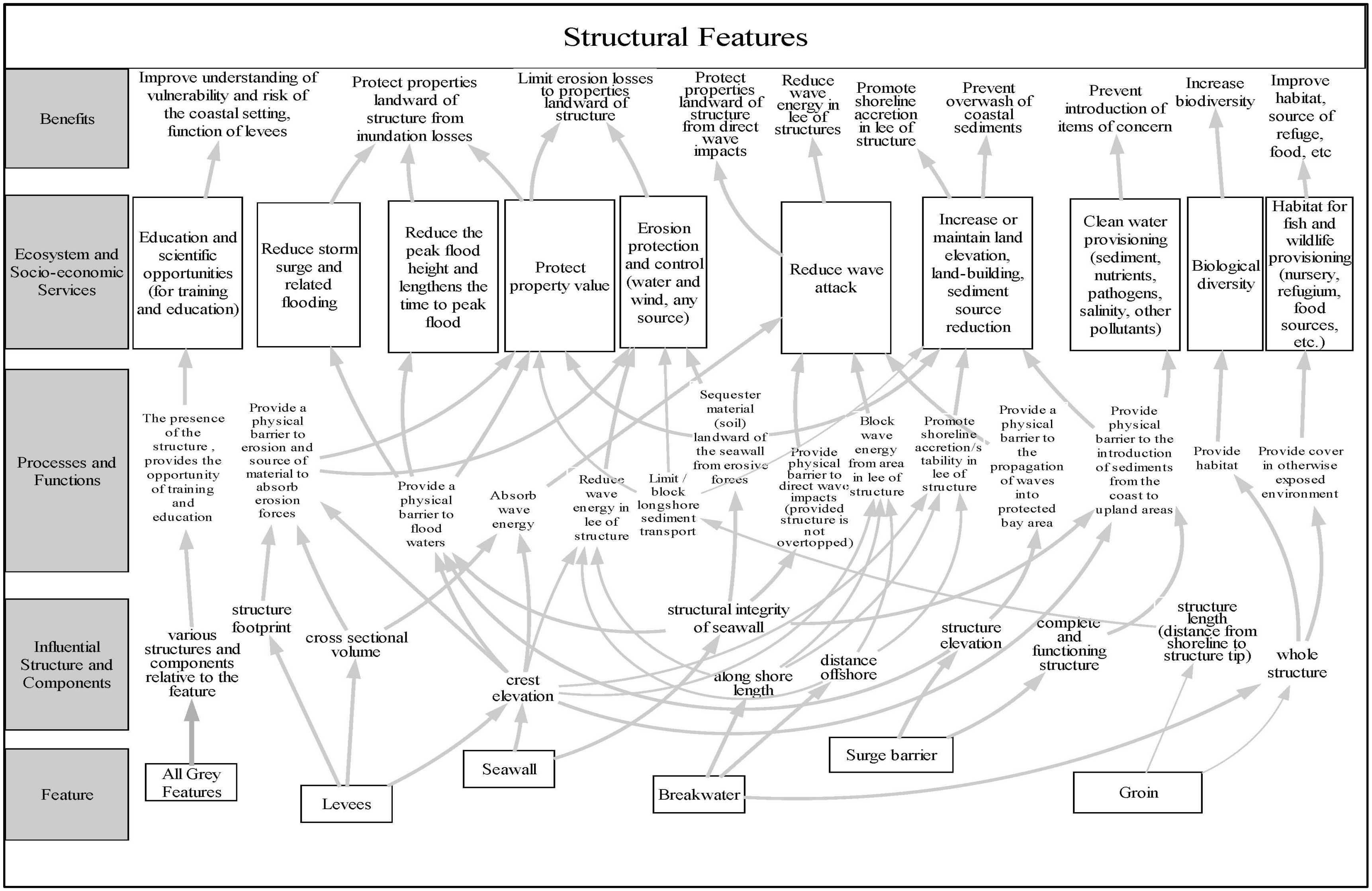


Figure 82. Causal map for NNBF and the pathways to providing reduced storm-surge related flooding damages benefits.

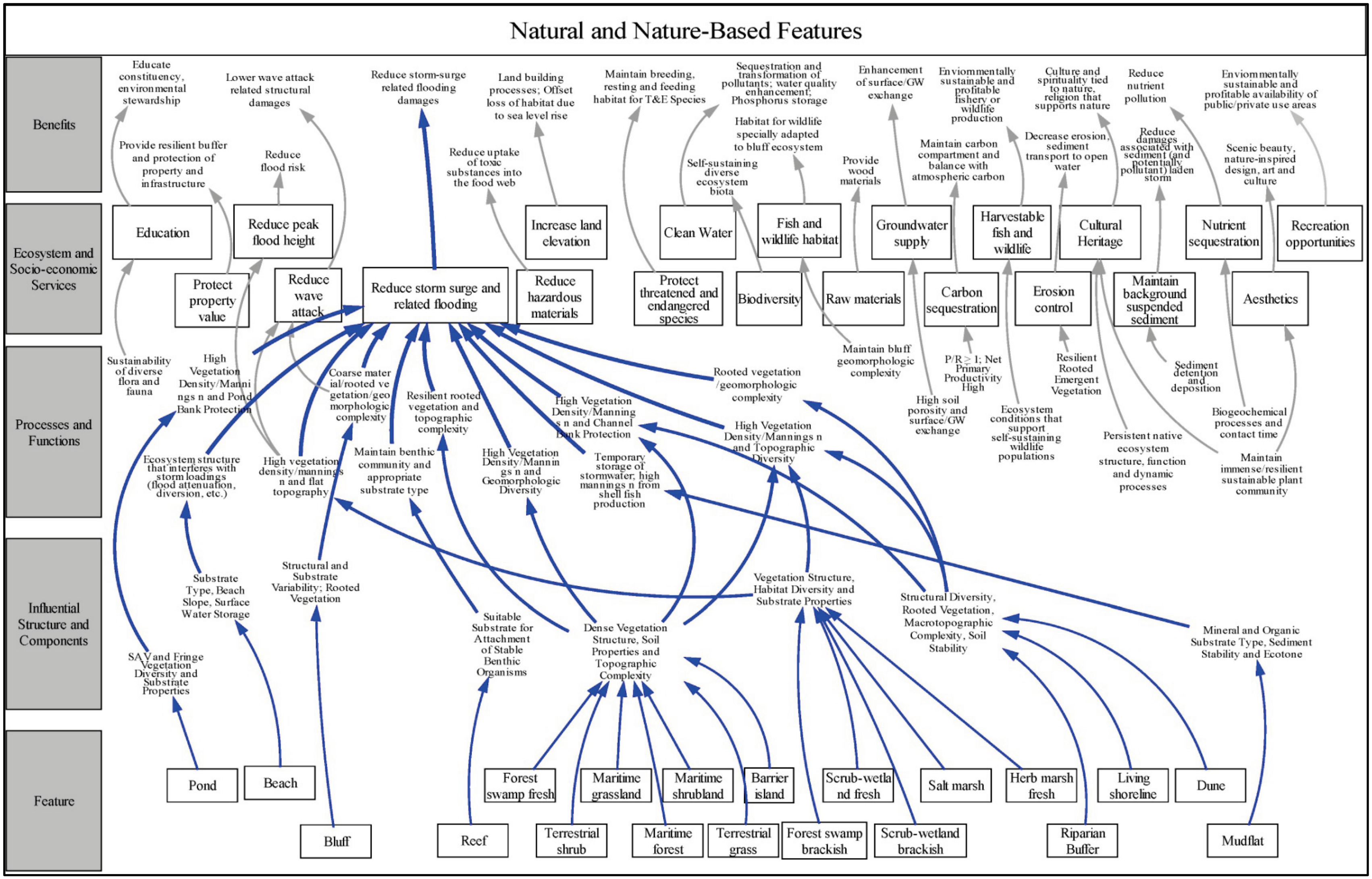
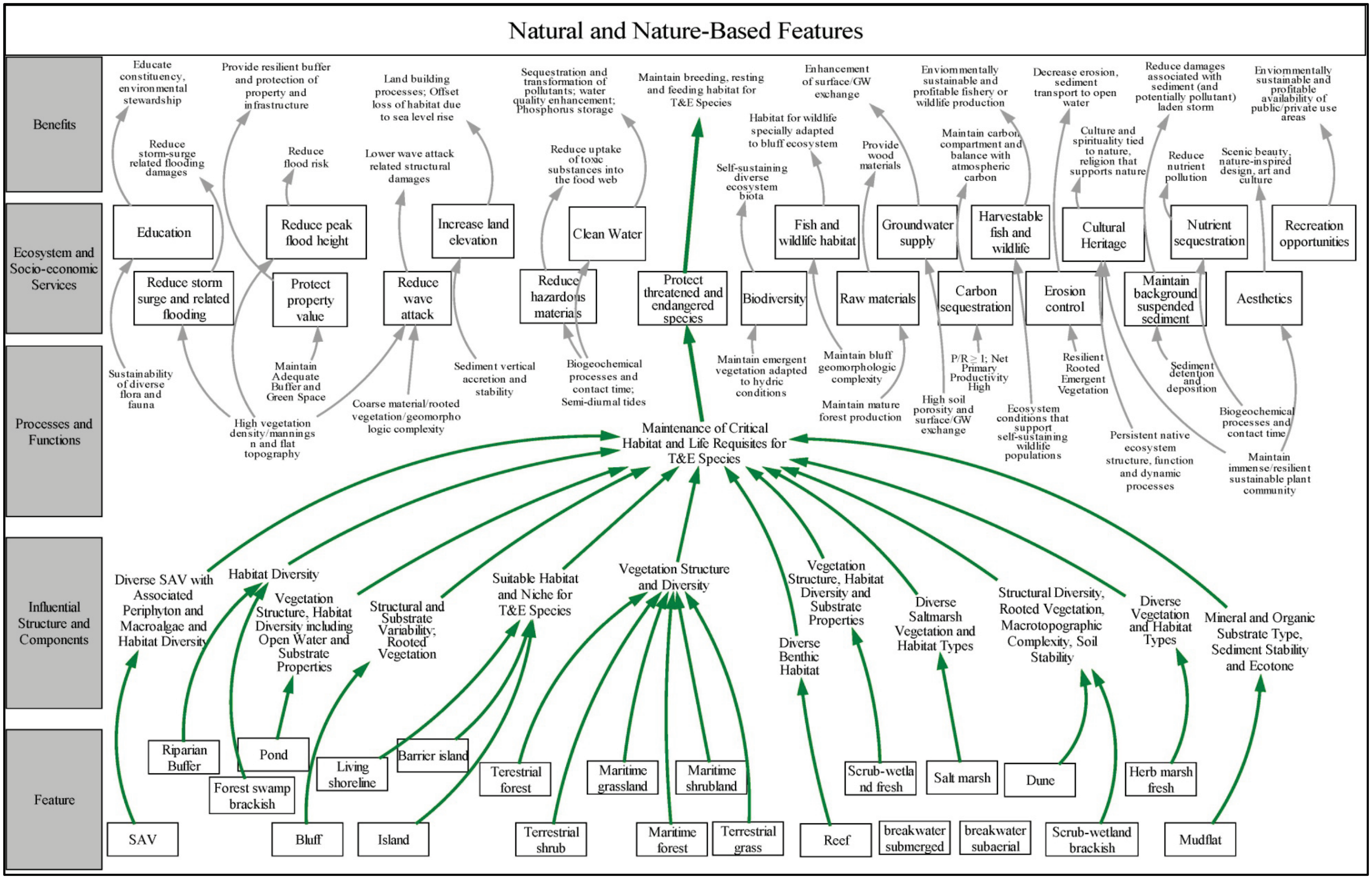


Figure 83. Causal map for NNBF and the pathways to providing habitat for TES species.



The analysis of NNBF included all 10 services identified for the structural feature model and an additional 11 services specific to NNBF (Figure 82). As with the structural features, the NNBF also have the potential for converging on given services to support similar benefits. The structural features causal map is used as a point of reference to illustrate the point. The service to reduce storm surge and related flooding is supported by 20 NNBF. These features cut across a spectrum of services, which also provide environmental and ecological benefits. As with the structural features, the storm reduction service for NNBF provides a direct benefit to reducing storm-related flood damages. As seen in the casual map, there are 11 processes and functions that link directly to the reduce storm surge and related flooding service. For example, beaches provide an ecosystem structure that interferes with storm loadings, which reduces storm surge. Several features converge to provide high vegetation density and channel bank protection to reduce storm surge, such as forest swamp fresh, terrestrial shrub, maritime grassland, maritime forest, maritime shrubland, terrestrial grass, and barrier islands. In addition, other NNBF that reduce storm surge converge on functions that provide rooted vegetation and geomorphic complexity, such as living shoreline, riparian buffer, and dunes. Causal mapping makes it easier to visualize the relationships to see areas where features that may not have a direct relationship in terms of function or process have similar potential benefits.

Figure 83 shows how a causal map may be used to identify robust solutions across divergent goals and objectives. The example shows the connection between flood risk and endangered species. The example is also important because the endangered species benefit is supported by all of the NNBF. In the previous example, there were 20 NNBF that supported the service to reduce storm surge and related flooding. Of those 20 features, all but three support the service to protect TES species. With that said, the path to these two services is quite different. The main function for all features that support the service to reduce TES species service provide a function for the Maintenance of critical habitat and life requisites for TES species. Despite sharing similar features, the influential structures and components vary across many of the NNBF. For example, the riparian buffer influential structure is habitat diversity, while the mudflat influential structure is mineral and organic substrate type, sediment stability, and ecotone.

From a higher level analysis, it is apparent that features which support both services in these examples (reduce storm surge and protect TES species) take different causal paths to achieve their end state. For example, barrier islands provided both flood risk and endangered species services, but achieve those services (and benefits) through slightly different causal paths. The barrier island influential component for protecting TES species is a suitable habitat and niche for TES species. However, the barrier island influential component for reducing storm surge is dense vegetation, soil properties, and topographic complexity. The causal map can be used to highlight many of these diverging and converging relationships. In summary, these examples show how causal mapping may provide insights on policy solutions with multiple benefits through various causal paths.

There would be three next steps to develop a quantitative model from these causal maps. First, the metrics defined in this study would be used to quantify the causal relationships between features and their corresponding benefits. Second, through expert elicitation and the collection of time-series data, reference modes would be defined to show trends on each of the metrics. Third, the causal map would be refined to a model of a closed-loop system, as discussed in the system dynamics introduction to this section. The reinforcing and balancing loops would represent the relationship between benefits in a current time period and actions which change the state (e.g., condition or performance) of features in future time periods. The model would be tested and refined with sensitivity analyses, extreme condition tests, and scenario tests, until the structure of the model reproduces the historical behavior in the system.

# Appendix J: Service Quantification Protocols

In most situations, specific peer-reviewed studies were not available to characterize important attributes of an ecosystem and its linkages with the surrounding environment. Thus, metric development in most cases relied on assumptions on the importance of key attributes and their relationships with functions and, ultimately, services. As pointed out previously, the metric need not be complex and serves as a starting point for site-appropriate and site-specific metric development. The metrics developed for each service category merit additional explanation on the choice of indicators and the mathematical operations combining the indicators into a final metric.

All indicators would be based on either normalized values or an absolute threshold with scoring ranging from 0 to 1.0. A score of 1.0 represents achievement of a desirable outcome, and a score of 0.0 represents an undesirable outcome. For most indicators for NNBF, there is little knowledge on acceptable values or threshold. In the absence of a specific value or threshold, indicators were normalized based on the maximum value of the indicator for a feature within the NACCS study area or other selected geographic area. For a shrub wetland, a height value of the shrub wetland would be normalized with respect to the maximum height value of all shrub wetlands in the geographic area. For population density within a planning reach, the population density value of the planning reach would be normalized with respect to the maximum population density value in the geographic area. Alternatively, there may be specific standards that could be the basis of scoring indicators. The standard may be 10% impervious cover of a buffer where having less than 10% impervious cover would result in an indicator score of 1.0. Another standard may be a specific elevation above MSL of a beach (e.g., 17.3 feet) to counter expected storm surge events of a certain height where the height of the beach exceeding the standard would result in an indicator score of 1.0.

When multiple indicators are involved, construction of a final metric involves a few mathematical operations. In most cases, a geometric mean of the indicators would serve as the final metric. A metric involving indicators for vegetation height, cover, and proportion of native habitats would be calculated using the geometric mean of the normalized values for height, cover, and proportion. When stressors are involved, the stressor indicator would be multiplied separately with the other indicators. As an example, if an estuary habitat has 100% cover and 100% native plant composition combined with 50% impervious cover in the 100 m buffer, high values for the vegetation structure indicators would not be able to counter the controlling effect of the stressor. For metrics with several stressor indicators, the stressors were arithmetically averaged to create a stressor submetric.

Metrics which were predominantly biological, physical, or biogeochemical did not use economic indicators. Establishing the actual ecosystem service would require economic demand functions, but these demand functions were not evaluated for this effort. Metrics that did involve a service that was primarily socioeconomic (e.g., aesthetics, cultural heritage, education) did not use a socio-economic indicator to highlight the possible uses by people and communities.

Many metrics used the same formula for a set of indicators. As an example, maritime forest, maritime shrub, upland forest, and upland shrub had similar metric formulas. The height differences between forest and shrub were accounted for by the vegetation height indicator. Maritime forest and upland forest were indistinguishable as were maritime shrub and upland shrub.

The following sections provide a synopsis of the construction of the metrics for the different NNBF. These metrics are meant to be an initial start with further refinement occurring based on availability of local data and better local knowledge of ecosystem processes. Table 105 summarizes each performance metrics on a service-by-service basis.

## Aesthetics and cultural heritage

The services for aesthetics and cultural heritage were indistinguishable and were treated the same using the same indicators and metrics. Indicators for this metric include those for characterizing human use and indicators characterizing the natural environment. The common indicator characterizing potential human usage was population density in the planning reach. The geographic unit could be planning reach, county, a buffer zone around the feature and would be expected to change depending on the context of the analysis. Indicators characterizing the natural environment included vegetation cover, vegetation height, elevation, distance of islands and reefs to mainland, and proportion of islands near the shore. These indicators of the natural environment were attributes associated with a sense of beauty or cultural attraction. Systems with high amounts of vegetation cover or high elevation features (e.g., tall trees) would be expected to be aesthetically and culturally pleasing. For ponds, which are not vegetated, the presence of nearby vegetation cover would make ponds more aesthetically pleasing. Unvegetated features (e.g., bluffs and dunes) would be more attractive if there were striking heterogeneous topography. For islands and reefs, an indicator based on inverse distance would highlight the ability of users to access the island. Another indicator for islands that would increase their aesthetic quality would be the amount of island within 100 m of the shore. Islands that appear to be no different than a mainland would be identified by the shore zone/island size ratio.

## Education

Metrics for education services used similar indicators as aesthetics and cultural heritage services. Metrics for education services included an additional indicator for enrolled students in the planning reach. The common indicator characterizing potential human usage was the average of population density in the planning reach and enrolled students in the planning reach. It was decided to average general population and student population rather than just use student population because the general public still benefits from educational experiences even out of school. The only other noteworthy variation from the indicator for potential human usage was for coral reefs, which used total enrollment of students in high school and college. Younger students were not expected to dive underwater. The indicators characterizing the natural environment were similar to those for the aesthetic and cultural heritage services.

## Recreation

Metrics for recreation services used similar indicators as aesthetics and cultural services. The common indicator characterizing potential human usage was the population density in the planning reach. Also, there was an additional indicator for whether there were public access to the feature. If there is public access, the score would be 1.0. Even if there is no public access, there would be recreation benefits just outside the boundaries, warranting a score of 0.1. There needs to be an additional data layer for public open space to be able to score this indicator for features not near beaches. The indicators characterizing the natural environment were similar to those for the aesthetic and cultural heritage services. For recreation services on beaches, the details of the metric were summarized previously and in Figure 23 in the main text of the report.

## Biodiversity

Biodiversity increases with greater ecosystem productivity and is reduced in the presence of stressors. Indicators characterizing the natural environment for promoting biodiversity metric included vegetation cover, vegetation height, proportion of native vegetation, MSPA factor, tree cover within 100 m, and open water and wetland cover within 1 km. Indicators characterizing adverse changes to the landscape include impervious cover within 100 m, agricultural cover within 100 m, and ditch density. These indicators were informed by the existing knowledge between landscape indicators and ecosystem condition (Schueler et al. 2009; Weller et al. 2007; Wickham et al. 2010). For wetland and nearshore NNBF, indicators were progressively added as more data became available. Mudflats and reefs were characterized solely by stressor indicators of impervious cover and agricultural cover mostly due to the lack of information on their structure. Vegetation cover was added as an indicator for SAV. Proportion of native vegetation was added as an indicator for beaches, bluffs, dunes, and salt marshes. Ditch density was added as an indicator for salt marshes, brackish shrub wetlands, and brackish forest swamps. Vegetation height was added for all tree and shrub wetland habitats. Freshwater wetlands had additional indicators due to a specific mid-Atlantic study (Weller et al. 2007) that showed tree cover in the vicinity and wetland cover at moderate distances had a supportive influence and ditch density had a negative influence. Because stressors can have an enormous effect on ecological condition, stressor indicators were not geometrically averaged with the other indicators but were used as a separate multiplier because of their controlling effect. For upland habitats, indicators were added in a similar progression. Metrics for grasslands were characterized by vegetation cover, proportion natives, and MSPA factors. For other upland habitats, an additional indicator for vegetation height was added.

## Habitat for fish and wildlife provisioning

Indicators for the metric for habitat provisioning used the identical indicators of the biodiversity metric with the additional use of net primary productivity values. The use of a primary productivity coefficients provides supplemental information on the productivity of NNBF. The NPP do provide some redundancy because indicators for vegetation height and cover does provide similar information. However, for NNBF such as mudflats, the lack of vegetation structure makes estimation of habitat provisioning services problematic without consideration of a metric such as NPP.

## Commercially harvestable fish and wildlife and TES species

Habitat for fish and wildlife provisioning would also support harvest of commercially harvestable fish and wildlife. In the NACCS study area, only aquatic sea life is commercially harvestable. Of the NNBF identified, only mudflats and reefs would allow for commercially harvesting of aquatic sea life. For those two NNBF, the metric for commercially harvestable fish would be the same as the metric for habitat for fish provisioning. For the metric of listed TES species, the chosen indicator was whether the county associated with the natural feature has any listed threatened or endangered species that could use the freshwater wetland, the saltwater wetland, upland forest, upland grassland, and other habitats. If there is a listed species in the county associated with the habitat, the indicator score would be 1.0. Otherwise, the score would be 0.

## Carbon sequestration and raw materials production

Carbon sequestration is related to ecosystem productivity. For the metric for carbon sequestration, there were several appropriate indicators related to productivity. One useful indicator (NPP) is a direct measure of biological productivity. Biological productivity varies so that actual NPP differs from mean NPP values provided in Table 31. The use of other indicators related to productivity would provide additional information on carbon sequestration. For herbaceous vegetation, vegetation cover captures the density of growth, complementing NPP estimates. For woody vegetation, vegetation cover and vegetation height provide further information on carbon sequestration. Unlike biodiversity and habitat provisioning, presence of non-native vegetation and other stressors should not affect carbon production and sequestration.

Raw materials production is related to the accumulation of carbon. For the metric for raw materials production, the same indicators from carbon sequestration apply because carbon sequestration and raw materials production are similar processes. The indicators are vegetation cover, vegetation height, and mean NPP. The two NNBF associated with this metric are riparian and upland forests.

## Nutrient sequestration or conversion

Nutrient sequestration or conversion occurs through uptake by plants or removal through microbial transformation. For the metric for nutrient sequestration/conversion, indicators were chosen to reflect activity by plants or that were supportive of microbial activity. Indicators for the metric for nutrient sequestration or conversion include vegetation cover, vegetation height, NPP coefficienticient, percent hydric soils, and percent organic material. Indicators associated with plant growth would measure plant activity and possible uptake of nitrogen and phosphorus. Indicators associated with microbial activity are associated with soil properties. Soils that are periodically inundated and have high organic matter content would be conducive to transforming nutrients. The metrics were consistent across the different NNBF. Herbaceous vegetation indicators consisted of vegetation cover and the NPP coefficienticient and indicators for hydric soil and organic matter. For shrubs and trees, an additional indicator of vegetation height was added. For habitats that are perpetually wet such as ponds, mudflats, and SAV, soil indicators were not used, and the lack of vegetation structure data prevented the use of indicators for cover or height. Because nutrient sequestration or conversion could occur independently, the geometric mean of the vegetation indicators and the geometric mean of the soil indicators were arithmetically averaged.

## Reduction of toxic materials

The same processes that govern plant uptake and microbial conversion of nutrients can also apply to reduction of toxic materials. Toxic compounds could also be taken up by plants and be immobilized through microbial action. Thus, the metric for the reduction of toxic materials would use the same indicators for the metric.

## Erosion protection and control

Erosion protection and control rely on feature attributes that stabilize soils and reduce erosive energy. The Indicators for the metric of erosion protection include vegetation cover and vegetation height. Greater vegetation cover stabilizes the soil and provides protection from rain and wind. Greater vegetation height intercepts falling rain and strong winds. For reefs, the erosion protection properties emerge as the reef is situated closer to the surface because the reef is in a better position to reduce wave damages. The indicator is the height relative to MSL in feet where having a height at MSL results in a score of 1.0 and having a height at –3.28 ft or lower results in a score of 0. For islands, erosion protection increases with islands that have a higher elevation and have a greater shadow of the mainland.

## Maintain background suspended sediments

Maintenance of background suspended sediments relies on the same processes as erosion protection. By stabilizing exposed soils and reducing erosive energy from rain and wind, suspended sediment can be reduced. The indicators that apply to erosion protection can also be applied to maintenance of suspended sediments. Thus, the metric for maintenance of background suspended sediments includes indicators for vegetation cover and height. For ponds, an indicator of reduced sediments to receiving waters could be the proportion of the watershed that drains to the pond.

## Reducing storm surge

Storm surges can raise water levels several feet above MSL (Table 30). The only indicator that fully addresses the rise in elevation is for beaches and dunes. Based on a surge of 17.3 ft above MSL factoring in a high tide event (MHHW), the metric assumes full achievement of scores at a beach width of 200 ft and when the 90th percentile height value of the beach exceeds 17.3 ft (i.e., approximately 10% of the beach is beyond the target elevation). This value is not meant to be a design standard, but is used to illustrate how the metric could be constructed. For other NNBF, the natural bottom elevation would be inundated by the surge. The metrics for other NNBF were based on the ability of the feature to slow down the surge using indicators for vegetation cover, vegetation height, and width of the feature. These indicators represent increased roughness and can change surge patterns. For barrier islands, the metric based on indicators for height of the island and the amount of the leeward shoreline being sheltered highlights the ability of barrier islands in providing a screen to direct surges.

## Reducing wave attack

The metric for reducing wave attacks did not account for effects from storm surges with a focus on larger-than-normal waves. Indicators either represented barriers to the waves or attributes that change wave attack patterns. Useful indicators included maximum height, vegetation cover, vegetation height, width of the feature, height of barrier islands, amount of leeward shoreline being sheltered by islands and barrier islands, and relative height of reefs. Height of beaches and islands impedes direct wave attacks whereas the other attributes provide roughness and resistance resulting in less energetic wave attacks.

### Provision of groundwater supply

Provision of groundwater supply relies on infiltration capacity. For all features, the indicator for infiltration could be derived from GIS soil survey maps. Features with greater area-weighted infiltration rate would promote greater groundwater replenishment.

Table 105. GIS operations for deriving metrics for Aesthetics/Cultural Heritage. GIS data layers for features were generated using procedures from Table 29. For the GIS operations, the tool is listed and input data layers are listed in parentheses. NNBF are listed in the GIS operation either generically as "FEAT" (i.e., feature) or specifically named. GIS operation input parameters are identified with p.

| Metric Formula | Applicable Feature | Data Layers | GIS Operations | Comment |
|---|---|---|---|---|
| **Aesthetics/Cultural Heritage** | | | | |
| Pop density in Plan Reach | Beach<br>Mudflat | 2010 Census population - NACCS Planning Reaches | Pop density:<br>Intersect (FEAT, Planning Reaches) | |
| (SD of elevation x Pop density of Plan Reach)1/2 | Bluff<br>Dune | NACCS Shoreline Types<br>10 m NED<br>2010 Census population<br>NACCS Planning Reaches | SD of elevation:<br>Buffer (Shoreline Types, 30 mp) (Bluff only)<br>Zonal statistics (Shoreline buffer OR Dune, 10 m NED)<br>Pop density:<br>Intersect (Census, Planning Reaches) | |
| (Veg cover x Pop density of Plan Reach)1/2 | Salt marsh<br>Maritime grassland<br>Herb marsh fresh<br>Terrestrial grass<br>SAV | Landfire-cover (poly)<br>SAV/Eelgrass<br>2010 Census population<br>NACCS Planning Reaches | Veg Cover:<br>Intersect (FEAT, Landfire-cover) OR Use Percent coverage from SAV/Eelgrass data layer<br>Calculate area-weighted % cover<br>Pop density:<br>Intersect (Census, Planning Reaches) | For herbaceous habitats, Landfire does not always provide cover values. In such instances, one would need to estimate percentage of area occupied by the herbaceous habitat. |
| (Veg cover x Veg height x Pop density of Plan Reach)1/3 | Scrub-wetland brackish<br>Forest-swamp brackish<br>Maritime shrub<br>Maritime forest<br>Riparian<br>Scrub-wetland fresh<br>Forest-swamp fresh<br>Terrestrial shrub<br>Terrestrial forest | Landfire-cover (poly)<br>Landfire-height (poly)<br>2010 Census population<br>NACCS Planning Reaches | Veg cover:<br>Intersect (FEAT, Landfire-cover)<br>Calculate area-weighted % cover<br>Veg height:<br>Intersect (FEAT, Landfire-height)<br>Calculate area-weighted mean height<br>Pop density:<br>Intersect (Census, Planning Reaches) | |

| Metric Formula | Applicable Feature | Data Layers | GIS Operations | Comment |
|---|---|---|---|---|
| (Veg cover in 100-m radius x Pop density of Plan Reach)1/2 | Pond | Landfire-cover (poly)<br>2010 Census population<br>NACCS Planning Reaches | Veg Cover:<br>Buffer (Pond, 100 mp)<br>Intersect (Pond buffer, Landfire-cover)<br>Calculate area-weighted % cover<br>Pop density:<br>Intersect (Census, Planning Reaches) | |
| (1/distance to mainland in km) x Pop density of Plan Reach)1/2 | Reef | Mainland layer<br>2010 Census population<br>NACCS Planning Reaches | Distance to mainland:<br>Near (Reef layer, Mainland)<br>Pop density:<br>Intersect (Census, Planning Reaches) | No reef layer has been identified. Mainland layer can be any land-based feature. |
| (Prop of island near shore x 1/distance to mainland in km x Pop density of Plan Reach)1/3 | Island<br>Barrier island | Mainland layer<br>2010 Census population<br>NACCS Planning Reaches | Proportion of island near shore:<br>Buffer (FEAT, 100 mp)<br>Intersect (FEAT, FEAT buffer)<br>Calculate proportion of island within 100 m by dividing buffer by area of island<br>Distance to mainland:<br>Near (FEAT, Mainland)<br>Pop density:<br>Intersect (Census, Planning Reaches) | |
| **Education** | | | | |
| (Pop density in Plan Reach + Enrolled students in Plan Area)/2 | Beach<br>Mudflat | 2010 Census population - Schools data layer<br>NACCS Planning Reaches | Pop density:<br>Intersect (FEAT, Planning Reaches)<br>School enrollment:<br>Intersect (FEAT, Schools data layer)<br>Calculate total enrollment across 3 school layers | There are 3 schools data layer for public grade school, private grade school, and colleges. |

| Metric Formula | Applicable Feature | Data Layers | GIS Operations | Comment |
|---|---|---|---|---|
| (SD of elevation x (Pop density in Plan Reach + Enrolled students in Plan Area)/2)1/2 | Bluff<br>Dune | NACCS Shoreline Types<br>10 m NED<br>2010 Census population<br>Schools data layer<br>NACCS Planning Reaches | SD of elevation:<br>Buffer (Shoreline Types, 30 mp) (Bluff only)<br>Zonal statistics(Shoreline buffer OR Dune, 10 m NED)<br>Pop density:<br>Intersect (Census, Planning Reaches)<br>School enrollment:<br>Intersect (FEAT, Schools data layer)<br>Calculate total enrollment across 3 school layers | There are 3 schools data layer for public grade school, private grade school, and colleges. |
| (Veg cover x (Pop density in Plan Reach + Enrolled students in Plan Area)/2)1/2 | Salt marsh<br>Maritime grassland<br>Herb marsh fresh<br>Terrestrial grass<br>SAV | Landfire-cover (poly)<br>SAV/Eelgrass<br>2010 Census population<br>Schools data layer<br>NACCS Planning Reaches | Veg Cover:<br>Intersect (FEAT, Landfire-cover) OR Use Percent coverage from SAV/Eelgrass data layer<br>Calculate area-weighted % cover<br>Pop density:<br>Intersect (Census, Planning Reaches)<br>School enrollment:<br>Intersect (FEAT, Schools data layer)<br>Calculate total enrollment across 3 school layers | For herbaceous habitats, Landfire does not always provide cover values. In such instances, one would need to estimate percentage of area occupied by the herbaceous habitat.<br><br>There are 3 schools data layer for public grade school, private grade school, and colleges. |
| (Veg cover x Veg height x (Pop density in Plan Reach + Enrolled students in Plan Area)/2)1/3 | Scrub-wetland brackish<br>Forest-swamp brackish<br>Maritime shrub<br>Maritime forest<br>Riparian<br>Scrub-wetland fresh<br>Forest-swamp fresh<br>Terrestrial shrub<br>Terrestrial forest | Landfire-cover (poly)<br>Landfire-height (poly)<br>2010 Census population<br>Schools data layer<br>NACCS Planning Reaches | Veg cover:<br>Intersect (FEAT, Landfire-cover)<br>Calculate area-weighted % cover<br>Veg height:<br>Intersect (FEAT, Landfire-height)<br>Calculate area-weighted mean height<br>Pop density:<br>Intersect (Census, Planning Reaches)<br>School enrollment:<br>Intersect (FEAT, Schools data layer)<br>Calculate total enrollment across 3 school layers | There are 3 schools data layer for public grade school, private grade school, and colleges. |

| Metric Formula | Applicable Feature | Data Layers | GIS Operations | Comment |
|---|---|---|---|---|
| (Veg cover in 100 m radius x (Pop density in Plan Reach + Enrolled students in Plan Area)/2)1/2 | Pond | Landfire-cover (poly)<br>2010 Census population<br>Schools data layer<br>NACCS Planning Reaches | Veg Cover:<br>Buffer (Pond, 100 mp)<br>Intersect (Pond buffer, Landfire-cover)<br>Calculate area-weighted % cover<br>Pop density:<br>Intersect (Census, Planning Reaches)<br>School enrollment:<br>Intersect (FEAT, Schools data layer)<br>Calculate total enrollment across 3 school layers | There are 3 schools data layer for public grade school, private grade school, and colleges. |
| (1/Distance to mainland in km) x (Pop density in Plan Reach + Enrolled students in Plan Area)/2)1/2 | Reef | Mainland layer<br>2010 Census population<br>Schools data layer for high schools and colleges<br>NACCS Planning Reaches | Distance to mainland:<br>Near (Reef layer, Mainland)<br>Pop density:<br>Intersect (Census, Planning Reaches)<br>School enrollment:<br>Intersect (FEAT, Schools data layer)<br>Calculate total enrollment across 3 school layers | No reef layer has been identified. Mainland layer can be any land-based feature.<br><br>Only high school and college students would be presumed to be old enough to dive to see reefs. |
| (Proportion of island within 100 m of shore x 1/Distance to mainland in km x (Pop density in Plan Reach + Enrolled students in Plan Area)/2)1/3 | Island<br>Barrier island | Mainland layer<br>2010 Census population<br>Schools data layer<br>NACCS Planning Reaches | Proportion of island near shore:<br>Buffer (FEAT, 100 mp)<br>Intersect (FEAT, Buffer)<br>Calculate proportion of island within 100 m by dividing buffer by area of island<br>Distance to mainland:<br>Near (FEAT, Mainland)<br>Pop density:<br>Intersect (Census, Planning Reaches)<br>School enrollment:<br>Intersect (FEAT, Schools data layer)<br>Calculate total enrollment across 3 school layers | There are 3 schools data layer for public grade school, private grade school, and colleges. |

| Metric Formula | Applicable Feature | Data Layers | GIS Operations | Comment |
|---|---|---|---|---|
| **Recreation** | | | | |
| (Public beach x Appropriate width x Pop density in Planning Reach)1/3 | Beach | EPA Beaches<br>2010 Census population data<br>NACCS Planning Reaches | <u>Public beach</u>:<br>Intersect (Beach, EPA Beaches)<br><u>Appropriate width</u>:<br>Add field for width<br>Calculate field using formula Area/(Perimeter/2)<br><u>Pop density</u>:<br>Intersect (Census, Planning Reaches) | If a beach feature intersects EPA Beaches, then it is public (score = 1.0); otherwise, the score is 0.1.<br><br>For a long beach polygon (L >>W), Perimeter ≈ 2*L, so L ≈ Perimeter/2 and W = Area/L or W ≈ Area/(perimeter/2).<br><br>Scoring of beach width is provided in Figure 23. |
| (Public beach x Pop density in Planning Reach)1/2 | Mudflat<br>Bluff<br>Dune | EPA Beaches<br>2010 Census population– NACCS Planning Reaches | <u>Public beach</u>:<br>Intersect (FEAT, EPA Beaches)<br><u>Pop density</u>:<br>Intersect (Census, Planning Reaches) | If a feature intersects EPA Beaches, then it is public (score = 1.0); otherwise, the score is 0.1. |
| (Public OS x Veg cover x Pop density of Plan Reach)1/3 | Salt marsh<br>Maritime grassland<br>Herb marsh fresh<br>Terrestrial grass<br>SAV | Public open space layer<br>Landfire-cover (poly)<br>SAV/Eelgrass<br>2010 Census population<br>NACCS Planning Reaches | <u>Public OS</u>:<br>Intersect (FEAT, Public OS data layer) OR Use Percent coverage from SAV/Eelgrass data layer<br><u>Veg Cover</u>:<br>Intersect (FEAT, Landfire-cover) OR Use Percent coverage from SAV/Eelgrass data layer<br>Calculate area-weighted % cover<br><u>Pop density</u>:<br>Intersect (Census, Planning Reaches) | Need public open space layer. If there is public access, then it is public (score=1.0); otherwise, the score is 0.1.<br><br>For herbaceous habitats, Landfire does not always provide cover values. In such instances, one would need to estimate percentage of area occupied by the herbaceous habitat. |

| Metric Formula | Applicable Feature | Data Layers | GIS Operations | Comment |
|---|---|---|---|---|
| (Public OS x Veg cover x Veg height x Pop density of Plan Reach)1/4 | Scrub-wetland brackish<br>Forest-swamp brackish<br>Maritime shrub<br>Maritime forest<br>Riparian<br>Scrub-wetland fresh<br>Forest-swamp fresh<br>Terrestrial shrub<br>Terrestrial forest | Public open space layer<br>Landfire-cover (poly)<br>Landfire-height (poly)<br>2010 Census population<br>NACCS Planning Reaches | Public OS:<br>Intersect (FEAT, Public OS data layer) OR Use Percent coverage from SAV/Eelgrass data layer<br>Veg cover:<br>Intersect (FEAT, Landfire-cover)<br>Calculate area-weighted % cover<br>Veg height:<br>Intersect (FEAT, Landfire-height)<br>Calculate area-weighted mean height<br>Pop density:<br>Intersect (Census, Planning Reaches) | Need public open space layer. If there is public access, then it is public (score=1.0); otherwise, the score is 0.1. |
| (Public OS x Veg cover in 100 m radius x Pop density of Plan Reach)1/3 | Pond | Public open space layer<br>Landfire-cover (poly)<br>2010 Census population<br>NACCS Planning Reaches | Public OS:<br>Intersect (FEAT, Public OS data layer)<br>Veg Cover:<br>Buffer (Pond, 100 mp)<br>Intersect (Pond buffer, Landfire-cover)<br>Calculate area-weighted % cover<br>Pop density:<br>Intersect (Census, Planning Reaches) | Need public open space layer. If there is public access, then it is public (score=1.0); otherwise, the score is 0.1. |
| (Public OS x 1/distance to mainland in km) x Pop density of Plan Reach)1/3 | Reef | Public open space layer<br>Mainland layer<br>2010 Census population<br>NACCS Planning Reaches | Public OS:<br>Intersect (FEAT, Public OS data layer)<br>Distance to mainland:<br>Near (Reef layer, Mainland)<br>Pop density:<br>Intersect (Census, Planning Reaches) | No reef layer has been identified. Mainland layer can be any land-based feature.<br><br>Need public open space layer. If there is public access, then it is public (score=1.0); otherwise, the score is 0.1. |

| Metric Formula | Applicable Feature | Data Layers | GIS Operations | Comment |
|---|---|---|---|---|
| (Public OS x Proportion of island within 100 m of shore x 1/distance to mainland in km) x Pop density of Plan Reach)1/4 | Island<br>Barrier island | Public open space layer<br>Mainland layer<br>2010 Census population<br>NACCS Planning Reaches | Public OS:<br>Intersect (FEAT, Public OS data layer)<br>Proportion of island near shore:<br>Buffer (FEAT, 100 mp)<br>Intersect (FEAT, Buffer)<br>Calculate proportion of island within 100 m by dividing buffer by area of island<br>Distance to mainland:<br>Near (FEAT, Mainland)<br>Pop density:<br>Intersect (Census, Planning Reaches) | Need public open space layer. If there is public access, then it is public (score=1.0); otherwise, the score is 0.1. |
| **Biodiversity** | | | | |
| (Veg cover x Prop native)1/2 x ((25 -% impervious cover in 100 m radius)/15 + (50 - % agric cover in 100 m radius)/25)/2 | Beach<br>Dune | Landfire-cover (poly)<br>Landfire-type (poly)<br>NLCD-impervious cover<br>CCAP-agric cover | Veg cover:<br>Intersect (FEAT, Landfire-cover)<br>Calculate area-weighted % cover<br>Prop native:<br>Intersect (FEAT, Landfire-type)<br>Calculate % area with native veg<br>Imperv cover:<br>Buffer (FEAT,100 mp)<br>Zonal statistics (FEAT buffer, NLCD-imp cover)<br>Agric cover:<br>Buffer (FEAT,100 mp)<br>Intersect (FEAT buffer, CCAP-agric cover)<br>Calculate % area with agriculture | |

| Metric Formula | Applicable Feature | Data Layers | GIS Operations | Comment |
|---|---|---|---|---|
| (Veg cover x Prop native)1/2 x ((25 -% impervious cover in 100 m radius)/15 + (50 - % agric cover in 100 m radius)/25)/2 | Bluff | Landfire-cover (poly)<br>Landfire-type (poly)<br>NLCD-impervious cover<br>CCAP-agric cover | Veg cover:<br>Buffer Shoreline Types (30 mp)<br>Intersect (Shoreline buffer, Landfire-cover)<br>Calculate area-weighted % cover<br>Prop native:<br>Buffer Shoreline Types (30 mp)<br>Intersect(Shoreline buffer, Landfire-type)<br>Calculate % area with native veg<br>Imperv cover:<br>Buffer (FEAT,100 mp)<br>Zonal statistics (FEAT Buffer, NLCD-imp cov)<br>Agric cover:<br>Buffer (FEAT,100 mp)<br>Intersect (FEAT buffer, CCAP-agric cover)<br>Calculate % area with agriculture | |
| ((25 -% impervious cover in 100 m radius)/15 + (50 - % agric cover in 100 m radius)/25)/2 | Mudflat<br>Reef | NLCD-impervious cover<br>CCAP-agric cover | Imperv cover:<br>Buffer (FEAT,100 mp)<br>Zonal statistics (FEAT buffer, NLCD-imp cov)<br>Agric cover:<br>Buffer(FEAT,100 mp)<br>Intersect (FEAT buffer, CCAP-agric cover)<br>Calculate % area with agriculture | No reef layer has been identified. |
| Veg cover x ((25 -% impervious cover in 100 m radius)/15 + (50 - % agric cover in 100 m radius)/25)/2 | SAV | SAV/Eelgrass<br>NLCD-impervious cover<br>CCAP-agric cover | Veg Cover:<br>Use Percent coverage from SAV/Eelgrass data layer<br>Calculate area-weighted % cover<br>Imperv cover:<br>Buffer (FEAT,100 mp)<br>Zonal statistics (FEAT buffer, NLCD-imp cov)<br>Agric cover:<br>Buffer (FEAT,100 mp)<br>Intersect (FEAT buffer, CCAP-agric cover)<br>Calculate % area with agriculture | |

| Metric Formula | Applicable Feature | Data Layers | GIS Operations | Comment |
|---|---|---|---|---|
| (Veg cover x Prop native)1/2 x ((25 -% impervious cover in 100 m radius)/15 + (50 - % agric cover in 100 m radius)/25 + Ditch density)/3 | Salt marsh | Landfire-cover (poly)<br>Landfire-type (poly)<br>NLCD-impervious cover<br>CCAP-agric cover<br>NHDDitches | Veg cover:<br>Intersect (FEAT, Landfire-cover)<br>Calculate area-weighted % cover<br>Prop native:<br>Intersect (FEAT, Landfire-type)<br>Calculate % area with native veg<br>Imperv cover:<br>Buffer (FEAT,100 mp)<br>Zonal statistics (FEAT buffer, NLCD-imp cov)<br>Agric cover:<br>Buffer (FEAT,100 mp)<br>Intersect (FEAT buffer, CCAP-agric cover)<br>Calculate % area with agriculture<br>Ditch Density:<br>Intersect (NHDDitches, FEAT)<br>Calculate length of ditches/area of feature | For herbaceous habitats, Landfire does not always provide cover values. In such instances, one would need to estimate percentage of area occupied by the herbaceous habitat. |

| Metric Formula | Applicable Feature | Data Layers | GIS Operations | Comment |
|---|---|---|---|---|
| (Veg cover x Veg height x Prop native)1/3 x ((25 -% impervious cover in 100 m radius)/15 + (50 - % agric cover in 100 m radius)/25 + Ditch density)/3 | Scrub-wetland brackish<br>Forest-swamp brackish | Landfire-cover (poly)<br>Landfire-height (poly)<br>Landfire-type (poly)<br>NLCD-impervious cover<br>CCAP-agric cover<br>NHDDitches | Veg cover:<br>Intersect (FEAT, Landfire-cover)<br>Calculate area-weighted % cover<br>Veg height:<br>Intersect (FEAT, Landfire-height)<br>Calculate area-weighted mean height<br>Prop native:<br>Intersect (FEAT, Landfire-type)<br>Calculate % area with native veg<br>Imperv cover:<br>Buffer (FEAT,100 mp)<br>Zonal statistics (FEAT buffer, NLCD-imp cov)<br>Agric cover:<br>Buffer (FEAT,100 mp)<br>Intersect (FEAT buffer, CCAP-agric cover)<br>Calculate % area with agriculture<br>Ditch Density:<br>Intersect (NHDDitches, FEAT)<br>Calculate length of ditches/area of feature | For herbaceous habitats, Landfire does not always provide cover values. In such instances, one would need to estimate percentage of area occupied by the herbaceous habitat. |
| (Veg cover x Prop native x MSPA factor)1/3 | Maritime grassland<br>Terrestrial grass | Landfire-cover (poly)<br>Landfire-type (poly)<br>MSPA (poly) | Veg cover:<br>Intersect (FEAT, Landfire-cover)<br>Calculate area-weighted % cover<br>Prop native:<br>Intersect (FEAT, Landfire-type)<br>Calculate % area with native veg<br>MSPA Factor:<br>Intersect (FEAT, MSPA) | For herbaceous habitats, Landfire does not always provide cover values. In such instances, one would need to estimate percentage of area occupied by the herbaceous habitat.<br><br>MSPA factors: Core = 1, Edge/perforation = 0.7, Branch/bridge/loop = 0.4, and islet = 0.1 |

| Metric Formula | Applicable Feature | Data Layers | GIS Operations | Comment |
|---|---|---|---|---|
| (Veg cover x Veg height x Prop native x MSPA factor)1/4 | Maritime shrub<br>Maritime forest<br>Riparian<br>Terrestrial shrub<br>Terrestrial forest<br>Island<br>Barrier island | Landfire-cover (poly)<br>Landfire-height (poly)<br>Landfire-type (poly)<br>MSPA (poly) | <u>Veg cover</u>:<br>Intersect (FEAT, Landfire-cover)<br>Calculate area-weighted % cover<br><u>Veg height</u>:<br>Intersect (FEAT, Landfire-height)<br>Calculate area-weighted mean height<br><u>Prop native</u>:<br>Intersect (FEAT, Landfire-type)<br>Calculate % area with native veg<br><u>MSPA Factor</u>:<br>Intersect (FEAT, MSPA) | MSPA factors: Core = 1, Edge/perforation = 0.7, Branch/bridge/loop = 0.4, and islet = 0.1 |
| (Veg cover x Prop native x Tree cover in 100 m radius x Cover of open water and wetlands in 1 km radius) 1/4 x Ditch density | Herb marsh fresh | Landfire-cover (poly)<br>Landfire-type (poly)<br>CCAP-tree cover<br>CCAP-open water+wetlands<br>NHDDitches | <u>Veg cover</u>:<br>Intersect (FEAT, Landfire-cover)<br>Calculate area-weighted % cover<br><u>Prop native</u>:<br>Intersect (FEAT, Landfire-type)<br>Calculate % area with native veg<br><u>Tree cover in 100 m radius</u>:<br>Buffer (FEAT,100 mp)<br>Intersect (FEAT, CCAP-tree cover)<br>Calculate % area with trees<br><u>OW+wetlands in 1000 m radius</u>:<br>Buffer (FEAT,1000 mp)<br>Intersect (FEAT, CCAP-OW+wetlands)<br>Calculate % area with OW+wetlands<br><u>Ditch Density</u>:<br>Intersect (NHDDitches, FEAT)<br>Calculate length of ditches/area of feature | |

| Metric Formula | Applicable Feature | Data Layers | GIS Operations | Comment |
|---|---|---|---|---|
| (Veg cover x Veg height x Prop native x Tree cover in 100 m radius x Cover of open water and wetlands in 1 km radius) 1/5 x Ditch density | Scrub-wetland fresh<br>Forest-swamp fresh | Landfire-cover (poly)<br>Landfire-height (poly)<br>Landfire-type (poly)<br>CCAP-tree cover<br>CCAP-open water+wetlands<br>NHDDitches | Veg cover:<br>Intersect (FEAT, Landfire-cover)<br>Calculate area-weighted % cover<br>Veg height:<br>Intersect (FEAT, Landfire-height)<br>Calculate area-weighted mean height<br>Prop native:<br>Intersect (FEAT, Landfire-type)<br>Calculate % area with native veg<br>Tree cover in 100 m radius:<br>Buffer (FEAT,100 mp)<br>Intersect (FEAT, CCAP-tree cover)<br>Calculate % area with trees<br>OW+wetlands in 100 m radius:<br>Buffer (FEAT,1000 mp)<br>Intersect (FEAT, CCAP-OW+wetlands)<br>Calculate % area with OW+wetlands<br>Ditch Density:<br>Intersect (NHDDitches, FEAT)<br>Calculate length of ditches/area of feature | |
| (Tree cover in 100 m radius x Cover of open water and wetlands in 1 km radius) 1/2 | Pond | CCAP-tree cover<br>CCAP-open water+wetlands | Tree cover in 100 m radius:<br>Buffer (FEAT,100 mp)<br>Intersect (FEAT, CCAP-tree cover)<br>Calculate % area with trees<br>OW+wetlands in 100 m radius:<br>Buffer (FEAT,1000 mp)<br>Intersect (FEAT, CCAP-OW+wetlands)<br>Calculate % area with OW+wetlands | |

| Metric Formula | Applicable Feature | Data Layers | GIS Operations | Comment |
| --- | --- | --- | --- | --- |
| **Habitat Provisioning** | | | | |
| (Veg cover x Prop native x NPP coefficient)1/3 x ((25 -% impervious cover in 100 m radius)/15 + (50 - % agric cover in 100 m radius)/25)/2 | Beach<br>Dune | Landfire-cover (poly)<br>Landfire-type (poly)<br>NPP coefficients<br>NLCD-impervious cover<br>CCAP-agric cover | Veg cover:<br>Intersect (FEAT, Landfire-cover)<br>Calculate area-weighted % cover<br>Prop native:<br>Intersect (FEAT, Landfire-type)<br>Calculate % area with native veg<br>NPP coefficients:<br>Table 31. values<br>Imperv cover:<br>Buffer (FEAT,100 mp)<br>Zonal statistics (FEAT buffer, NLCD-imp cover)<br>Agric cover:<br>Buffer (FEAT,100 mp)<br>Intersect (FEAT buffer, CCAP-agric cover)<br>Calculate % area with agriculture | |
| (Veg cover x Prop native x NPP coefficient)1/3 x ((25 -% impervious cover in 100 m radius)/15 + (50 - % agric cover in 100 m radius)/25)/2 | Bluff | Landfire-cover (poly)<br>Landfire-type (poly)<br>NPP coefficients<br>NLCD-impervious cover<br>CCAP-agric cover | Veg cover:<br>Buffer Shoreline Types (30 mp)<br>Intersect (Shoreline buffer, Landfire-cover)<br>Calculate area-weighted % cover<br>Prop native:<br>Buffer Shoreline Types (30 mp)<br>Intersect (Shoreline buffer, Landfire-type)<br>Calculate % area with native veg<br>NPP coefficients:<br>Table 31. values<br>Imperv cover:<br>Buffer (FEAT,100 mp)<br>Zonal statistics (FEAT Buffer, NLCD-imp cov)<br>Agric cover:<br>Buffer (FEAT,100 mp)<br>Intersect (FEAT buffer, CCAP-agric cover)<br>Calculate % area with agriculture | |

| Metric Formula | Applicable Feature | Data Layers | GIS Operations | Comment |
|---|---|---|---|---|
| NPP coefficient x ((25 -% impervious cover in 100 m radius)/15 + (50 - % agric cover in 100 m radius)/25)/2 | Mudflat<br>Reef | NPP coefficients<br>NLCD-impervious cover<br>CCAP-agric cover | NPP coefficients:<br>Table 31. values<br>Imperv cover:<br>Buffer (FEAT,100 mp)<br>Zonal statistics (FEAT buffer, NLCD-imp cov)<br>Agric cover:<br>Buffer (FEAT,100 mp)<br>Intersect (FEAT buffer, CCAP-agric cover)<br>Calculate % area with agriculture | No reef layer has been identified. |
| (Veg cover x NPP coefficient)1/2 x ((25 -% impervious cover in 100 m radius)/15 + (50 - % agric cover in 100 m radius)/25)/2 | SAV | SAV/Eelgrass<br>NPP coefficients<br>NLCD-impervious cover<br>CCAP-agric cover | Veg Cover:<br>Use Percent coverage from SAV/Eelgrass data layer<br>Calculate area-weighted % cover<br>NPP coefficients:<br>Table 31. values<br>Imperv cover:<br>Buffer (FEAT,100 mp)<br>Zonal statistics (FEAT buffer, NLCD-imp cov)<br>Agric cover:<br>Buffer (FEAT,100 mp)<br>Intersect (FEAT buffer, CCAP-agric cover)<br>Calculate % area with agriculture | |

| Metric Formula | Applicable Feature | Data Layers | GIS Operations | Comment |
|---|---|---|---|---|
| (Veg cover x Prop native x NPP coefficient)1/3 x ((25 -% impervious cover in 100 m radius)/15 + (50 - % agric cover in 100 m radius)/25 + Ditch density)/3 | Salt marsh | Landfire-cover (poly)<br>Landfire-type (poly)<br>NPP coefficients<br>NLCD-impervious cover<br>CCAP-agric cover<br>NHDDitches | <u>Veg cover</u>:<br>Intersect (FEAT, Landfire-cover)<br>Calculate area-weighted % cover<br><u>Prop native</u>:<br>Intersect (FEAT, Landfire-type)<br>Calculate % area with native veg<br><u>NPP coefficients</u>:<br>Table 31. values<br><u>Imperv cover</u>:<br>Buffer (FEAT,100 mp)<br>Zonal statistics (FEAT buffer, NLCD-imp cov)<br><u>Agric cover</u>:<br>Buffer (FEAT,100 mp)<br>Intersect (FEAT buffer, CCAP-agric cover)<br>Calculate % area with agriculture<br><u>Ditch Density</u>:<br>Intersect (NHDDitches, FEAT)<br>Calculate length of ditches/area of feature | For herbaceous habitats, Landfire does not always provide cover values. In such instances, one would need to estimate percentage of area occupied by the herbaceous habitat. |

| Metric Formula | Applicable Feature | Data Layers | GIS Operations | Comment |
|---|---|---|---|---|
| (Veg cover x Veg height x Prop native x NPP coefficient)1/4 x ((25 -% impervious cover in 100 m radius)/15 + (50 - % agric cover in 100 m radius)/25 + Ditch density)/3 | Scrub-wetland brackish<br>Forest-swamp brackish | Landfire-cover (poly)<br>Landfire-height (poly)<br>NPP coefficients<br>Landfire-type (poly)<br>NLCD-impervious cover<br>CCAP-agric cover<br>NHDDitches | Veg cover:<br>Intersect (FEAT, Landfire-cover)<br>Calculate area-weighted % cover<br>Veg height:<br>Intersect (FEAT, Landfire-height)<br>Calculate area-weighted mean height<br>Prop native:<br>Intersect (FEAT, Landfire-type)<br>Calculate % area with native veg<br>NPP coefficients:<br>Table 31. values<br>Imperv cover:<br>Buffer (FEAT,100 mp)<br>Zonal statistics (FEAT buffer, NLCD-imp cov)<br>Agric cover:<br>Buffer (FEAT,100 mp)<br>Intersec t(FEAT buffer, CCAP-agric cover)<br>Calculate % area with agriculture<br>Ditch Density:<br>Intersect (NHDDitches, FEAT)<br>Calculate length of ditches/area of feature | For herbaceous habitats, Landfire does not always provide cover values. In such instances, one would need to estimate percentage of area occupied by the herbaceous habitat. |
| (Veg cover x Prop native x MSPA factor x NPP coefficient)1/4 | Maritime grassland<br>Terrestrial grass | Landfire-cover (poly)<br>Landfire-type (poly)<br>MSPA (poly)<br>NPP coefficients | Veg cover:<br>Intersect (FEAT, Landfire-cover)<br>Calculate area-weighted % cover<br>Prop native:<br>Intersect (FEAT, Landfire-type)<br>Calculate % area with native veg<br>MSPA Factor:<br>Intersect (FEAT, MSPA)<br>NPP coefficients:<br>Table 31. values | For herbaceous habitats, Landfire does not always provide cover values. In such instances, one would need to estimate percentage of area occupied by the herbaceous habitat.<br><br>MSPA factors: Core = 1, Edge/perforation = 0.7, Branch/bridge/loop = 0.4, and islet = 0.1 |

| Metric Formula | Applicable Feature | Data Layers | GIS Operations | Comment |
|---|---|---|---|---|
| (Veg cover x Veg height x Prop native x MSPA factor x NPP coefficient)1/5 | Maritime shrub<br>Maritime forest<br>Riparian<br>Terrestrial shrub<br>Terrestrial forest<br>Island<br>Barrier island | Landfire-cover (poly)<br>Landfire-height (poly)<br>Landfire-type (poly)<br>MSPA (poly)<br>NPP coefficients | <u>Veg cover</u>:<br>Intersect (FEAT, Landfire-cover)<br>Calculate area-weighted % cover<br><u>Veg height</u>:<br>Intersect (FEAT, Landfire-height)<br>Calculate area-weighted mean height<br><u>Prop native</u>:<br>Intersect (FEAT, Landfire-type)<br>Calculate % area with native veg<br><u>MSPA Factor</u>:<br>Intersect (FEAT, MSPA)<br><u>NPP coefficients</u>:<br>Table 31. values | MSPA factors: Core = 1, Edge/perforation = 0.7, Branch/bridge/loop = 0.4, and islet = 0.1<br><br>For islands with multiple habitat types, it may not be practicable to generate NPP coefficients. The indicator may be dropped. |
| (Veg cover x Prop native x Tree cover in 100 m radius x Cover of open water and wetlands in 1 km radius x NPP coefficient) 1/5 x Ditch density | Herb marsh fresh | Landfire-cover (poly)<br>Landfire-type (poly)<br>CCAP-tree cover<br>CCAP-open water+wetlands<br>NPP coefficients<br>NHDDitches | <u>Veg cover</u>:<br>Intersect (FEAT, Landfire-cover)<br>Calculate area-weighted % cover<br><u>Prop native</u>:<br>Intersect (FEAT, Landfire-type)<br>Calculate % area with native veg<br><u>Tree cover in 100 m radius</u>:<br>Buffer (FEAT,100 mp)<br>Intersect (FEAT, CCAP-tree cover)<br>Calculate % area with trees<br><u>OW+wetlands in 1000 m radius</u>:<br>Buffer (FEAT,1000 mp)<br>Intersect (FEAT, CCAP-OW+wetlands)<br>Calculate % area with OW+wetlands<br><u>NPP coefficients</u>:<br>Table 31. values<br><u>Ditch Density</u>:<br>Intersect (NHDDitches, FEAT)<br>Calculate length of ditches/area of feature | |

| Metric Formula | Applicable Feature | Data Layers | GIS Operations | Comment |
|---|---|---|---|---|
| (Veg cover x Veg height x Prop native x Tree cover in 100 m radius x Cover of open water and wetlands in 1 km radius x NPP coefficient) 1/6 x Ditch density | Scrub-wetland fresh<br>Forest-swamp fresh | Landfire-cover (poly)<br>Landfire-height (poly)<br>Landfire-type (poly)<br>CCAP-tree cover<br>CCAP-open water+wetlands<br>NPP coefficients<br>NHDDitches | Veg cover:<br>Intersect (FEAT, Landfire-cover)<br>Calculate area-weighted % cover<br>Veg height:<br>Intersect (FEAT, Landfire-height)<br>Calculate area-weighted mean height<br>Prop native:<br>Intersect (FEAT, Landfire-type)<br>Calculate % area with native veg<br>Tree cover in 100 m radius:<br>Buffer (FEAT,100 mp)<br>Intersect (FEAT, CCAP-tree cover)<br>Calculate % area with trees<br>OW+wetlands in 100 m radius:<br>Buffer(FEAT,1000 mp)<br>Intersect (FEAT, CCAP-OW+wetlands)<br>Calculate % area with OW+wetlands<br>NPP coefficients:<br>Table 31. values<br>Ditch Density:<br>Intersect (NHDDitches, FEAT)<br>Calculate length of ditches/area of feature | |
| (Tree cover in 100 m radius x Cover of open water and wetlands in 1 km radius x NPP coefficient) 1/2 | Pond | CCAP-tree cover<br>CCAP-open water+wetlands<br>NPP coefficients | Tree cover in 100 m radius:<br>Buffer (FEAT,100 mp)<br>Intersect (FEAT, CCAP-tree cover)<br>Calculate % area with trees<br>OW+wetlands in 100 m radius:<br>Buffer (FEAT,1000 mp)<br>Intersect (FEAT, CCAP-OW+wetlands)<br>Calculate % area with OW+wetlands<br>NPP coefficients:<br>Table 31. values | |

| Metric Formula | Applicable Feature | Data Layers | GIS Operations | Comment |
|---|---|---|---|---|
| **Commercially Harvestable Fish and Wildlife** | | | | |
| Same as Habitat Provisioning | Mudflat<br>Reef | | | Only mudflat and reefs were identified as having commercially harvestable fish and wildlife production. |
| **TES Species** | | | | |
| Presence of TES species | All | TES species by county | None | Need to look up whether there is a TES species listed in the county of the geographic feature. If there is a listed species present, then the indicator value would be 1. Otherwise, the value would be 0. |
| **Carbon Sequestration** | | | | |
| (Veg cover x NPP coefficient)1/2 | Salt marsh<br>Herb marsh fresh<br>SAV<br>Maritime grassland<br>Terrestrial grass | Landfire-cover (poly)<br>SAV/Eelgrass<br>NPP coefficients | Veg Cover:<br>Intersect (FEAT, Landfire-cover) OR Use Percent coverage from SAV/Eelgrass data layer<br>Calculate area-weighted % cover<br>NPP coefficients:<br>Table 31. values | |
| (Veg cover x Veg height x NPP coefficient)1/3 | Scrub-wetland brackish<br>Forest-swamp brackish<br>Scrub-wetland fresh<br>Forest-swamp fresh<br>Maritime shrub<br>Maritime forest<br>Riparian<br>Terrestrial shrub<br>Terrestrial forest | Landfire-cover (poly)<br>Landfire-height (poly)<br>NPP coefficients | Veg cover:<br>Intersect (FEAT, Landfire-cover)<br>Calculate area-weighted % cover<br>Veg height:<br>Intersect (FEAT, Landfire-height)<br>Calculate area-weighted mean height<br>NPP coefficients:<br>Table 31. values | |

| Metric Formula | Applicable Feature | Data Layers | GIS Operations | Comment |
|---|---|---|---|---|
| **Raw Materials** | | | | |
| (Veg cover x Veg height x NPP coefficient)1/3 | Riparian<br>Terrestrial forest | Landfire-cover (poly)<br>Landfire-height (poly)<br>NPP coefficients | Veg cover:<br>Intersect (FEAT, Landfire-cover)<br>Calculate area-weighted % cover<br>Veg height:<br>Intersect (FEAT, Landfire-height)<br>Calculate area-weighted mean height<br>NPP coefficients:<br>Table 31. values | |
| **Nutrient Sequestration or Conversion** | | | | |
| ((Veg cover x NPP coefficient)1/2 + (Perc hydric soils x Perc org matter)1/2)/2 | Beach<br>Dune<br>Salt marsh<br>Herb marsh fresh<br>Maritime grassland<br>Terrestrial grass | Landfire-cover (poly)<br>NPP coefficients<br>Soil Survey Geographic Database (SSURGO) | Veg Cover:<br>Intersect (FEAT, Landfire-cover)<br>Calculate area-weighted % cover<br>NPP coefficients:<br>Table 31. values<br>Perc hydric soils:<br>Intersect (FEAT,SSURGO)<br>Calculate area-weighted % hydric soils<br>Perc org matter<br>Intersect (FEAT,SSURGO)<br>Calculate area-weighted % hydric soils | |

| Metric Formula | Applicable Feature | Data Layers | GIS Operations | Comment |
|---|---|---|---|---|
| ((Veg cover x Veg height x NPP coefficient)1/3 + (Perc hydric soils x Perc org matter)1/2)/2 | Scrub-wetland brackish<br>Forest-swamp brackish<br>Scrub-wetland fresh<br>Forest-swamp fresh<br>Maritime shrub<br>Maritime forest<br>Riparian<br>Terrestrial shrub<br>Terrestrial forest | Landfire-cover (poly)<br>Landfire-height (poly)<br>NPP coefficients<br>SSURGO | Veg cover:<br>Intersect (FEAT, Landfire-cover)<br>Calculate area-weighted % cover<br>Veg height:<br>Intersect (FEAT, Landfire-height)<br>Calculate area-weighted mean height<br>NPP coefficients:<br>Table 31. values<br>Perc hydric soils:<br>Intersect (FEAT,SSURGO)<br>Calculate area-weighted % hydric soils<br>Perc org matter<br>Intersect (FEAT,SSURGO)<br>Calculate area-weighted % hydric soils | |
| NPP coefficient | Mudflat<br>Pond | NPP coefficients | NPP coefficients:<br>Table 31. values | |
| (Veg cover x NPP coefficient)1/2 | SAV | SAV/Eelgrass<br>NPP coefficients | Veg Cover:<br>Use Percent coverage from SAV/Eelgrass data layer<br>Calculate area-weighted % cover<br>NPP coefficients:<br>Table 31. values | |

| Metric Formula | Applicable Feature | Data Layers | GIS Operations | Comment |
|---|---|---|---|---|
| **Removal of Toxic Materials** | | | | |
| ((Veg cover x NPP coefficient)1/2 + (Perc hydric soils x Perc org matter)1/2)/2 | Dune<br>Salt marsh<br>Herb marsh fresh<br>Maritime grassland<br>Terrestrial grass | Landfire-cover (poly)<br>NPP coefficients<br>SSURGO | Veg Cover:<br>Intersect (FEAT, Landfire-cover)<br>Calculate area-weighted % cover<br>NPP coefficients:<br>Table 31. values<br>Perc hydric soils:<br>Intersect (FEAT,SSURGO)<br>Calculate area-weighted % hydric soils<br>Perc org matter<br>Intersect (FEAT,SSURGO)<br>Calculate area-weighted % org matter | |
| ((Veg cover x Veg height x NPP coefficient)1/3 + (Perc hydric soils x Perc org matter)1/2)/2 | Scrub-wetland brackish<br>Forest-swamp brackish<br>Scrub-wetland fresh<br>Forest-swamp fresh<br>Maritime shrub<br>Maritime forest<br>Riparian<br>Terrestrial shrub<br>Terrestrial forest | Landfire-cover (poly)<br>Landfire-height (poly)<br>NPP coefficients<br>SSURGO | Veg cover:<br>Intersect (FEAT, Landfire-cover)<br>Calculate area-weighted % cover<br>Veg height:<br>Intersect (FEAT, Landfire-height)<br>Calculate area-weighted mean height<br>NPP coefficients:<br>Table 31. values<br>Perc hydric soils:<br>Intersect (FEAT,SSURGO)<br>Calculate area-weighted % hydric soils<br>Perc org matter<br>Intersect (FEAT,SSURGO)<br>Calculate area-weighted % org matter | |
| NPP coefficient | Mudflat | NPP coefficients | NPP coefficients:<br>Table 31. values | |

| Metric Formula | Applicable Feature | Data Layers | GIS Operations | Comment |
|---|---|---|---|---|
| (Veg cover x NPP coefficient)1/2 | SAV | SAV/Eelgrass<br>NPP coefficients | Veg Cover:<br>Use Percent coverage from SAV/Eelgrass data layer<br>Calculate area-weighted % cover<br>NPP coefficients:<br>Table 31. values | |
| **Erosion Protection and Control** | | | | |
| Veg cover | Beach<br>Dune<br>Salt marsh<br>Herb marsh fresh<br>Maritime grassland<br>Terrestrial grass | Landfire-cover (poly) | Veg Cover:<br>Intersect (FEAT, Landfire-cover)<br>Calculate area-weighted % cover | |
| (Veg cover x Veg height)1/2 | Scrub-wetland brackish<br>Forest-swamp brackish Scrub-wetland fresh<br>Forest-swamp fresh<br>Maritime shrub<br>Maritime forest<br>Riparian<br>Terrestrial shrub<br>Terrestrial forest | Landfire-cover (poly)<br>Landfire-height (poly) | Veg cover:<br>Intersect (FEAT, Landfire-cover)<br>Calculate area-weighted % cover<br>Veg height:<br>Intersect (FEAT, Landfire-height)<br>Calculate area-weighted mean height | |
| (Relative height – MSL + 3.28)/3.28 | Reef | Reef layer<br>Bathymetry | Relative height:<br>Manual calculation from bathymetry<br>. | No reef layer has been identified. The heights need to be in feet. Max score is 1.0 if the maximum reef height is at MSL. |
| (Mean height x Prop of leeward shoreline in island shadow)1/2 | Island<br>Barrier island | 10 m NED | Mean Height:<br>Zonal statistics (FEAT, 10 m NED)<br>Prop of leeward shoreline in island shadow:<br>Manual calculation | |

| Metric Formula | Applicable Feature | Data Layers | GIS Operations | Comment |
|---|---|---|---|---|
| **Maintenance of Background Suspended Sediments** | | | | |
| Veg cover | Beach<br>Dune<br>Salt marsh<br>Herb marsh fresh<br>Maritime grassland<br>Terrestrial grass<br>SAV | Landfire-cover (poly)<br>SAV/Eelgrass | <u>Veg Cover</u>:<br>Intersect (FEAT, Landfire-cover) OR Use Percent coverage from SAV/Eelgrass data layer<br>Calculate area-weighted % cover | |
| (Veg cover x Veg height)1/2 | Scrub-wetland brackish<br>Forest-swamp brackish Scrub-wetland fresh<br>Forest-swamp fresh<br>Maritime shrub<br>Maritime forest<br>Riparian<br>Terrestrial shrub<br>Terrestrial forest | Landfire-cover (poly)<br>Landfire-height (poly) | <u>Veg cover</u>:<br>Intersect (FEAT, Landfire-cover)<br>Calculate area-weighted % cover<br><u>Veg height</u>:<br>Intersect (FEAT, Landfire-height)<br>Calculate area-weighted mean height | |
| Prop of watershed draining to pond | Pond | Watershed boundary dataset (WBD)<br>10 m DEM | <u>Prop of watershed draining to pond</u>:<br>FlowDirection(10 m DEM)<br>Watershed (FlowDirection, FEAT)<br>Calculate the area of the derived watershed and divide by area of WBD watershed draining to ocean | No reef layer has been identified. |
| **Reducing Storm Surge** | | | | |
| (90th Perc height/17.3 x Width/200)1/2 | Beach<br>Dune | 10 m NED | <u>90th Perc height</u>:<br>Zonal statistics as table (FEAT, 10 m NED)<br>Use MS Excel to calculate 90th perc height.<br><u>Width</u>:<br>Add field for width<br>Calculate field using formula Area /(Perimeter/2) | Height and width is in feet. For a long beach polygon (L >>W), Perimeter ≈ 2*L, so L ≈ Perimeter/2 and W = Area/L or W ≈ Area/(perimeter/2). |

| Metric Formula | Applicable Feature | Data Layers | GIS Operations | Comment |
|---|---|---|---|---|
| (Veg cover x Width)1/2 | Salt marsh<br>Herb marsh fresh | Landfire-cover (poly) | Veg cover:<br>Intersect (FEAT, Landfire-cover)<br>Calculate area-weighted % cover<br>Width:<br>Manual calculation | The width needs to be manually calculated. A mean width can be calculated across several transect points in GIS. |
| (Veg cover x Veg height x Width)1/3 | Scrub-wetland brackish<br>Forest-swamp brackish Scrub-wetland fresh<br>Forest-swamp fresh<br>Riparian | Landfire-cover (poly)<br>Landfire-height (poly) | Veg cover:<br>Intersect (FEAT, Landfire-cover)<br>Calculate area-weighted % cover<br>Veg height:<br>Intersect (FEAT, Landfire-height)<br>Calculate area-weighted mean height<br>Width:<br>Manual calculation | The width needs to be manually calculated. A mean width can be calculated across several transect points in GIS. |
| (Mean height x Prop of leeward shoreline in island shadow)1/2 | Barrier island | 10 m NED | Mean Height:<br>Zonal statistics (FEAT, 10 m NED)<br>Prop of leeward shoreline in island shadow:<br>Manual calculation | |
| **Reducing Wave Attack** | | | | |
| Max height/3.28 – 1 | Beach<br>Dune | 10 m NED | Max height:<br>Zonal statistics (FEAT, 10 m NED) | Height is in feet.<br>Max score is 1.0 |
| Width | Mudflat | Landfire-cover (poly) | Width:<br>Manual calculation | The width needs to be manually calculated. A mean width can be calculated across several transect points in GIS. |
| (Veg cover x Width)1/2 | Salt marsh | Landfire-cover (poly) | Veg cover:<br>Intersect (FEAT, Landfire-cover)<br>Calculate area-weighted % cover<br>Width:<br>Manual calculation | The width needs to be manually calculated. A mean width can be calculated across several transect points in GIS. |

| Metric Formula | Applicable Feature | Data Layers | GIS Operations | Comment |
|---|---|---|---|---|
| (Veg cover x Veg height x Width)1/3 | Scrub-wetland brackish<br>Forest-swamp brackish | Landfire-cover (poly)<br>Landfire-height (poly) | Veg cover:<br>Intersect (FEAT, Landfire-cover)<br>Calculate area-weighted % cover<br>Veg height:<br>Intersect (FEAT, Landfire-height)<br>Calculate area-weighted mean height<br>Width:<br>Manual calculation | The width needs to be manually calculated. A mean width can be calculated across several transect points in GIS. |
| (Mean height x Prop of leeward shoreline in island shadow)1/2 | Island<br>Barrier island | 10 m NED | Mean Height:<br>Zonal statistics (FEAT, 10 m NED)<br>Prop of leeward shoreline in island shadow:<br>Manual calculation | |
| (Relative height – MSL + 3.28)/3.28 | Reef | Reef layer<br>Bathymetry | Relative height:<br>Manual calculation from bathymetry | Max score is 1.0 if the max reef height is at MSL. |
| **Provision of Groundwater Supply** | | | | |
| Infiltration rate | Herb-wetland fresh<br>Scrub-wetland fresh<br>Forest-swamp fresh<br>Pond<br>Maritime grassland<br>Maritime shrub<br>Maritime forest<br>Riparian<br>Terrestrial grassland<br>Terrestrial shrub<br>Terrestrial forest | SSURGO | Infiltration Rate<br>Intersect (FEAT,SSURGO)<br>Calculate area-weighted infiltration rate | |

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**14. ABSTRACT**
Coastal systems are increasingly vulnerable to flooding due to the combined influence of coastal storms, development and population growth, geomorphic change, and sea level rise. This reality has given rise to efforts to make greater use of ecosystem-based approaches to reduce risks from coastal storms, approaches which draw from the capacity of wetlands, beaches and dunes, biogenic reefs, and other natural features to reduce the impacts of storm surge and waves. This report offers details regarding the use of natural and nature-based features (NNBF) to improve coastal resilience and was designed to support post-Hurricane Sandy recovery efforts under the North Atlantic Coast Comprehensive Study (NACCS). An integrative framework is offered herein that focuses on classifying NNBF, characterizing vulnerability, developing performance metrics, incorporating regional sediment management, monitoring and adaptively managing from a systems perspective, and addressing key policy challenges. As progress is made on these and other actions across the many organizations contributing to the use of NNBF, implementation of the full array of measures available will reduce the risks and enhance the resilience of the region's coastal systems.

**15. SUBJECT TERMS**
Natural and nature-based features (NNBF)
North Atlantic Coastal Comprehensive Study (NACCS)
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Vulnerability assessment
Ecosystem goods and services (EGS)
Regional sediment management (RSM)
Blended solutions
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