TECHNIQUES FOR SPATIAL ANALYSIS AND VISUALIZATION OF BENTHIC MAPPING DATA

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1.0 INTRODUCTION

The mapping and geospatial analysis of benthic environments are multidisciplinary tasks that have become more accessible in recent years because of advances in technology and cost reductions in survey systems. The complex relationships that exist among physical, biological, and chemical seafloor components require advanced, integrated analysis techniques to enable scientists and others to visualize patterns and, in so doing, allow inferences to be made about benthic processes. Effective mapping, analysis, and visualization of marine habitats are particularly important because the subtidal seafloor environment is not readily viewed directly by eye. Research in benthic environments relies heavily, therefore, on remote sensing techniques to collect effective data. Because many benthic scientists are not mapping professionals, they may not adequately consider the links between data collection, data analysis, and data visualization. Projects often start with clear goals, but may be hampered by the technical details and skills required for maintaining data quality through the entire process from collection through analysis and presentation. The lack of technical understanding of the entire data handling process can represent a significant impediment to success.

While many benthic mapping efforts have detailed their methodology as it relates to the overall scientific goals of a project, only a few published papers and reports focus on the analysis and visualization components (Paton et al. 1997, Weihe et al. 1999, Basu and Saxena 1999, Bruce et al. 1997). In particular, the benthic mapping literature often briefly describes data collection and analysis methods, but fails to provide sufficiently detailed explanation of particular analysis techniques or display methodologies so that others can employ them. In general, such techniques are in large part guided by the data acquisition methods, which can include both aerial and water-based remote sensing methods to map the seafloor without physical disturbance, as well as physical sampling methodologies (e.g., grab or core sampling).

The terms *benthic mapping* and *benthic habitat mapping* are often used synonymously to describe seafloor mapping conducted for the purpose of benthic habitat identification. There is a subtle yet important difference, however, between general benthic mapping and benthic habitat mapping. The distinction is important because it dictates the sequential analysis and visualization techniques that are employed following data collection. In this paper general seafloor mapping for identification of regional geologic features and morphology is defined as benthic mapping. Benthic *habitat* mapping incorporates the regional scale geologic information but also includes higher resolution surveys and analysis of biological communities to identify the *biological* habitats. In addition, this paper adopts the definition of habitats established by Kostylev et al. (2001) as a “spatially defined area where the physical, chemical, and biological environment is distinctly different from the surrounding environment.”

1.1 Benthic Mapping Applications

Marine benthic environments are studied for numerous reasons, which can result in numerous and often-conflicting data analysis needs and requirements. The government policy and marine management initiatives that drive many habitat mapping and analysis projects often focus on fisheries habitats (i.e., submerged aquatic vegetation), and as a result concentrate on collecting underwater photography, and aerial remote sensing data suitable for analysis of biological communities (Chauvaud et al. 1998, Bruce et al. 1997). Projects motivated by commercial interests, such as marine cable and pipe laying require different methods of benthic data collection and analysis, such as multibeam sonar (depths) and bathymetric slope analysis to calculate the most suitable route for the cable or pipe. Often, government funded seafloor mapping projects may not collect data suitable for other government-led initiatives. For example, the National Oceanographic and Atmospheric Administration (NOAA) awards commercial contracts for bathymetric surveys to update navigational charts. The high density depth data that is collected would be much more useful to NOAA fisheries researchers, for instance, if it the signal backscatter from the multibeam sonar were also collected to provide a measure of relative differences in sediment type. There are indeed multiple agendas driving (and funding) the collection of benthic, and benthic habitat data that can result in incompatible analysis and integration for other benthic habitat applications.

1.2 Remote Sensing Platforms for Benthic Habitat Mapping

Mapping seafloor features, for the purpose of defining biological assemblages or habitats, is often conducted with remote sensing techniques that collect data without actually contacting or disturbing the seafloor. Remote sensing platforms used for benthic habitat mapping are divided into two basic classes: aerial and water-based. Aerial remote sensing includes all data (primarily color photography) collected from satellite or aircraft sensors, while water-based remote sensing platforms collect data while submerged in the water, usually towed or mounted from a survey vessel. In addition, aerial remote sensing primarily involves the use of optical (e.g. film-based or digital cameras), and water-based remote sensing is accomplished with both optical (photography), or acoustic (sonar), sensors. Similar to the difference between benthic mapping and benthic habitat mapping, the distinction between air and water-based techniques is important because the sensor platform directly affects the subsequent analysis and visualization methodology, as well as the ability to collect data in different environments.

The objective of this paper is to describe the techniques used for the analysis and presentation of data collected for the purpose of benthic habitat mapping, with the primary focus on data collected using water-based remote sensing platforms. Technical details on data *collection* methods are provided in a companion paper (Waddington 2003). The importance of taking into account both temporal and spatial scales in the analysis and visualization of estuarine benthic habitats is emphasized. In addition, through discussion of specific applications, this paper illustrates how the decision to use a particular analysis technique is strongly influenced by the data acquisition method. The habitat mapping projects presented as examples are intended to illustrate the flow from raw survey data to derived analytical spatial data. Understanding these main topics along with the “larger picture” scientific needs are essential before effective analysis can begin (Kvitek et al. 1999).

Rather than attempt to establish rigid guidelines for analysis of benthic mapping data, this paper discusses the major issues common to habitat mapping projects so researchers can approach their projects with a better understanding of analysis techniques, and hopefully a more thorough analysis and visualization methodology. Section 2.0 provides a brief review of the data models used to represent benthic habitats in a Geographic Information System (GIS). Understanding these data models, or “GIS building blocks” is essential to effectively analyzing and visualizing any mapping data in a GIS, particularly marine habitat data. Considerations for effective analysis and visualization of benthic habitat data are presented in Section 3.0. This section focuses on the topic of scale, both temporal and spatial, as it relates to the data models discussed in Section 2.0. Section 4.0 builds on the concepts of data models and scale issues and provides examples of general GIS spatial analysis techniques and software capabilities applied to benthic mapping. Finally, Section 5.0 integrates the discussion of these analysis and visualization techniques through presentation of methodological approaches successfully used in three example benthic habitat mapping projects. Section 6.0 discusses visualization techniques commonly used in presenting analysis while Section 7.0 identifies future needs in the multidisciplinary approach to benthic habitat projects.

2.0 SPATIAL DATA MODELS AND GIS CONCEPTS

The main tools for analyzing geospatial benthic habitat data are GIS and Image Processing (Remote Sensing [RS]) software. A number of commercially available GIS/RS software packages are suitable for use in analyzing benthic habitat data, and software selection often depends on one or more of the following variables: availability and cost, the level of expertise of the anticipated user(s), and the particular habitat application. Regardless of the GIS software utilized, the underlying GIS data models are the same for representing real world features like different benthic habitat types. Because an understanding of the two basic geospatial data models, vector and raster, is essential for effective GIS analysis and visualization of marine habitat data, a brief summary of the main concepts follows.

2.1 Vector Data Model

The vector data model is used to represent basic point, line, and polygon features, such as discrete sampling locations (point), planned survey transects (line), or areas of similar/different habitat types (polygon) (Burrough and McDonnell 1998, DeMers 1997). All three of these vector data model entities are commonly used and suitable for benthic habitat mapping applications. The point vector model represents a discrete location (x,y) with one or more attributes (Figure 1). Single-beam sonar is an example of point data because each "ping" of the sonar records a discrete point with longitude (x coordinate), latitude (y coordinate), and usually depth (z) values along survey transects, with the number of points determined by the sampling rate of the sonar and vessel speed. Some types of benthic survey data are converted to point data through data processing phases, prior to input to a GIS. For example, sub-bottom sonar data are collected along survey transects, producing a profile view of seafloor lithology. The layers below the seafloor are then digitized (i.e., traced) and converted to points, with each point containing a discrete x, y, and z value. Additional examples of point entities utilized in benthic mapping applications are sediment/water sampling locations, sediment-profile imagery (SPI), and underwater photography stations.

Linear features such as planned survey lines, or survey vessel track are often represented in a GIS with a line or polyline entity of the vector data model for illustrating a straight line (Figure 1). Examples of line and polyline vector data models used in benthic habitat analyses include survey lines, and digitized habitat boundaries derived from imagery analysis such as aerial and marine remote sensing data.

The third type of vector data model, polygon, is a closed polyline with an attribute, such as acreage, that defines what is within the boundary of the polygon (Figure 1). Polygons and polylines can both be used to delineate a boundary; however, unlike a polygon, a closed polyline has no associated attribute assigned describing the bounded feature. Polygons are often used to represent two-dimensional areas of homogenous biotope in benthic habitat applications. For example, the interpretation of aerial remote sensing imagery generally entails digitizing (i.e., tracing) polygons around areas that visually appear similar such as a coral reef assemblage, and then assigning an attribute such as "elkhorn coral" to the area. Assigning attributes, such as acreage or habitat code, to the polygon facilitates geospatial queries of the final digitized habitat data in a GIS that can calculate, for example, total acreage of elkhorn coral. Multiple contiguous polygons representing different habitats in a study area are an example of an interpreted or derived spatial data layer in a GIS.

2.2 Raster Data Model

The raster data model divides space into a series of uniformly shaped square cells, with one or more values per cell (DeMers 1997). Raster data sets are described primarily by the dimensions, or resolution, of the individual cells or pixels (e.g., 1 m^2 , 5 m^2, etc.) Raster data are acquired from both aerial (photography) and water-based remote sensing platforms (e.g., side-scan sonar, laser line scan, underwater photography), for benthic habitat mapping (Figure 2). Cell resolution of raster data is an important consideration in benthic habitat mapping applications because the dimensions of the cell determine the representational precision of mapped features. For example, side-scan sonar imagery with a resolution of less than 1 ft^2 is considered "high resolution" data because it can distinguish small features such as sand waves. However, if the resolution of the imagery were to be increased to 5 ft^2, small features like sand waves may no longer be visible.

Aerial photographs and side-scan sonar records are examples of data collected in raster form. However, data collected using the vector (point) model can be converted to raster, either "real-time" during data collection or in post-survey processing phases. Continuous records of water depth collected by single and multibeam sonar data are examples of benthic data collected in vector format and converted to raster using two different geospatial processing techniques. Single-beam sonar data are often collected along transect lines and converted to raster through interpolation, which involves calculating values for unsampled points based on the values of nearby sampled points. Multibeam sonar data are converted to a raster data model using GIS processing routines that essentially convert each point to a square pixel, based on user-defined input, without interpolation.

3.0 CONSIDERATIONS FOR EFFECTIVE BENTHIC HABITAT ANALYSIS AND VISUALIZATION

In addition to sensor platform and data model considerations, several other important parameters require consideration for *water-based* benthic mapping applications, such as the scale of the habitat and resolution of sensors. These are not specifically mentioned in the existing literature on benthic habitat mapping via *aerial* remote sensing because they are unique to water-based survey systems. While both air and water platforms share common considerations, stemming from their ability to map the same habitat with different sensors, the technical approach to analysis and visualization differs because of the fundamental differences between optical and acoustic data collection methods.

3.1 Spatial Scale

One of the fundamental concepts for understanding the distributions of benthic habitats is their variability over space and time, and it is important at the outset to note the distinction between "spatial scale" and "habitat scale." Spatial scale (or map scale) is defined as the relationship between the size of a feature (i.e., habitat) on a map and its size in the real world (Burrough and McDonnell 1998), and is typically expressed as the ratio of map units to real world units (e.g., 1 inch on the map equals 7,000 real world inches, or a scale of 1:7000). Maps are often referred to as "large scale" or "small scale" based on the ratio of map units to actual earth units. A map with a scale of 1 inch = 400,000 inches shows a large area and is considered a small-scale map. A large-scale map, showing a small area, could have a ratio of 1" = 500", thus these terms small and large scale technically refer to the ratio of map units to actual units. Unfortunately they are often (and erroneously) applied to describing the areal extent of a habitat (e.g., "large-scale habitats"). The following section discusses the terminology that should be used in describing habitat scale.

3.2 Habitat Scale

Habitat scale is generally determined by the areal extent of a distinct biological community or geological feature(s) of interest. Habitat scale is that scale which best defines the areal extent of a distinct biological community, independent of a sensor's capability to detect and measure it and independent of a map's ability to visualize it. The terms "macro," "meso," or "micro" are useful to describe the general geographic scales at which a particular habitat (or sub-habitat) can be defined or mapped. Figure 4 illustrates the general relationships among scales of habitat and associated data collection methods and further illustrates the nominal habitat scale concept. For example, SPI data are effective for mapping micro scale benthic features that are generally .01m^2–0.1m^2. Again, there are no strict rules for establishing these scales for individual habitats because often the same benthic habitat can occur in both large and small assemblages, requiring different data collection and analysis methods. For instance, "eelgrass habitat" could be described as occurring on a meso to macro scale, as eelgrass often grows in large areas of coastal waters (e.g., hundreds of m^2) and can therefore be delineated from aerial photographs in clear water (Finkbeiner et al. 2001). However, eelgrass can also occur in much smaller patches of less than 1 m^2 and in turbid (not clear) waters. At this micro scale, mapping of the distribution of the eelgrass may require higher resolution data than available from most aerial photography. Survey techniques like underwater photography or diver transects can effectively measure and map these microscale habitats (SAIC 2003).

3.3 Habitat Delineation

Understanding the distinction between spatial and habitat scales is an important concept for habitat analysis and delineation because the detail at which a habitat is delineated from mapping data (e.g. airphotos or bathymetry) is related to both the spatial scale of final maps and the habitat scale of marine habitats. With the possible exception of coral reefs, most marine habitats do not have distinct "hard" boundaries, however, the boundary between different habitats must be calculated to represent them as georeferenced point, line, polygon, or raster cells in a GIS. Boundaries between sediments (e.g., silt, cobble, and sand) are not actually precise multi-shaped polygons, but are instead an assemblage of gradual transitional (or soft) boundaries. How then does one define such soft boundaries? The precision (i.e., where to digitize the boundary) of the defined polygons is determined by the resolution of the survey data and the *habitat scale* of the particular habitat. This facilitates the recognition of habitat as an "area" or "region." Representing habitat with point data is less effective at most scales because a point identifies location but not extent (or other useful attributes like area) of a particular biotope.

The digital resolution of a habitat, as it is represented in a GIS, is directly related to the both the spatial and habitat scale of benthic features. For instance, multibeam sonar bathymetric data collected to identify small cracks and ledges in bed rock for lobster habitat mapping requires the capability to resolve those small cracks. These multibeam sonar data would generally need high resolution (~1 to 2ft^2) to identify these small geologic features. Multibeam data collected at resolution greater than 5 ft^2 would not detect the micro scale ledge features because they occur at resolutions finer than 5 ft^2. Figure 5 illustrates the effect of different resolutions of multibeam bathymetric data on the ability to visualize micro scale habitat features. The 1 ft^2 resolution data in Figure 5a are very high resolution, capable of measuring micro scale features like sand waves and rock ledges and even lobster traps. These features are more generalized with increasing data resolution from Figure 5a–5b until they are no longer visible.

3.4 Habitat Classification

The classification of the seafloor into areas of similar habitats, or biotopes, is closely tied to the habitat scale and spatial extent of the habitat. Although a complete discussion of habitat classification is provided in a companion paper (Diaz and Solan 2003), it is briefly mentioned here to further illustrate the role of scale, and particularly habitat scale, to the analysis and visualization of benthic habitats. Habitat classification systems are as varied worldwide as the habitats they represent. European efforts to standardize terrestrial and marine habitats are coordinated by the European Union Nature Information System—EUNIS (European Environment Agency 1999). In the United States, many government and state agencies have individual classifications schemes; however, these may only cover local conditions and may not be suitable for national applications (NOAA 2000). Only recently, federal and local ecological groups in the United States developed a standardized national marine and estuary ecosystem and habitat classification system (NOAA 2000). While still in development, this effort is more focused on marine habitats than EUNIS (European Environment Agency 1999). The Marine and Estuarine Ecosystem and Habitat Classification (NOAA 2000) recognizes and addresses the link between habitat scale and habitat classification through a hierarchical classification system combining global scale ecological systems with regional ecological systems.

3.5 Temporal Scale

Seasonal or annual fluctuations in sunlight, water temperatures, and current velocity can significantly change the biomass extent of habitats comprised of SAVs. Consideration of potential temporal variations is particularly important when collecting and analyzing baseline biological data, because accurate detection of changes over time depends on comparing two or more data sets collected under similar, if not identical conditions. Calculating annual changes in eelgrass cover or density, for example, depends on collecting data at the same time each year to reduce error from seasonal fluctuations. The degree to which benthic habitats vary through time is strongly influenced by the physical oceanographic environment. For example, benthic habitats in the intertidal zone can be expected to vary with much higher frequency than habitats in deeper offshore waters. Time scales on the order of hours can be important in shallow estuarines. For example, extreme tidal events or floods can scour the bottom of a river or estuary and significantly alter the distribution of sediment and associated biological communities.

3.6 Project Planning

Scale issues are indeed integral to the analysis of benthic data and some are unique to water based benthic mapping. However, at a conceptual or planning level the primary considerations for data collection and analysis for both aerial and water-based platforms are similar and summarized as follows:

1. What is the scale of mapped features in time and space? (Habitat Scale)
2. What are the general bottom characteristics of area of concern? (Spatial Scale)
3. How will these data be analyzed and visualized? (Analysis Scale)
4. Will this survey be replicated in the future as part of a monitoring/change detection effort? (Analysis Scale)
5. What is the available funding for data collection and analysis? (Survey/Analysis Scale)

The importance of these and other parameters depends on the goals of a particular project and therefore may periodically require adjustment to accommodate effective use of resources. Figure 3 illustrates the relationship between the general considerations, with habitat scale being the parameter that dictates the most suitable sensors, analysis, and required funding. However, often a benthic mapping project will have one of the above parameters fixed, such as funding, in which case the relative importance of the other parameters must adjust in an iterative process until the goals of the project are obtainable within the budget.

3.7 Historical Data

The scale and resolution of acquisition, analysis, and visualization methods must be compatible with overall project objectives. The spatial scale of the particular benthic habitat, in both time and space, is important to quantify before any data collection or analysis begins because it will determine the most suitable survey, analysis, and visualization methods. Many researchers may not address this vital step in a habitat mapping and analysis project; however, it can mean the success or failure of the project and should not be overlooked. Without previous knowledge of the conditions, there are a several sources of historical or regional spatial data useful for background information, provided the limitations of such data and methods are recognized.

Government agencies such as NOAA, USGS, and EPA distribute numerous regional thematic spatial data sets that may be useful for planning habitat mapping projects. Synthesis of these historical or background data from multiple scale sensors for survey planning or analysis can present additional challenges, because the scale and resolution of these historical data may not be compatible with that of the current planned project. For example, raster bathymetric data distributed by NOAA (NOS, http://seaserver.nos.noaa.gov/bathy/index.html) have a spatial resolution of 90 m^2 and 30 m^2. This resolution might be informative for regional features, however, it may not be able to identify smaller features such as coral heads, or bedrock ledges that may be the aim of higher resolution surveys. Addressing this problem of scale linkage often proves difficult when using previous data and analysis from different scales. Often there is no solution to quantitatively integrating historical datasets because of scale, resolution, and positional issues, however, these data can serve as useful qualitative background data.

4.0 SPATIAL ANALYSIS TECHNIQUES FOR BENTHIC HABITAT MAPPING DATA

Interpretation and analysis of benthic habitat data includes processing and analysis phases using computer hardware and software packages. Foremost in the benthic habitat analysis toolbox are GISs. While the science of GIS is constantly developing, the application of GIS to marine science and benthic applications is well established (Wright and Bartlett 2000, Wright 2002). Currently the problem is not whether GIS is applicable; rather it is learning to use GIS more effectively in addressing the scientific questions that drive the initial mapping. There are indeed many techniques for analyzing and visualizing benthic data; the issue is which technique, or combination of techniques, is best suited to a particular marine environment. Benthic researchers need to utilize the advanced tools and spatial analysis functions available in most GISs to progress from the simple display of benthic survey data to multiscale data integration and increased analysis and visualization that will further the study of benthic habitats.

4.1 Data Display versus Data Analysis

The level of spatial analysis conducted in a typical benthic mapping project depends on a number of factors, foremost of which is technical expertise. Current commercial GIS packages can facilitate complex spatial analysis and data display without a significant amount of GIS knowledge, which may lead to confusion regarding the difference between simple data display and more complex spatial analysis of derived and calculated data. Advanced analysis and query are typically needed to illustrate and display relationships among multiple benthic parameters, such as bottom topography and sediment type, that often have been measured using widely different techniques. The spatial display of results from point samples (e.g., SPI, sediment grab sampling) is easily accomplished, but it is almost always of greater interest to determine the relationship between the point data and broader scale benthic structure. The basic difference between data display and data analysis is illustrated in Figure 6. The display of point sample symbolized by sediment type (Figure 6a) is a useful first step in mapping benthic habitats, however, it is too often the *last* step in characterizing seafloor sediments in many projects (SAIC 2003). More effective data *analysis* includes converting these point data to raster data using interpolation algorithms such as inverse distance weighted (IDW), or spline, commonly available in most GISs (Figure 6b). The conversion of point samples to raster is an effective technique because it recognizes and presents benthic parameters (e.g., sediment) as spatially continuous areal features, although they are sampled with discrete point samples. Additionally, this point-raster conversion facilitates analysis and data *integration* with other continuous benthic features such as bathymetry, (Figure 6c) provided the different spatial scales (based on the distribution of bathymetric and sediment sample points) are acknowledged.

Raster representation of continuous data such as bathymetry is particularly effective in benthic habitat mapping because it provides an uninterrupted surface that can be queried or classified in a GIS to derive additional raster or vector data. Aerial remote sensing data used for benthic habitat mapping is also represented in a GIS as a continuous raster surface; because it is acquired optically, it captures all data (e.g., land, water, clouds, and seafloor) in the sensor's field of view (footprint). These features divide the imagery into discrete areas of different attributes. The boundary between land and water in such imagery does not represent a transition between different values of a single attribute such as depth, and does not facilitate the same analysis techniques applied to other single attribute raster data. Figure 7 provides examples of how various types of data are derived from spatial queries of a single raster dataset. Raster data (e.g., bathymetry) can be queried to calculate additional vector data such as isolines (contours), raster data sets representing slope, hillshade, or three-dimensional representation (Figure 7). As indicated previously, raster data are either collected directly in raster form (imagery) or converted from vector (point) data.

4.2 Accuracy Assessment

All mapping data, including benthic mapping data, have errors inherent in the data collection process. The challenge is to assess both the positional and thematic accuracy of data collected for benthic habitat applications and quantify acceptable error for analyzing a given benthic community. Complete discussion of the techniques used for calculating positional and thematic accuracy are sensor specific and require more detail than warranted here. However, a brief discussion identifying major issues and solutions follows. The purpose here is to identify several sources of error in benthic mapping data and briefly describe how this error is quantified.

4.2.1 Positional Accuracy

In general, the increased use of global positioning system (GPS) technology for benthic habitat mapping has increased the positional accuracy of simple point data collection. However, georeferencing raster data sets such as aerial remote sensing and side-scan sonar imagery still requires careful examination of positional accuracy at the outer edges of the image. Methods for calculating positional accuracy for aerial remote sensing of terrestrial environments involve the use of ground control points and are well established (Sabins 1997). However, these methods are generally not applicable in aquatic environments because of the inability and difficulty to establish known control points in dynamic coastal or offshore areas. Bruce et al. (1997) present a detailed assessment of positional accuracy for mapping seagrass in Shark Bay, Western Australia using aerial photography and Landsat TM imagery. In this study eighteen transects were surveyed with underwater video and single-beam sonar to verify seagrass density and species type. Boundaries between species type and density were calculated from the transects, and the line representing the transect was divided based on field surveys and compared to the boundaries from the imagery in a GIS (Bruce et al. 1997).

4.2.2 Thematic Accuracy

Thematic accuracy is the probability that an attribute assigned to a mapped feature is the type actually found at that location (Sabins 1997); it is an important data element to ensure the reliability of the final interpreted data set. Assessing thematic accuracy is useful for sensors with a wide footprint such as aerial photography or side-scan sonar imagery, because they are collected across a large swath of seafloor and across variable habitats. A recent habitat mapping project conducted by NOAA in Puerto Rico and the U.S. Virgin Islands used random sample points in each habitat type to compare the habitat type calculated from aerial photography and diver surveys (Kendall et al. 2001). Accuracy assessment and error calculations are not usually within the scope of most benthic mapping projects because of time and budget constraints. However, all benthic mapping data and accompanying analyses can provide empirical measures of data reliability, which allows users to assess spatial and thematic accuracy of the data (Bruce et al. 1997).

4.3 Processing and Analysis Software

While most sensors and acquisition tools have processing software bundled with the survey system, they often provide limited analysis capabilities. Additional software, primarily GIS and statistical packages, is required. Survey data are often collected, processed, and stored in a proprietary, sensor-specific format (e.g., the Extended Triton Format (xtf) used by Triton) that must then be converted to a more generic format and data model for use in a GIS. The more common data formats accepted by most GISs are ASCII for point and vector data, and georeferenced raster data.

Computer hardware and software systems used for benthic habitat analysis can be as simple as a laptop computer with free software, or as complex as networked workstations, custom software packages, and database management systems (DBMS). Current GIS software provides robust analysis and visualization routines, but these easy-to-use formats unfortunately allow analysis and map creation without complete comprehension of the suitability of the underlying geoprocessing algorithms or spatial concepts. In addition, no single software package is capable of all the processing, analysis, and visualization needed in typical habitat mapping application and combinations of two or more software packages are usually required. Custom GIS software can streamline repetitive tasks during manual digitizing of habitats and establish a substantial level of quality control, because multiple analysts must use the same methods. For example, NOAA developed the NOAA Habitat Digitizer for ArcView to facilitate standardized habitat classification by multiple photo interpreters, and distribute both the data and software extension via the internet and project CD (Kendall et al. 2001).

5.0 EXAMPLES OF BENTHIC HABITAT ANALYSIS

This section presents projects to illustrate practical examples of nearshore benthic habitat mapping projects to illustrate the key considerations discussed in this paper. For examples of methodologies used in aerial remote sensing the reader is referred to detailed guidance documents from NOAA (Finkbeiner et al. 2001, Kendall et al. 2001, Analytic Laboratories of HI 2002).

Manually digitizing areas of similar acoustic signal from a side-scan sonar mosaic is an example of benthic mapping (Figure 8). This figure illustrates how point data providing information about sediment characteristics at a much finer scale data (e.g., SPI, towed video, or sediment samples) can be used to refine the original benthic map into a benthic habitat map showing sub-habitats. Because of the reflectance or color discontinuities that occur in towed side-scan records from water column and lane boundaries, such records are difficult to classify with the same type of supervised classification schemes typically applied to terrestrial remote sensing data (Cochrane and Lafferty 2002). There is promise, however, associated with the increased use of new backscatter data from vessel-mounted multibeam sonars that record the relative strength of the acoustic reflectance of the seafloor (Figure 9). Unlike towed side-scan, multibeam backscatter does not have the problem of data discontinuity under the sensor and therefore is more amenable to supervised classification. Broad-scale mapping techniques such as side-scan or multibeam sonar are particularly useful because they cover the seafloor with 100% coverage. Nevertheless, these data must be validated (i.e., trained or "ground truthed") with benthic sampling or bottom photography to verify the accuracy of the digitized geologic and substrate classification.

5.1 Side-scan and Multibeam Sonar

Side-scan sonar is used often in benthic mapping because it collects data over a relatively large area of the seafloor and provides an excellent picture of the physical seafloor characteristics based on differences in acoustic reflectance signature (Blondel and Murton 1997, Fish and Carr 2001). Unlike optical methods, water characteristics such as turbidity and light penetration do not effect the acoustic side-scan sonar sensor, which makes it ideal for the deep or turbid waters of most non-tropical benthic habitats. Side-scan sonar data are collected along survey lanes based on the depth of the water and the desired amount of bottom coverage. The individual records collected along each lane are merged together in a georeferenced image or “mosaic” with specialized processing software. The considerations for collecting side-scan sonar data are detailed in a companion paper (Waddington 2003). Once data are processed, mosaiced, and georeferenced, they are ready for interpretation in a GIS. Interpretation of side-scan sonar data generally entails viewing the processed mosaic in a GIS and digitizing areas of similar acoustic return with polygons and adding attributes. As mentioned in previous sections, the important considerations for the interpretation of side-scan sonar data for benthic habitats is the resolution of the mosaic, the spatial scale of the mosaic, and the scale of the habitat.

The Geologic Survey of Canada has successfully mapped large, macro scale portions of the offshore shelf waters in the Atlantic Ocean with multibeam bathymetry and side-scan sonar for use in fisheries management (Todd et al. 2000, Kostylev 2001). In these studies, benthic habitats were defined using geophysical and geologic sediment characteristics from the side-scan and multibeam sonar imagery, water depth,and benthic associations. The relative strength of the returned sonar signal (defined as backscatter and measured in decibels (dB)) of the multibeam sonar provides an indication of sediment type (Figure 10). Additional data were collected to validate and check the thematic accuracy of the interpreted sediment map including geophysical profiles, side-scan sonar, sediment grabs, and bottom photography. Target stations and survey lanes for these complimentary data were based on the interpreted geophysical data from the multibeam backscatter, and used to refine sediment boundaries. Benthic organisms visible in the bottom photographs were analyzed to the lowest possible taxonomic level and analyzed using Principal Components Analysis (PCA) and One-way analysis of variance (ANOVA) to correlate the distribution of the interpreted sediment types from backscatter with benthic community composition. This interdisciplinary approach using backscatter, bathymetry, sediment samples, and bottom photography has successfully mapped benthic habitats in large areas of shelf waters for natural resource and fisheries management in both U.S. and Canadian waters. (Valentine et al. 2001)

5.2 Point Data Interpolation

Among the more common survey techniques for marine benthic habitat mapping that involve sampling at discrete point locations are sediment cores and grab sampling, SPI and other types of bottom photography, as wells as single-beam sonar, sub-bottom profiling (digitized), and seabed classification systems. GIS display of data from these various sampling methods is a simple task, provided the geographic coordinates were recorded with the sample. However, such displays in their simplest form provide little indication of values at unsampled points to present a larger picture of the benthos and related habitat. This shortfall associated with point samples can be addressed by converting points into a continuous raster surface, using either of two basic methods. Interpolation converts sample points into a raster surface of equal cell sizes, using algorithms such as spline, inverse distance weighted (IDW), and kriging (Lam 1983, Burrough and McDonnell 1998, Desmet 1997). The second method, used primarily with multibeam sonar, does not require interpolation because the data are very dense and cover the seafloor with a high sampling density, as fine as 1 ft^2. Multibeam sonar data can be converted directly to a raster surface without interpolation.

A whole range of interpolation methods may be suitable for benthic habitat studies, and most GISs feature automated functions that do not require substantial knowledge of the data or the process. Generating statistically valid interpolated surfaces from point data, however, is an iterative process that requires applying several different interpolation techniques, followed by visual and/or statistical comparison of the results. While a full discussion of interpolation routines is not in the scope of this paper, a basic understanding of geostatistics and interpolation algorithms is suggested for benthic habitat applications (Lam 1983, Burrough 1986, Oliver 1990, Desmet 1997).

There are a number of variables that must be considered in selecting the most suitable algorithms for each benthic data set, including data density, data value range, and the scale of the habitat. Data density is typically determined by the sampling design, and most designs are either random or stratified. A stratified sampling design is often used for systematically covering a large area. The regularly spaced survey lines used for single-beam sonar or bottom classification systems surveys represent a stratified sampling design. Random sampling is often used for sediment grab sampling or SPI. To illustrate some basic principles, a public domain sediment dataset from Raritan Bay, New Jersey is highlighted below (Iocco et al. 2000).

Sediment grab samples and SPI images were collected at 190 stations in Raritan Bay, NJ to provide information for siting potential dredged material disposal sites and habitat restoration projects within New York Harbor (Iocco et al. 2000). Three different interpolation methods (inverse distance weighting (IDW), spline, and Kriging) were used to evaluate spatial patterns in sediment total organic carbon (TOC) concentrations (Figure 11). A constant raster resolution of 500 m was used for all three interpolation methods because it was the finest resolution that did not produce error messages from routines. The three grids are generally the same from visual observations and further statistical analysis is required to decide the most suitable technique. Analysis of the basic descriptive statistics from the resulting grids suggests the spline method may not be appropriate for these data because the minimum TOC values were ~ 1-2 % higher than the actual minimum values of the input data set (Figure 11). The spline method generates smooth contours but can increase data ranges to accomplish because of the smoothing higher order polynomials in the algorithm (Burrough and McDonnell 1998)

Further analysis of the rasters produced by the IDW and the kriging methods is required to decide which is most suitable for this particular application. The data range from the IDW is closer to the input data range than the kriging method and could be a basis for choosing the IDW method. However, kriging is a powerful geostatistical method that can also produce a variance grid from the interpolation procedure that provides a calculation of variance between the actual sampled points and the calculated value for that same location (Burrough and McDonnell 1998) (Figure 11). For this example, additional kriging runs with different parameters is suggested to reduce the variance values in the area of sparse data samples. This statistical data exploration is a valuable technique applied to benthic habitat data to illustrate statistical relationships in the data. Customized GIS software such as EPA's Field Environmental Decision Support (FIELDS), or ESRI's Geostatistical Analyst (ESRI, Redlands California) facilitate this statistical data exploration useful in many benthic habitat mapping applications. In this example, three common interpolation methods (IDW, spline, and kriging) were examined only to illustrate considerations for interpolation of point data and are not intended as a complete discussion and comparison of interpolation methods (Lam 1983, Burrough 1986, Oliver 1990, Desmet 1997, Burrough and McDonell 1998).

5.3 Mapping of Microscale SAV

Both aerial and water-based remote sensing techniques have been used successfully for mapping the distribution of submerged aquatic vegetation such as eelgrass (Bruce et al. 1997, Finkbeiner et al. 2001, SAIC 2001). Eelgrass is found in a number of spatial extents, including patches less than an acre, that cannot be mapped from aerial remote sensing platforms because they are too small. An example methodology for monitoring small eelgrass patches for cover and density is discussed here to highlight alternative methods and illustrate the importance of evaluating the various considerations for effective analysis and visualization of benthic habitats.

A small eelgrass bed (~ 1 acre) in Narragansett Bay, Rhode Island was mapped to assess any potential impacts from the dredging associated with the reclamation of a nearby shoreline landfill (SAIC 2001). Although a general idea of the extent of the eelgrass bed was known, reconnaissance side-scan sonar and single-beam bathymetric surveys were conducted to provide baseline data for higher resolution surveys of the approximately 1500 ft^2 survey area. Depths in the area ranged from 0–15 ft. Bathymetric survey lane spacing of 25 ft was used to collect dense data within the funded survey window of one day and facilitate interpolation to a small raster resolution to match the scale of micro features. Resolution of side-scan sonar data was 0.1 ft, and bathymetric trackline data were interpolated to a raster surface using kriging and a resolution of 10 ft. A higher resolution survey using "plan view" or drop cameras followed the initial baseline surveys. The planning phases for this survey considered the following:

1. **Scale of the eelgrass habitat**—what are the sizes of the eelgrass patches?
2. **Scale of analysis**—at what resolution could the eelgrass cover and density be represented?
3. **Navigational Precision and Accuracy** of Differential GPS.
4. **Vessel Maneuverability**—Ability of survey boat to maintain station while in shallow water.
5. **Budget**—Time and funding allotted for survey.
6. **Repeatability** of the survey techniques in sequential monitoring surveys.

Based on the above considerations, sample locations for planview photography that were 20 ft apart were used to sample an area larger than the estimated extent of the eelgrass bed. Three planview images were acquired at each of the 200 target stations (Figure 12). Images were processed and analyzed to calculated percent cover and density (plants/m^2) of eelgrass. Three diver transect surveys were conducted in the survey area to evaluate the thematic accuracy of the density and cover calculated from the planview photography. Actual sample locations greater than 20 ft from the central target coordinates of each station were identified through buffer analysis and reassigned to the nearest cell for cover and density calculations. All samples located in each 20-ft cell were averaged, and the average value assigned to the center (target) of the cell. These regularly spaced point values were then converted to a raster with 20-ft cell resolution. Unlike point interpolation, the conversion of point to raster did not involve any interpolation because the points were already spaced at equal intervals on the original sampling grid. Instead a GIS process was used that converted the point features to a raster based on bounding coordinates and a grid cell size. This methodology for monitoring small eelgrass beds with water-based remote sensing techniques proved effective based on the size of the eelgrass bed, the shallow water, and the survey and analysis systems available for this project.

6.0 VISUALIZATION OF BENTHIC MAPPING DATA

As the tools for benthic mapping allow us to collect and analyze data of increasing density and resolution, effective visualization of these data is challenging. Too often, complex marine data sets must be simplified to black and white graphs and images for journal articles because of the added costs associated with producing color figures. Various types of media are currently used for visualization and delivery of benthic data, such as hard copy 2D and 3D graphics, and internet and virtual flythroughs. Benthic habitat data are often too complex, or have resolution too fine, to be represented adequately in traditional 8"x11" reports. For example, 10 km^2 side-scan mosaics simply cannot be displayed effectively on one standard-sized page. These display limitations are partially resolved by publishing final data and reports in a digital format via CD or the internet, as increasingly practiced by various government agencies and academic research groups. This enables other scientists to use these public domain data for additional research and marine management applications. Published literature strictly on visualization of marine benthic environments is scarce. Rather, these topics are incorporated into application papers on such subjects as deep sea seismics (Goldfinger and McNeill 1997, Wright 1996), hydrographic surveys (Harding et al. 2000), macro scale geologic mapping (Hughes-Clarke et al. 1996, Shaw and Courtney 1997), or marine navigation (Ford 2002). The few articles published strictly on 3D visualization are primarily authored by the developers of leading 3D software packages (Paton et al. 1997).

Three-dimensional visualization facilitates new and encouraging avenues to process, explore, and present complex processes in marine science (Wolanski et al. 2000) and, in particular, benthic habitats. While spatial databases and spatial analysis have made major advances in recent years, the integration of 3D visuals has not. This will continue to be a problem until internet publishing is more widely accepted; in the meantime research continues to be presented primarily in paper-based professional journals.

As computers become more powerful, specialized graphics and video cards are required to generate truly effective visualizations of benthic environments. Many GIS and mapping software packages have basic visualization features, while some software is designed specifically for 3D visualization of marine data. Many marine data acquisition and processing software packages have limited display capabilities, which require additional software for analysis and visualizations. There are a multitude of data visualization software packages currently available including commercial (ESRI, MapInfo, Erdas, Envi, Surfer, Fledermaus), open source academia (Gzui, GMT), and free (ArcExplorer). Most GIS display is two dimensional, even when it provides hillshading functionality, which gives the appearance of 3D relief. The majority of data included in published benthic mapping reports is simple two-dimensional data display rather than more complex visualization. All benthic data can be represented in two dimensions (x,y). However, not all data can be represented in three dimensions.

Viewing benthic data in an interactive 3D environment can provide the additional display and analysis environment needed to view relationships not recognized in 2D. Effective 3D visualizations of complex data sets make it easier for scientists in different disciplines to perceive patterns because the spatial relationships are easier to recognize and comprehend. Marine scientists often struggle to explain complex interrelationships among biological, geologic, and oceanographic data sets because data analysis techniques specific to one field may not be used or understood by other disciplines. Effective 3D visualization cuts through such problems and facilitates viewing of complex data in a medium that is inherently easier to understand by most audiences. Nonetheless, limitations to 3D display exist, particularly for shallow estuarine benthic environments. Estuaries are typically low relief environments, which require significant vertical exaggeration to discern differences in bottom topography. Substantial vertical exaggeration also magnifies any errors in the data.

6.1 Hard Copy Visualizations

Benthic analysis results are usually presented in hard copy format in maps, journal articles, posters, and conference presentations or published on the internet. Presenting benthic habitat data in a typical journal article creates challenges with regard to color, cost, resolution, size of image, and quality. Few habitat maps can be accurately displayed as black and white images. Some interpreted maps depicting areas of habitat can be portrayed, however, detailed classified images of regional side-scan data cannot. One of the biggest hurdles is simply the price of publishing color images in articles.

6.2 Virtual Flythrough Visualizations

Many benthic environments are so complex that static 3D images in hard copy reports do not sufficiently visualize the data. Interactive 3D visualization such as virtual reality modelling language (VRML) and flythroughs are required to effectively display macro scale regional habitat data for visualization because of the large extent and variability. The internet is currently the most dynamic media and can deliver interactive geospatial data, allow viewing and downloading of movies, and also display high-resolution color graphics of benthic environments without requiring a color printer.

7.0 FUTURE NEEDS

Benthic habitat mapping and analysis are currently in a transition phase between validating the tools used for mapping and applying these validated tools to more advanced spatial analyses. While marine mapping and analysis has made great strides in the last decade, primarily through new hardware and software, greater challenges are on the horizon. For example, increased analysis and display in a 3D environment is the best avenue for diverse scientific fields to utilize the same data because it shows spatial interrelationships in a more intuitive media. Additionally, more effort is required to standardize collection and interpretation of results in conjunction with integrated habitat classification schemes (NOAA 2000). Perhaps the largest future need is really a paradigm shift in the way mapping data have been viewed. Until recently, all mapping data—terrestrial and aquatic—were presented only as a static map either in reports, posters, or figures. Today's demands for increased mapping and analysis of nearshore benthic environments requires a more dynamic interactive data display and query available to many, rather than a static map made by a geologist, which may be of no use to a benthic ecologist. Progress has been made on this front with interactive internet mapping sites that allow users to generate custom maps and advanced 3D virtual "flythroughs" where the user can actually move anywhere through the data (Paton et al. 1997, Mayer et al. 2000). Additionally, more coordination of estuarine benthic mapping projects among academia, state, and federal organizations is suggested to facilitate multi-user analysis for coastal and estuarine management.

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FIGURES

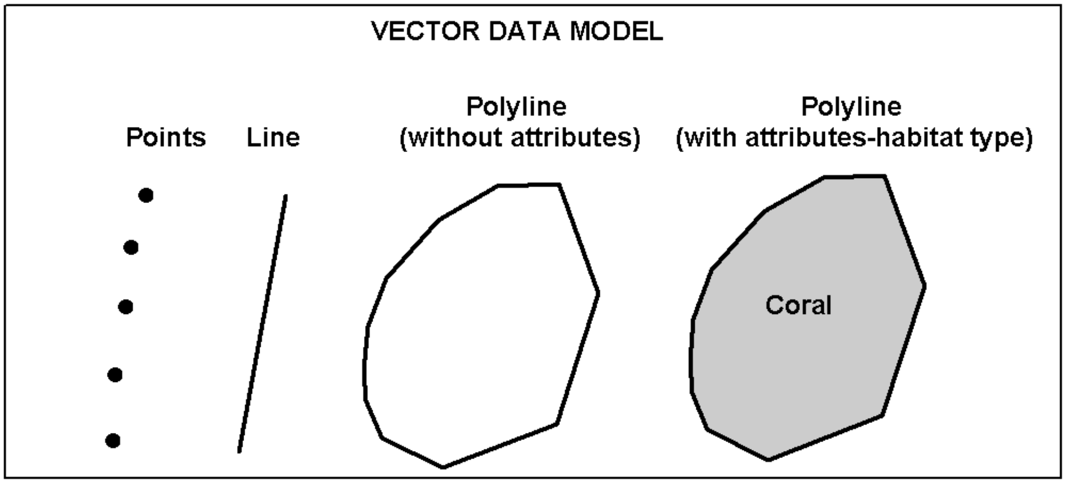


Figure 1. Examples of vector data model used for representing benthic habitat features in a GIS.

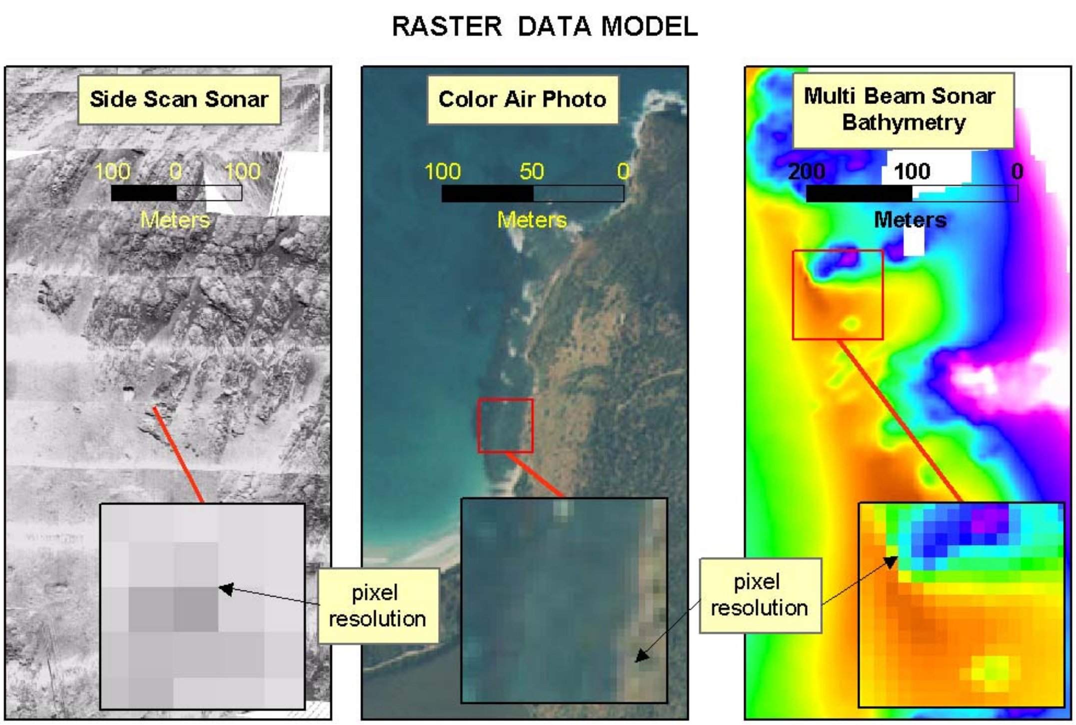


Figure 2. Examples of raster data model used for representing benthic habitat features in a GIS.

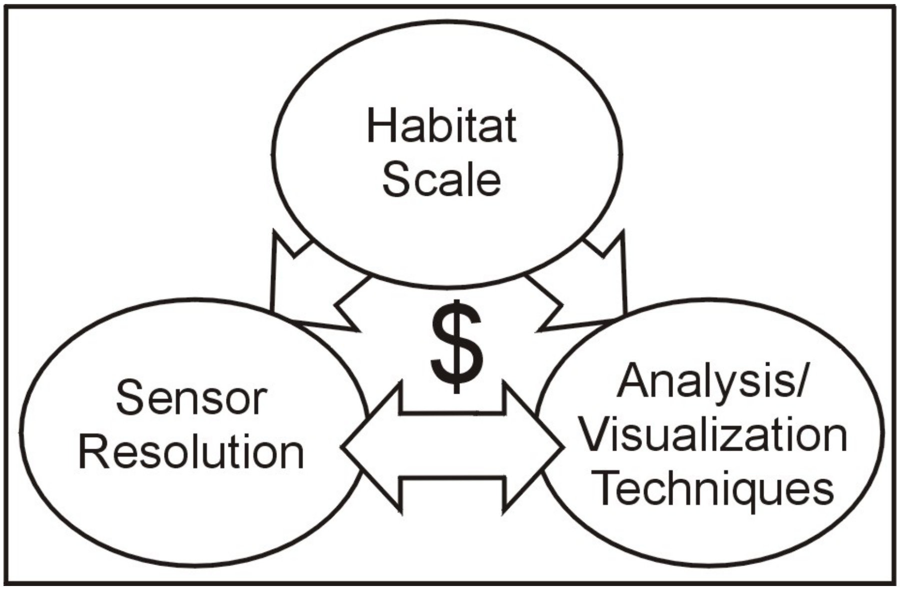


Figure 3. Relationship among habitat scale, sensor resolution, and techniques for analysis/visualization, and funding for benthic habitat mapping.

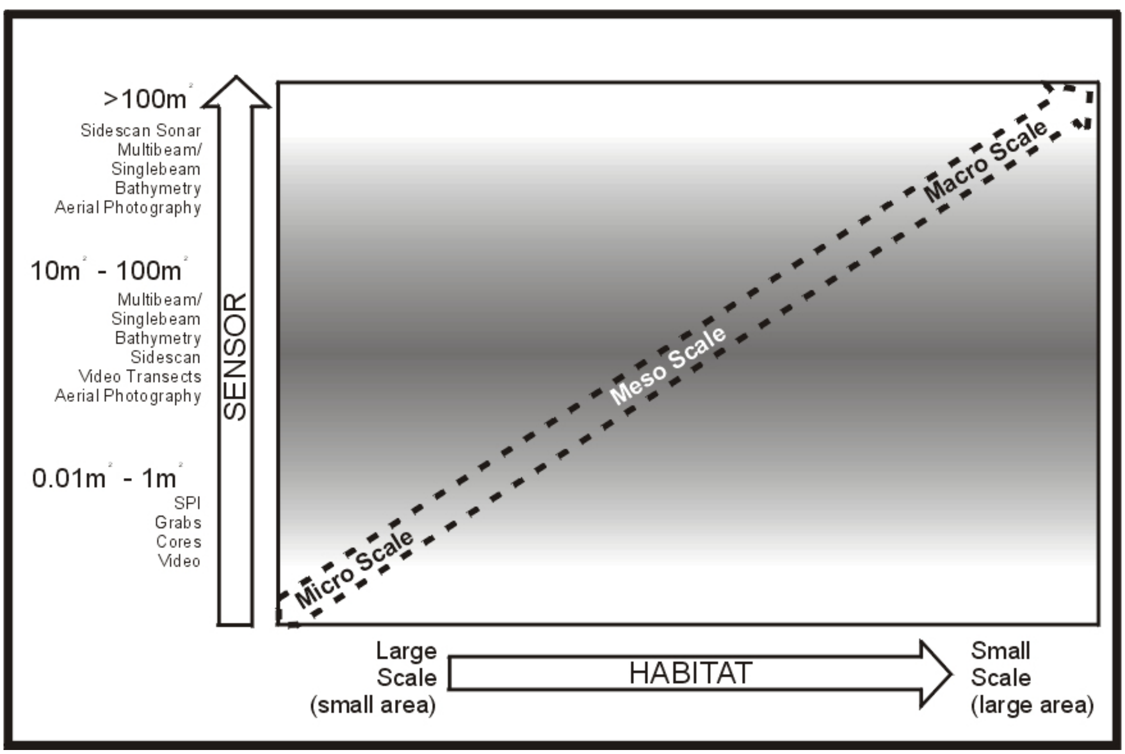


Figure 4. Relative scales of sensors and analysis for benthic habitat mapping.

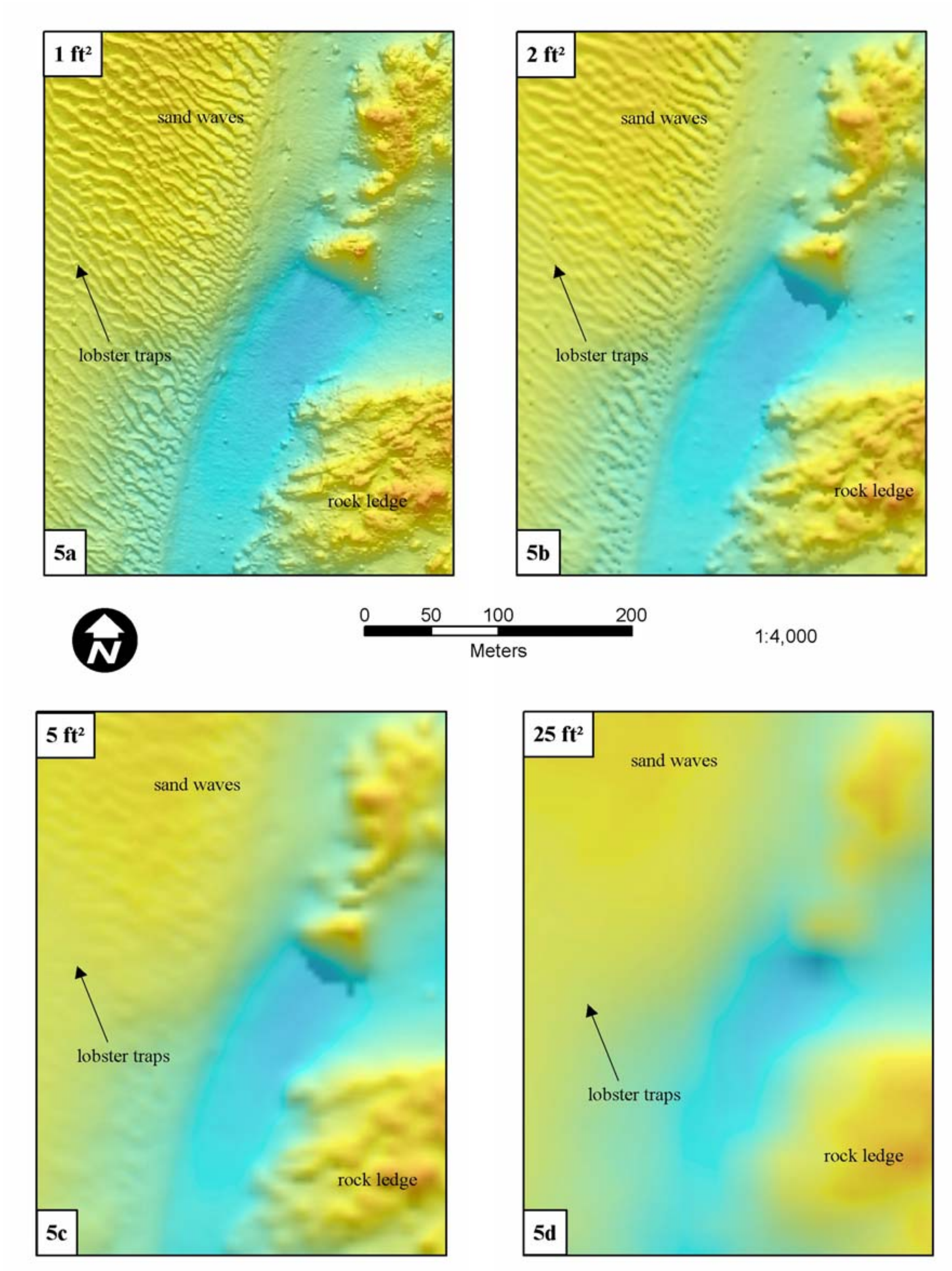


Figure 5. Multibeam bathymetric data showing affect of data resolution on visualizing benthic habitat at different spatial scales. Hillshade is from the North (000°) at 30° declination. Depths are vertically exaggerated 5x.

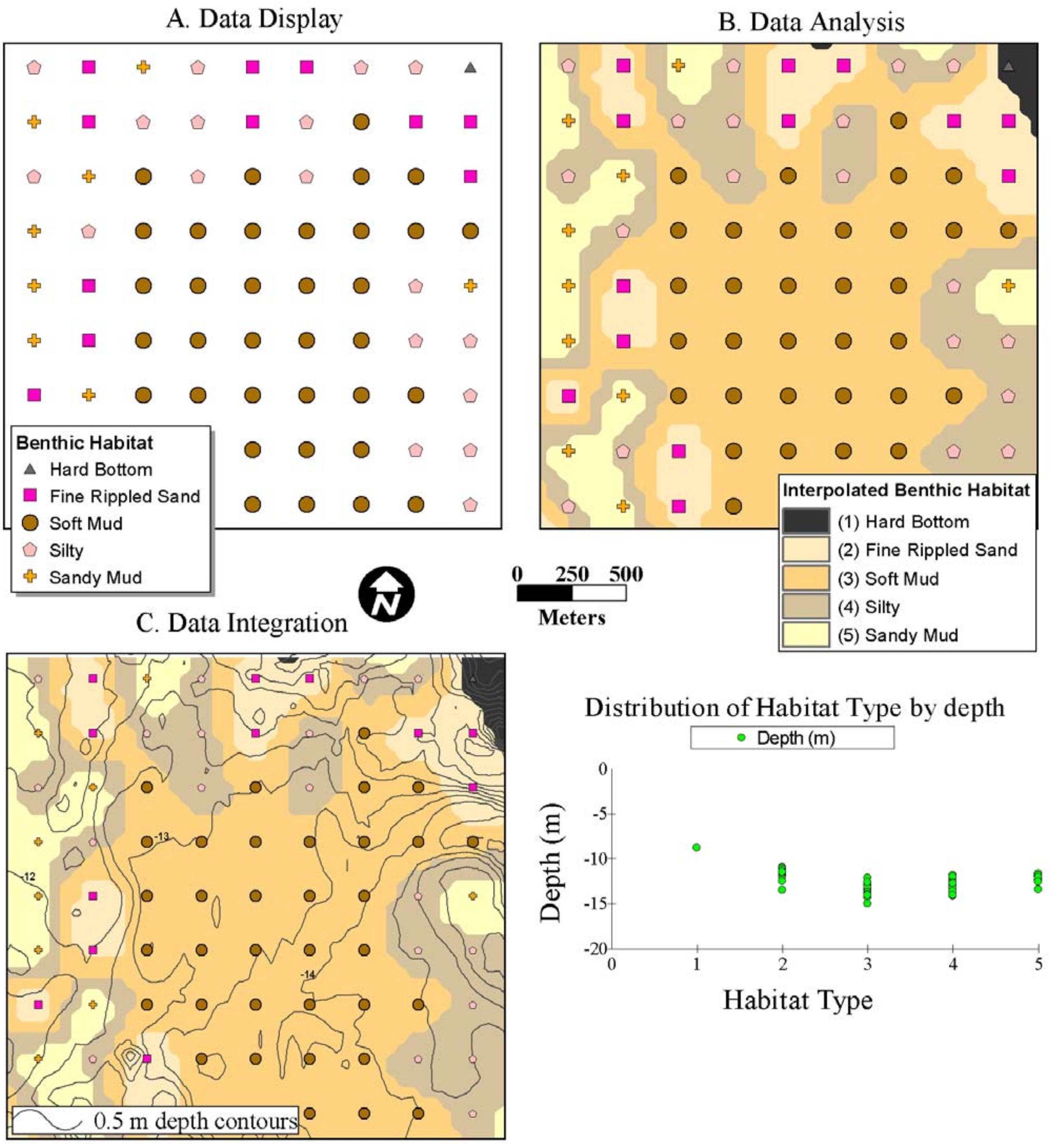
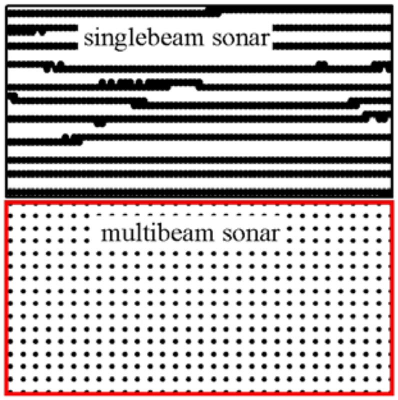
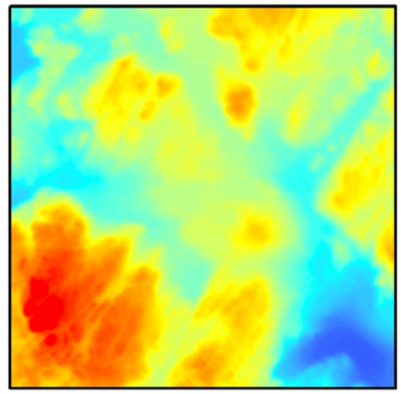


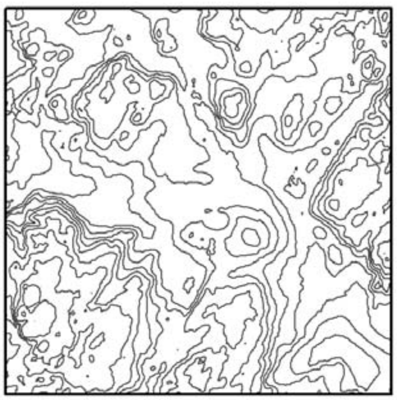
Figure 6. Examples of differences among data display, data analysis and data integration of benthic habitat data. Display of point data showing sediment type from SPI results (5a) is limited to sample points. Interpolation of point data into raster data (5b) facilitates understanding and analysis of sediment type as continuous feature (i.e. habitat). Relationship between sediment type and depth can be calculated through integration and queries of additional benthic data (5c) (i.e., bathymetry).



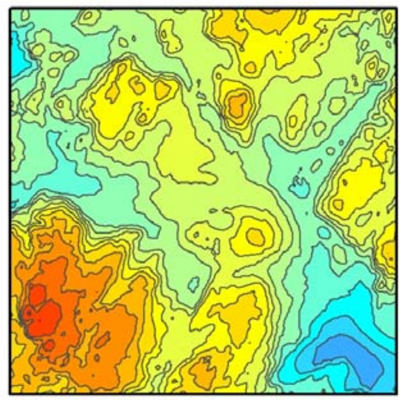
a) bathymetric point data from single-beam and multibeam sonar



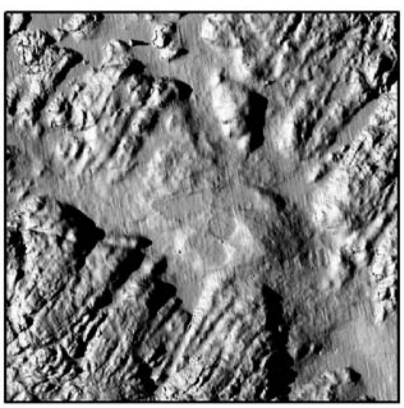
b) multibeam bathymetric grid (raster)



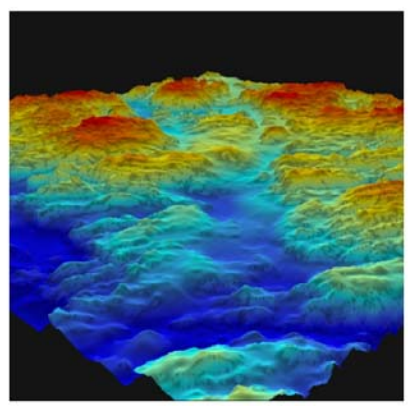
c) 2 meter bathymetric contours from multibeam bathymetric grid



d) Integration of 2 meter bathymetric contours and multibeam bathymetric grid



e) 2D Sun illuminated hillshade of multibeam bathymetric grid



f) 3D Sun illuminated hillshade of multibeam bathymetric grid

Figure 7. Figures showing different techniques for display and analysis of bathymetric data. Bathymetric point data (a) converted to a raster (b) can be queried to derive additional data such as depth contours (c). Integrating the raster and the vector forms of the same data can be more effective than separate display (d). Two-dimensional hillshading (e) and three-dimensional visualization (f) provide further types of visualization for benthic habitats.

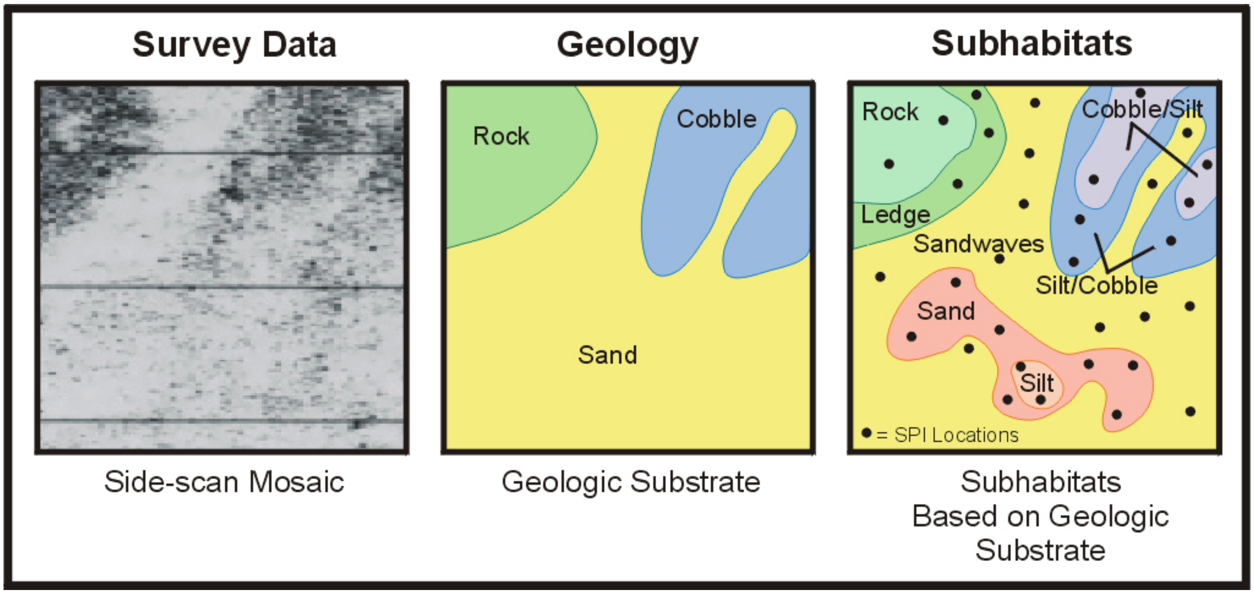
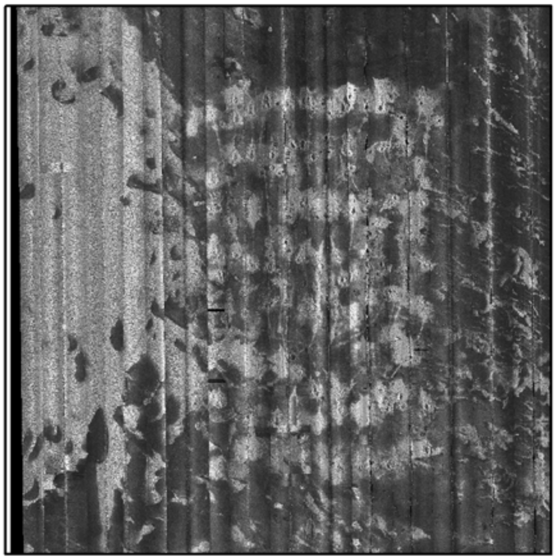
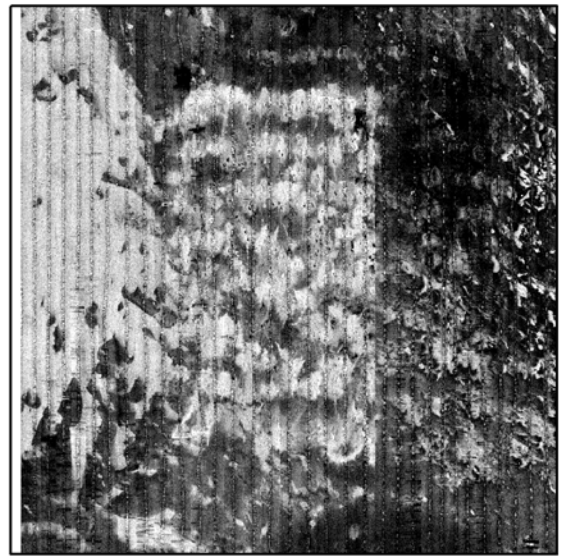


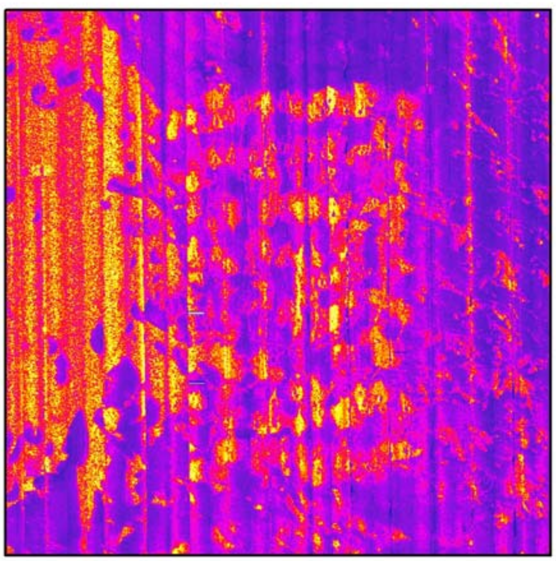
Figure 8. Figures illustrating delineation of geologic substrate from side-scan sonar mosaic and subsequent delineation of sub habitats using higher resolution SPI samples.



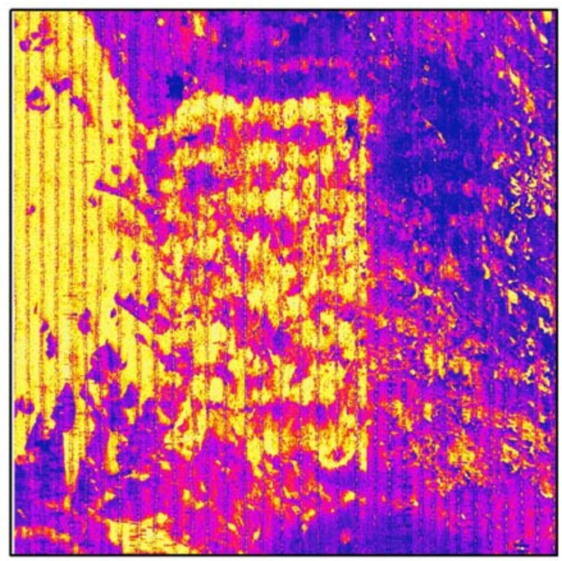
a) Side-scan mosaic



b) Multibeam backscatter data



c) False colored side-scan mosaic



d) False colored multibeam backscatter data

Figure 9. Comparison of side-scan and multibeam sonar data showing differences in data continuity. The towed side-scan data is more difficult to analyze because of noise from lane overlap and no data values below sensor (a&c). Patterns of sediment distribution are easier to visualize in the multibeam backscatter data (b&d).

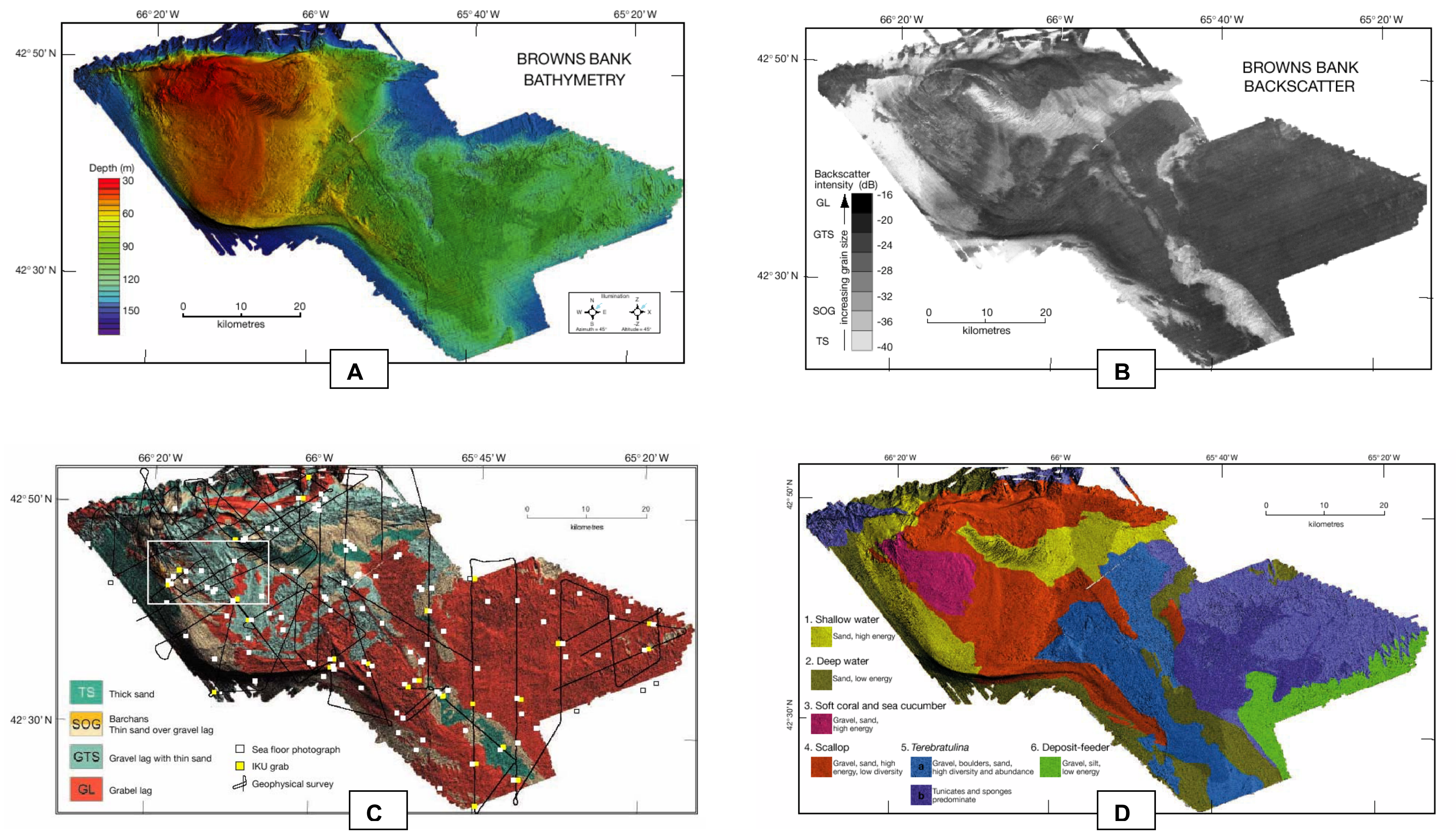
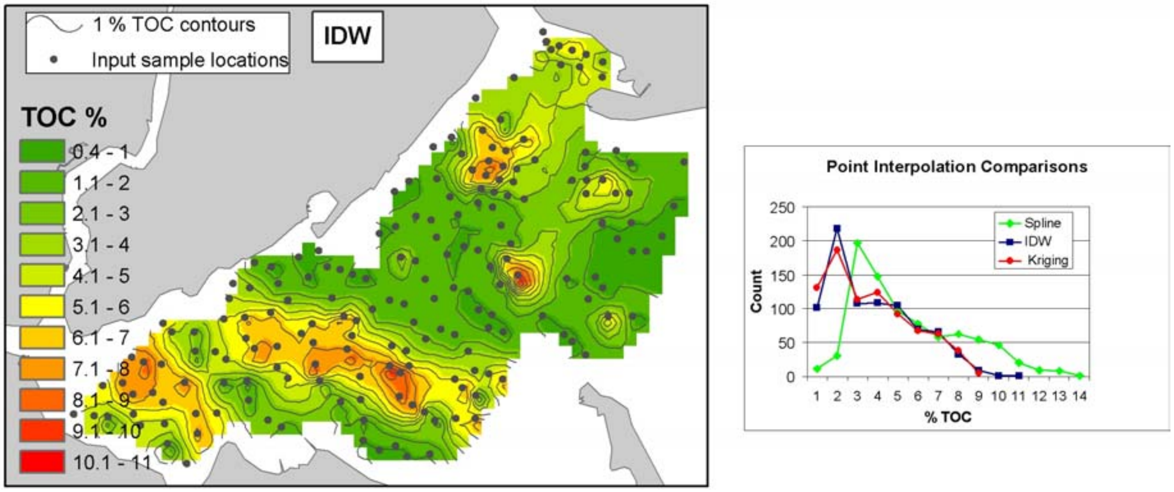
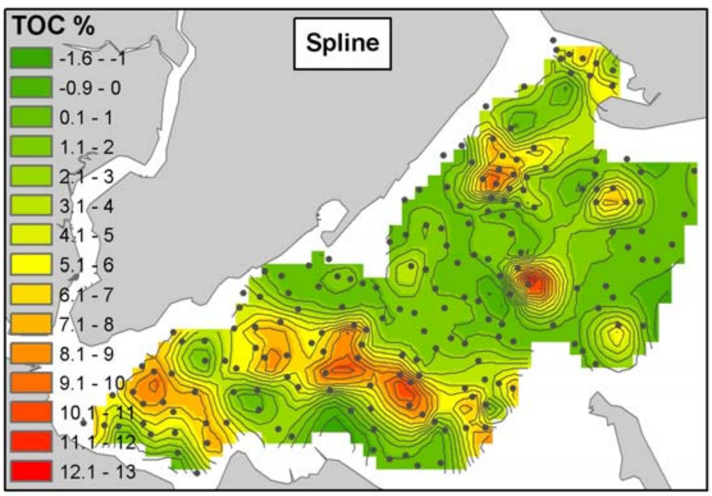


Figure 10. Examples of benthic habitat mapping from Kostylev et al. 2001. High resolution multibeam depth (a) and multibeam backscatter data (b), were analyzed with sea floor photographs, sediment grabs and geophysical data to generate map of geologic substrate and benthic habitats (d) on Browns Bank on the Scotian Shelf off the eastern coast of Canada.





	Input Data	IDW	Spline	Kriging
Count	189.0	821.0	821.0	821.0
Min	0.3	0.4	-1.6	0.2
Max	11.4	10.5	12.0	8.9
Sum	642.0	2676.4	2500.0	2600.0
Mean	3.4	3.3	3.0	3.2
SD	3.0	2.1	2.7	2.1

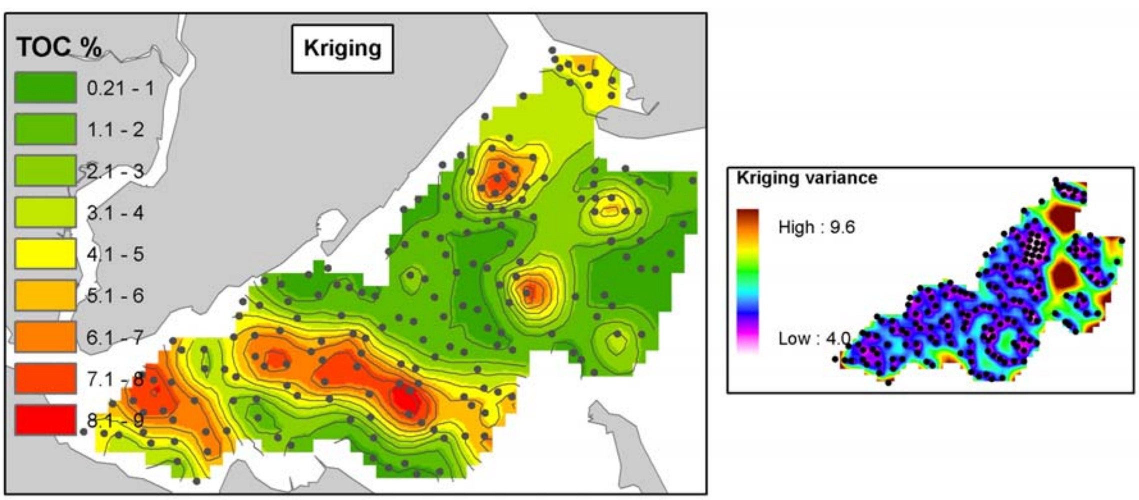


Figure 11. Comparison of different point interpolation techniques. Inverse distance weighted (IDW), spline, and kriging.

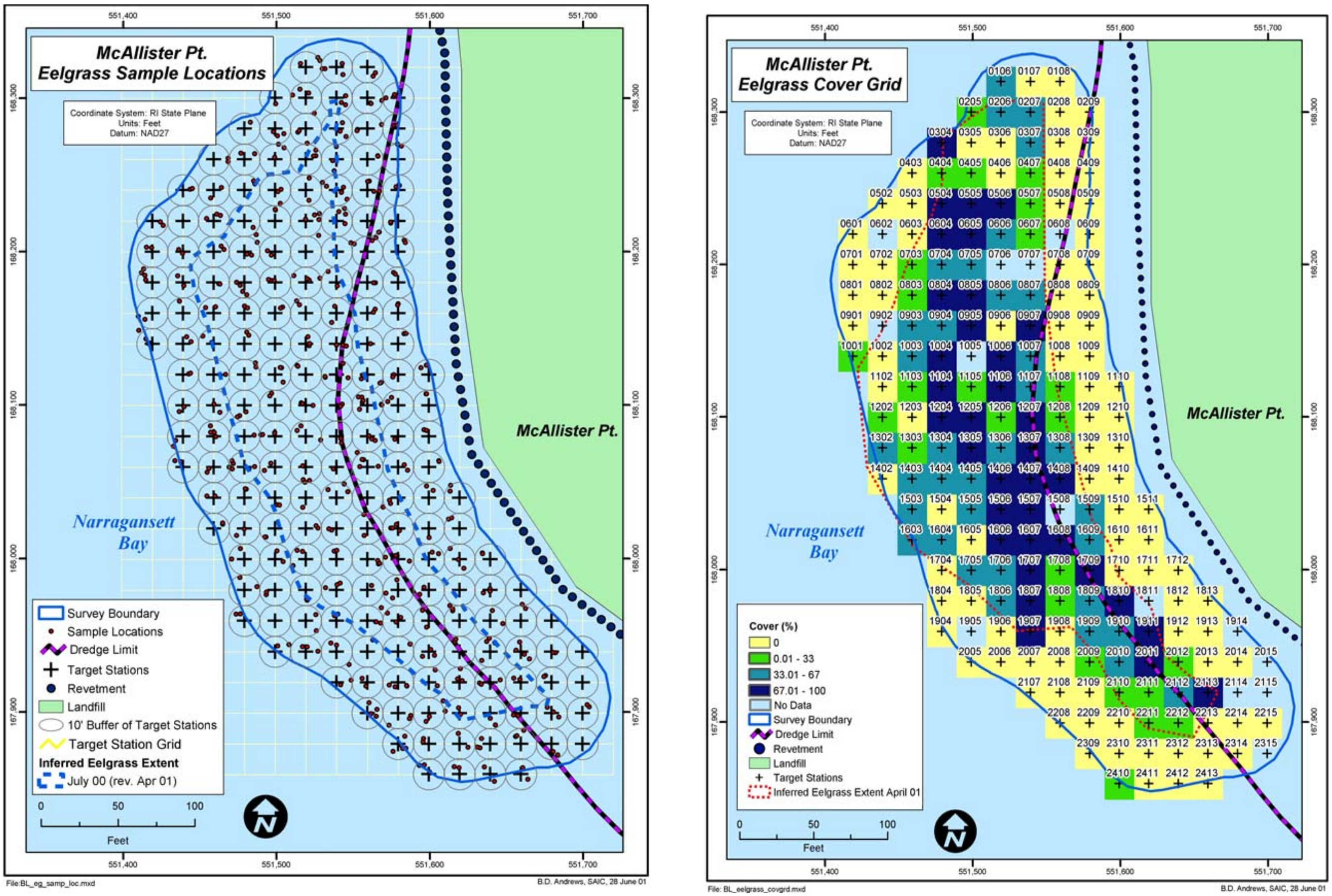


Figure 12. Example data collection and analysis methodology for eelgrass monitoring using plan view photography.