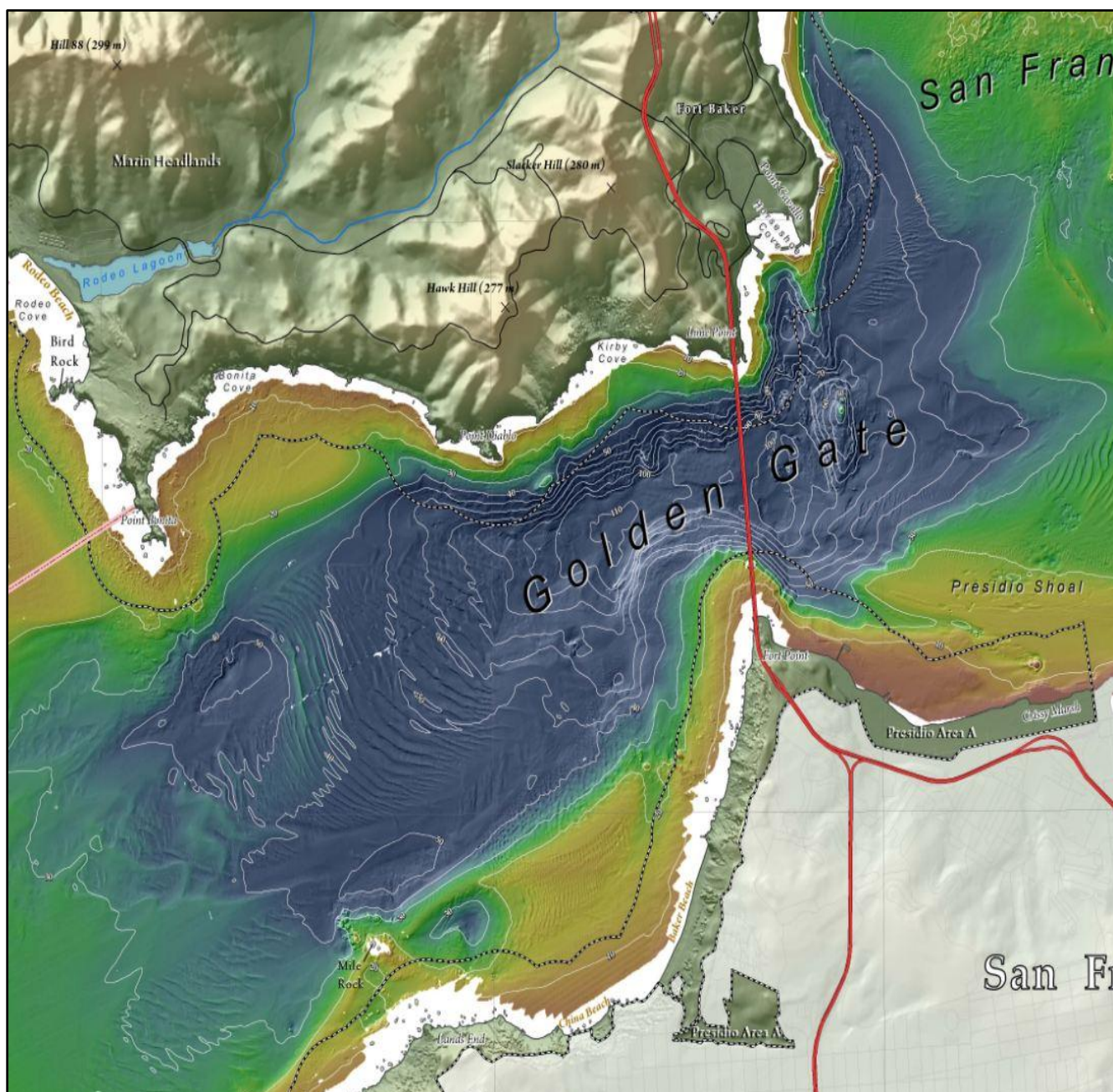




Benthic Mapping Guidance Document

Lessons Learned from NPS Benthic Mapping Pilot Projects

Natural Resource Report NPS/NRSS/WRD/NRR—2013/682



ON THE COVER

Acoustic multibeam echosounder data were used to create this color-coded bathymetry map (with contour lines) showing depth and seafloor features in the entrance to San Francisco Bay, Golden Gate National Recreation Area, CA. Dynamic sand waves seaward of the Golden Gate Bridge are up to 6 m (20 ft) high. These sedimentary features are shaped and modified on a daily basis by strong tidal currents flowing in and out of the bay. Other features such as rock outcrops, dredge scours, outflow pipes and shipwrecks are visible in the imagery. The map was compiled in 2009 by Charlie Endris, Gary Greene, Bryan Dieter and Eric Niven, with contributions from Patrick Barnard and Eleyne Phillips (Greene et al., 2009).

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Natural Resource Report NPS/NRSS/WRD/NRR—2013/682

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Fort Collins, Colorado

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All manuscripts in the series receive the appropriate level of peer review to ensure that the information is scientifically credible, technically accurate, appropriately written for the intended audience, and designed and published in a professional manner.

Data in this report were collected and analyzed using methods based on established, peer-reviewed protocols and were analyzed and interpreted within the guidelines of the protocols.

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Executive Summary

The National Park Service (NPS) has 85 ocean, coastal and Great Lakes parks with more than 11,000 miles of shoreline and 2.5 million acres of marine and estuarine areas across 22 States and four U.S. territories. Benthic habitat data and maps are lacking for most of these parks, but are essential for understanding and managing park resources.

From 2008 to 2011, the NPS Inventory and Monitoring (I&M) Program provided funding for benthic mapping pilot projects in 10 parks. The pilot projects, which were managed by the NPS Ocean & Coastal Resources Branch (OCRB), were chosen based on geographic, ecosystem, and partner diversity, and included parks in Alaska, California, Great Lakes, Gulf of Mexico, and Caribbean.

The objective of this report is to review the OCRB benthic mapping pilot projects, distill the lessons learned and provide guidance for parks wishing to embark on their own benthic mapping projects. A description of benthic mapping technologies is provided to give readers a basic understanding of the major challenges and decisions that should be considered before undertaking benthic habitat mapping.

Acknowledgements

The pilot benthic mapping projects described in this document would not have been possible without funding from the National Park Service Inventory & Monitoring Program (I&M). We thank Steve Fancy, chief of I&M when pilot project funding was approved, for his support. We also thank Julia Brunner and Rebecca Beavers of the National Park Service Geological Resources Division who, as acting chiefs of the Ocean and Coastal Resources Branch, selected the 2008 pilot projects and developed the interagency agreements necessary to execute the projects with cooperators.

Acronyms and Abbreviations

AGDS – acoustic ground discrimination systems
ASIS – Assateague Island National Seashore, Maryland and Virginia
ASTER – Advanced Spaceborne Thermal Emission and Reflection Radiometer (NASA satellite)
ASV – autonomous surface vehicle
ATRIS – Along-Track Reef Imaging System (bottom visualization system)
AUV – autonomous underwater vehicle
AVHRR – Advanced Very High Resolution Radiometer (NOAA satellite)
BB – Biogeography Branch of NOAA’s Center for Coastal Monitoring and Assessment
BISC – Biscayne National Park, Florida
BUIS – Buck Island Reef National Monument, U.S. Virgin Islands
CACO – Cape Cod National Seashore, Massachusetts
CANA – Canaveral National Seashore, Florida
CHIS – Channel Islands National Park, California
CMECS – Coastal and Marine Ecological Classification Standard
CSMP – California State Mapping Program
DRTO – Dry Tortugas National Park, Florida
FGDC – Federal Geographic Data Committee
FY – fiscal year
GGNRA – Golden Gate National Recreation Area, California. This is the acronym used in the final report for the benthic mapping pilot project (Greene, et al., 2009). Also see GOGA.
GIS – geographic information system
GLBA – Glacier Bay National Park and Preserve, Alaska
GOGA – Golden Gate National Recreation Area, California. This is the National Park Service unit code. Also see GGNRA.
GPS – global positioning system
GUIS – Gulf Islands National Seashore, Florida and Mississippi
GV – ground validation
HAE – height above ellipsoid
I&M – National Park Service Inventory & Monitoring Program
IKONOS – Commercial high-resolution satellite operated by GeoEye; not an acronym
IMAC – Inventory & Monitoring Program Advisory Committee
IMU – inertial measurement unit
IRMA – integrated resource management application
km – kilometer
kn – knots. One knot equals one nautical mile per hour (~1.15 miles per hour).
Lidar (also LiDAR or LIDAR) – Light Detection and Ranging; a technique that emits pulses of laser light to determine elevation or bathymetry values.
LED – light emitting diode
m – meter
m/s – meters per second
MBES – multibeam echo sounder
MHW – mean high water
MHHW – mean higher-high water
MLW – mean low water

MLLW – mean lower-low water
 MMU – minimum mapping unit
 MsCIP – Mississippi Coastal Improvement Project
 MSL – mean sea level
 MWL – mean water level
 NAD83 – North American Datum of 1983
 NASA – National Aeronautics and Space Administration
 NAVD88 – North American Vertical Datum of 1988
 NGOM – Northern Gulf of Mexico
 NGOM-ECHS – Northern Gulf of Mexico Ecosystem Change and Hazard Susceptibility project
 NGS – National Geodetic Survey
 NOAA – National Oceanic and Atmospheric Administration
 nm – nanometer
 NPS – National Park Service
 NSRS – National Spatial Reference System
 OCRB – NPS Ocean and Coastal Resources Branch, Water Resources Division, Fort Collins, Colorado
 PORE – Point Reyes National Seashore, California.
 PORES – acronym used in the final PORE benthic mapping report (Greene et al., 2011).
 PDBS – phase differencing bathymetric sonar, also referred to as interferometric sonar
 PI – principal investigator
 QC – quality control
 ROV – remotely operated vehicle
 SAJH – San Juan Island National Historical Park, Washington
 SAV – submerged aquatic vegetation
 SBMP – Servicewide Benthic Mapping Program
 SLR – sea level rise
 Sonar (also SoNAR) – Sound navigation and ranging; a technique that propagates sound waves to determine depth and surface qualities of the seafloor.
 SPI – sediment profiling imagery
 SST – sea surface temperature
 USACE – United States Army Corps of Engineers
 USGS – United States Geological Survey
 VICR – Virgin Islands Coral Reef National Monument, U.S. Virgin Islands
 VIIS – Virgin Islands National Park, U.S. Virgin Islands

Introduction

Managers of coastal and marine national park units are facing ever increasing impacts from coastal development, increased recreational use, altered upland runoff, non-native species invasions, and a multitude of other potentially resource altering influences in carrying out their management responsibilities. To effectively address these issues, a complete and comprehensive understanding of the type, geographic extent, and condition of marine resources included within their park is necessary. However, such understanding is often difficult to obtain when dealing with marine resources. Unlike in terrestrial parks, marine area managers and others cannot readily observe their resources. Their most spectacular topography and geographic features are hidden from casual view and may only be detected and even become known with systematic, [technically challenging and expensive] detailed surveys. In terrestrial parks, the location of forests, meadows, marshes, and other vegetative communities are readily observable and quickly included in a park's index of habitat types present. Within marine parks, only the most general knowledge and vague understanding of the extent, nature and general health of the biological communities present is known until detailed benthic surveys and species inventories are completed. Within terrestrial parks, casual daily observations by park staff and others can often provide a good general understanding of wildlife activity patterns, areas of importance, and general abundance of the most common species. However, within marine parks, even the most basic determination of common species present usually requires a rather comprehensive and expensive systematic inventory to determine (Tilmant et al., 2007)

The National Park Service (NPS) manages 85 ocean, coastal and Great Lakes parks comprising more than 11,000 miles of shoreline and 2.5 million acres of marine and estuarine areas across 22 States and four U.S. territories (Curdts, 2010)¹. Benthic habitat data and maps are lacking for most of these parks, but are essential for understanding and managing NPS resources. Habitat maps in marine and coastal systems, like maps of forests, grasslands and streams in terrestrial systems, are the foundation for ecosystem-based management and for detecting and monitoring human-caused changes. Without habitat inventories and maps, park managers cannot locate, let alone manage, their natural resources.

In December 2006, the NPS Inventory and Monitoring (I&M) Program Advisory Committee (IMAC) recognized that mapping ocean, coastal and Great Lakes resources required a dedicated program to address the complex nature of the data collection, processing, and interpretation. The IMAC recommended establishing a Servicewide Benthic Mapping Program (SBMP) with a long-term resource commitment from the NPS I&M program. A three-day workshop was held in 2008 where 45 coastal and marine managers and experts met to clarify the needs and goals of a SBMP (Moses et al., 2010a). Despite IMAC's recommendations, early planning efforts and a clear need, NPS did not establish the SBMP. The I&M Program did provide short-term funding

¹ Fort Monroe National Monument (VA) was included in the National Park System after the publication of Curdts (2010), which reported on 84 ocean, coastal and Great Lakes park units.

for several park-specific benthic mapping pilot projects that were managed by the NPS Ocean & Coastal Resources Branch (OCRB).

The objective of this report is to review the OCRB pilot benthic mapping projects conducted from 2008 to 2012, distill the lessons learned, and provide guidance for parks wishing to embark on their own benthic mapping projects. A brief description of benthic mapping technologies is provided to give readers a basic understanding of the major challenges and decisions that should be considered before undertaking benthic habitat mapping.

Benthic Mapping Technologies

A variety of technologies is available for benthic mapping, each with its own strengths and weaknesses. The technologies and techniques are constantly evolving, and a comprehensive technical description of all the tools and technologies is beyond the scope of this report. However, a basic understanding of these technologies is necessary to plan a benthic mapping project. Following is a primer on benthic mapping technologies.

While the ability to produce benthic maps depends on existing technologies, the mapping objectives should be the primary driver of the project, not the existing technologies. Some benthic mapping technologies are well tested and reliable, while others are rapidly advancing and experimental. The fundamental technologies fall into a few basic categories: satellite and airborne imagery, ship-based acoustic data, and bottom visualization and sampling (Figure 1) (Moses et al., 2010a; Hart et al., 2010).

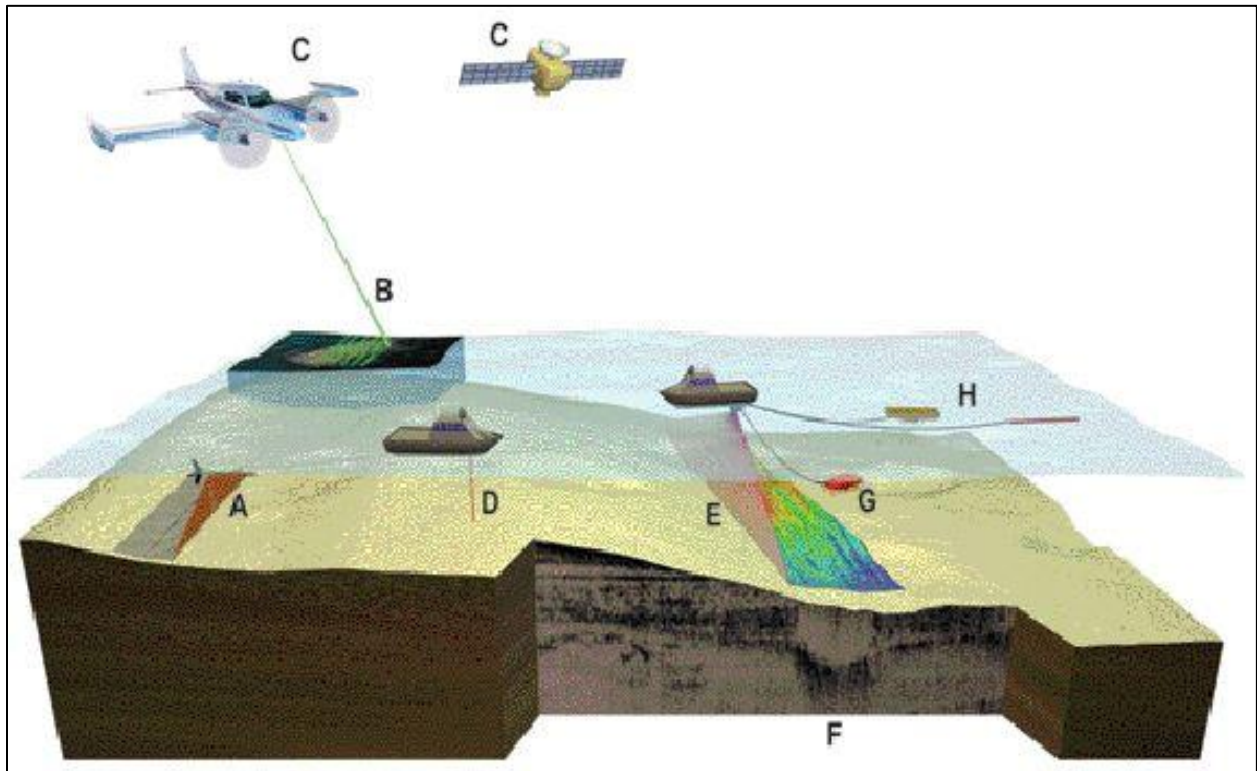


Figure 1. Diagram illustrating the basic types of remote sensing technologies with application to benthic habitat mapping. (A) Sidescan sonar; (B) Lidar; (C) Color aerial or satellite imagery; (D) Single-beam sonar; (E) Multibeam or swath sonar; (F) Seismic acquisition; (G) Bottom visualization; (H) water column data collection, and other devices (from Moses et al., 2010a).

Satellite and Airborne Imagery

For imagery based on visible light, the effectiveness for benthic mapping is determined by the ability to detect the bottom and distinguish features of interest, which depends on surface conditions, sun angle, water clarity, water depth, and the amount of contrast between bottom features. Under ideal conditions, imagery based on visible light is typically limited to water depths <30 m (98 ft).

Imagery collected from satellite and airborne platforms is useful for studying a range of ocean and coastal features, such as bottom structure, habitat, shoreline changes, sea surface temperature (SST), and harmful algal blooms over scales ranging from $<1 \text{ m}^2$ (11 ft^2) to 100 km^2 (37 mi^2) or more. Airborne sensors can generally provide higher resolution imagery than satellites because the distance to the target is shorter, but options for sub-meter satellite imagery are increasing as new sensors are developed. Airborne lidar (discussed below) is commonly used to create bathymetric data in clear, shallow water. Under certain conditions, a combination of satellite or aerial imagery and ground/depth truth data can be used to derive bathymetry data (PCI, 2002; Deidda and Sanna, 2012; Vanderstraete et al., 2003).

Multispectral sensors measure the energy in several discrete sections (bands) of the visible and the infrared portions of the electromagnetic spectrum. Infrared data are useful for terrestrial vegetation mapping and necessary for SST measurements, but are not as useful for mapping submerged aquatic vegetation because water absorbs most infrared light. Multispectral sensors like the NASA Moderate Resolution Imaging Spectrometer (MODIS) and the NOAA Advanced Very High Resolution Radiometer (AVHRR) satellites provide SST and information on bottom features with a spatial resolution of $\sim 1 \text{ km}$ (0.6 mi). Higher resolution multispectral sensors, such as Landsat [30-m (98-ft) spatial resolution] and IKONOS (4-m [13-ft] spatial resolution), can be used to map submerged resources in clear, shallow waters. WorldView-2, launched in 2009 by DigitalGlobe, is a high resolution (0.5 m [1.6 ft] panchromatic and 2.0 m [6.6 ft] multispectral) 8-band multispectral commercial satellite. It is unique among current commercial satellites in that it has a blue “coastal” band (400–450 nm) designed specifically for water penetration and coastal applications (Digital Globe, 2010).

Under favorable conditions, satellite and airborne sensors can collect consistent benthic mapping data over large areas of clear, shallow water in a short time. This is a distinct advantage over ship-based surface and subsurface data collection techniques because it eliminates navigational hazard issues as well as many data collection and processing challenges associated with shallow water (discussed below). Satellite and airborne sensors are ineffective in optically deeper waters (deep and/or turbid) where light cannot penetrate and acoustic technologies provide the primary benthic data collection capabilities.

Digital Orthoimagery

Orthoimagery is remotely sensed imagery (aerial or satellite) from which distortions due to sensor tilt and topographic relief have been removed. It combines the visual content of a photograph with the geometric properties of a map from which distance and area can be accurately measured. Orthoimagery can be a useful tool for delineating and mapping benthic cover in areas with clear, shallow water and calm surface conditions.

Lidar

Lidar (light detection and ranging) is analogous to radar (radio detection and ranging) and sonar (sound navigation and ranging), except that it is based on light pulses (instead of radio or sound waves) and precisely measured travel times. Lidar, radar, and sonar are referred to as active remote sensing technologies because the energy used to measure distances is generated by the systems. Since active remote systems are not dependent on ambient light, they can be used at night when the air is often clearer and air traffic is reduced. But unlike radar, lidar cannot penetrate clouds, rain, dense haze, or turbid water, and must be flown during fair weather (NOAA Coastal Services

Center, 2008). Current research on turbidity-penetrating lidar looks promising, but is not yet operational.²

Lidar technology was developed in the 1970s as a ground-based system to measure particles in the atmosphere. The development of the Global Positioning System (GPS) and extremely accurate and precise GPS receivers and inertial measurement units (IMUs) made airborne lidar possible by allowing the absolute positioning of the rapidly moving airborne laser.

Lidar creates bathymetric data sets by bouncing a green laser signal off the ocean floor. Even though the green laser penetrates water better than a red laser (typically used in terrestrial lidar systems), effective use of bathymetric lidar is limited to optically shallow water. Lidar devices are typically mounted on aircraft, although they can also be ship-mounted or ground-based. One advantage of lidar systems is that they can be used over land as well as over water, allowing simultaneous mapping of topography/bathymetry across the terrestrial-marine transition. Depending on the needs, laser system, and environmental conditions, horizontal spatial resolution can range from sub-meter to 10 m (33 ft), and vertical precision of 10-15 cm (4-6 in) can be obtained. Lidar has been used successfully to map U.S. coastlines and submerged lands, including projects in several national parks (e.g., Dry Tortugas National Park [Brock, et al., 2006]; Gulf Islands National Seashore [Brock, et al., 2007]).³

Ground-based lidar systems yield higher spatial resolution (~0.1 m; 4 in) and are generally less expensive to set up and operate, but have a limited range and are most effective in smaller study areas. Ground-based lidar is traditionally used to map facilities and infrastructure where shots of the same features, taken from multiple angles, produce precise 3-D models. Ground-based systems can be useful for mapping features in the intertidal and coastal zones, especially cliffs and vertical features that would be difficult to map with aerial techniques (Storlazzi et al., 2007). The systems can be mounted on vessels to map bluffs and other coastal landforms from the water. The instruments can be part of an acoustic, vessel-based survey where marine and terrestrial resources are mapped simultaneously using acoustic and laser technologies, respectively.⁴

Acoustic Technologies

Several different acoustic technologies provide imaging capabilities of the ocean floor in areas where light cannot penetrate. In deep or turbid waters, data can be gathered about bottom depth, seafloor hardness (induration), and seafloor roughness (rugosity). Information about bottom composition (e.g., mud, sand, rock) can be derived from induration and rugosity data.

Multibeam Sonar

Multibeam echo sounder (MBES) instruments transmit hundreds of sound beams arranged in a fan-like swath and, similar to radar and lidar, measure the time it takes for the signal to go out, reflect off of the target, and return to the sensor. The transit time, angle, and intensity of the reflected signals yield information about water depth, seafloor rugosity, and induration. High-resolution, three-dimensional models of the seafloor can be created from the data, which allow visualization of bottom topography. The width of the swath is proportional to water depth and an

² Tim Battista, NOAA Biogeography Branch, personal communication, May 16, 2012.

³ For additional USGS Open-File Reports about lidar projects in coastal national parks, see <http://ngom.usgs.gov/dsp/pubs/ofr/index.php>.

⁴ Mark Borelli, Provincetown Center for Coastal Studies, personal communication, April 30, 2013.

MBES swath is typically limited to 3-5 times water depth for high-quality data (Gostnell et al., 2007). This makes MBES systems particularly useful in deep water where their swaths are wider, and less efficient in shallow water (<15 m [49 ft]) where full bottom coverage requires closely spaced transect lines.

Sidescan Sonar

Sidescan sonar is a viable option for shallow-water data collection. It operates on the same principles as MBES systems, but has a wider swath, is typically towed behind the vessel, and is configured to look to the side rather than down. Sidescan can provide high-resolution seafloor imagery in a wide swath, and can identify three dimensional bottom features based on their acoustic shadow.

Traditional sidescan systems do not collect bathymetric data. The high quality imagery is a valuable tool for interpreting sea floor characteristics, but data from towed instruments (“towfish”) are difficult to precisely geo-reference (Finlayson, 2008).

Interferometric Sonar

Interferometric sonar, also known as phase differencing bathymetric sonar (PDBS), is particularly useful in shallow water because its swath is wider (10-15 times water depth) than an MBES swath. PDBS systems can image an area with fewer passes, which is safer and more efficient, since the survey vessel spends less time in shallow, potentially dangerous areas. In one test, the PDBS system had a survey line spacing of 20-30 m (66-98 ft) in ~2 m (6.6 ft) of water, while a multibeam system had a survey line spacing of only 7 m (23 ft) in the same area (Gostnell et al., 2007). However, there are higher levels of uncertainty and decreased quality associated with the returns in the outer portion of a PDBS swath. While it may be appropriate to use the full swath of 10-15 times the water depth for some applications, the reduced quality of the outer swath would not be appropriate for habitat mapping. The increase in efficiency gained by the wide swath comes at a price in the form of less accurate habitat information in the outer swath. For habitat mapping, PDBS data are typically reliable out to about 3-5 times the water depth.⁵

Another feature of PDBS systems that make them well-suited for shallow water is their ability to collect sidescan sonar imagery, while simultaneously capturing collocated swath bathymetry. The ability to use one instrument to collect data previously requiring two instruments (MBES and traditional sidescan sonar) increases efficiency and reduces cost and effort. Collocation of the two data sets during collection eliminates the time-consuming process of merging the two datasets, with the inherent difficulties and unavoidable increase in positional uncertainty. However, PDBS systems are not as useful in deeper waters (>15-20 m; 49-66 ft) because the instrument needs to be close to the bottom to collect sidescan sonar imagery at useful resolutions. In these instances, towed sidescan sonar is still preferred. Advances in deeper-water PDBS systems are being seen in these developing technologies.⁶

NOAA is moving away from discrete soundings and toward surfaces as a final survey product of domestic nautical surveys. Recent advances in PDBS technology have reduced the differences between surfaces generated by PDBS and surfaces generated by MBES, making the use of PDBS feasible for surface generation. However, a significant weakness of PDBS is a higher level of uncertainty in the discrete soundings depth data compared with MBES data. “With a standard deviation approximately twice that of MBES, using discrete soundings from PDBS may not yet be

⁵ Bryan Costa and Tim Battista, NOAA Biogeography Branch, personal communication, May 16, 2013.

⁶ Mark Borelli, Provincetown Center for Coastal Studies, personal communication, April 30, 2013.

advisable but may become possible as algorithmic advances are made” (Gostnell et al., 2007:9). For this reason MBES is preferred over PDBS technology for mapping discrete objects (e.g., cultural artifacts and navigational hazards).

Single-beam Sonar

Single-beam sonar is a down-looking system that can accurately determine depth directly beneath the vessel. Some systems can also determine bottom texture by analyzing multiple returns of the sonic pulse. The systems are said to have waveform-resolving capabilities and are sometimes referred to as acoustic ground discrimination systems (AGDS) (Moses et al., 2010b). Single-beam systems are relatively inexpensive and easy to deploy, but collect low-resolution data in a very narrow beam beneath the vessel, leaving most of the seafloor unmapped in a typical mission (Figure 2).

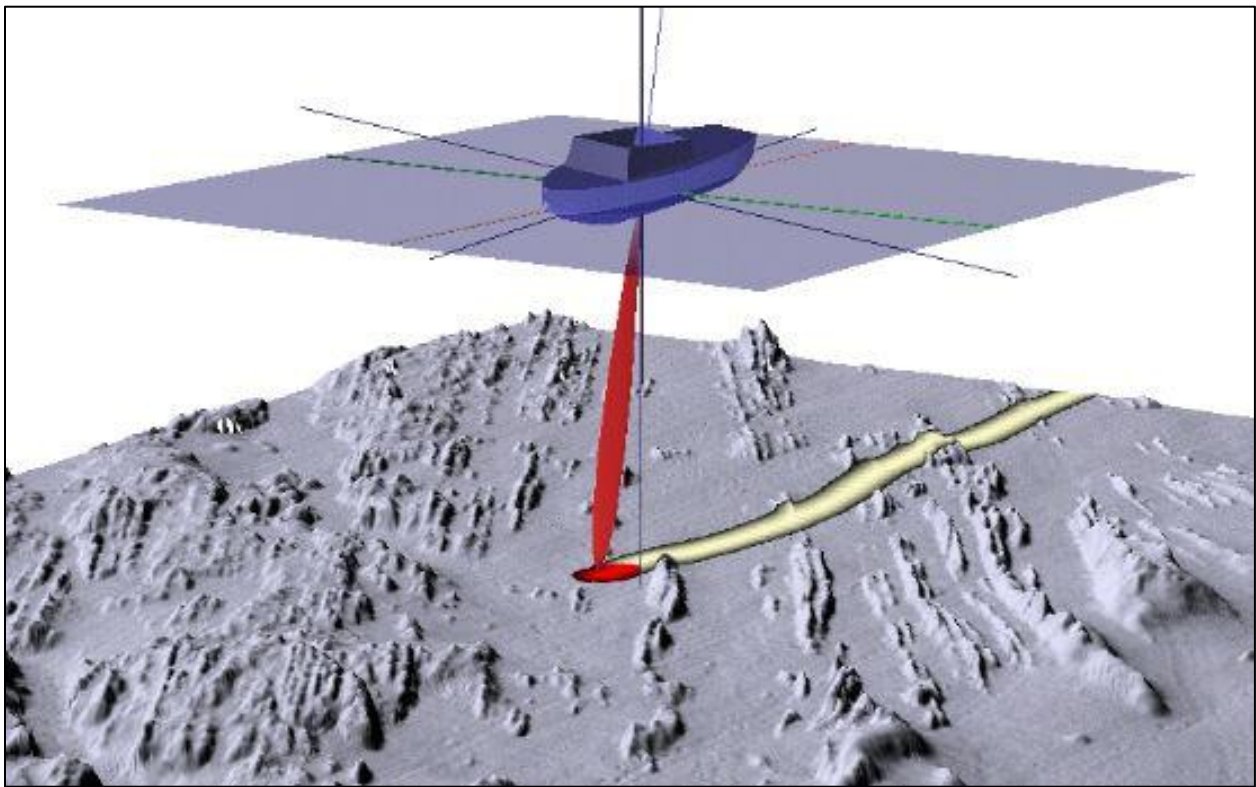


Figure 2. Single-beam sonar schematic (from Finlayson, 2008).

Bottom Visualization and Sampling Systems

All of the remote sensing methods (except land-based lidar) discussed above can be applied over large geographic areas. Small, discrete samples can be collected from benthic habitats with point and transect sampling methods. The techniques can collect physical samples (e.g., core or grab samples of bottom sediments) or images (still or video), and can yield detailed information on bottom type and condition and biological and chemical processes. The methods can be used as ground-truthing validation techniques or, depending on sampling density and extent, can be used to produce a map through statistical interpolation (Finkbeiner et al., 2001).

Drop, Towed and Scuba Camera Systems

It is often desirable to collect images of the bottom, either as a primary data sampling technique or to validate classifications of large areas derived from remotely sensed data. There are various imaging techniques, ranging from technologically simple (scuba divers or snorkelers with hand-held cameras) to technologically advanced (autonomous underwater vehicles [AUVs]). A common technique is a remotely operated camera (still or video) that is either towed behind or lowered beside the vessel (drop camera), or deployed on a remotely operated vehicle (ROV) or AUV.

The Along-Track Reef Imaging System (ATRIS), developed by the USGS Coastal and Marine Geology Program in St. Petersburg, FL, is an example of a bottom-imaging camera system that can either be mounted directly to the vessel for shallow-water operations (2-10 m; 7-10 ft) or towed at up to 27 m (89 ft) depth for moderate-depth operations. The system can be towed at speeds of up to 2.6 m/s (5.1 kn) permitting much greater coverage than validation using divers. The camera system records high-resolution digital images (Figure 3) at 20 frames/s with a GPS location recorded for each image to ensure spatially accurate image placement. The system is equipped with LED lights to adjust for light absorption at moderate depth. The system was developed to validate remotely sensed data, but has evolved into a primary data collection system (Moses et al., 2010b).

Two other bottom-visualization systems are built and operated by the Bedford Institute of Oceanography (BIO) in Canada. Towcam is a towed video camera system designed to be deployed 2-4 m (6-13 ft) above the bottom and towed at 4-8 km/hr (2-4 kn). With a working depth of 150 m (493 ft), Towcam can record continuous video of a swath 1-2 m (3.3-6.6 ft) wide. Towcam also includes a digital still camera with a strobe that can record one high-resolution digital still image every 3-4 seconds. Videograb is another bottom-visualization system operated by BIO that consists of a hydraulic bottom grab with mounted video cameras. The operator can select the precise sampling area and validate a successful grab before retrieving the instrument. The video camera is slightly forward looking to assist the operator's depth perception (Moses et al., 2010b).

Seaviewer Sea-Drop 950 is an example of a relatively simple video drop camera system (Figure 4) that was used for accuracy assessment in the St. John Shallow Water Benthic Mapping project. Location data were logged separately with a Trimble GeoXT GPS receiver on the vessel. Each site was categorized from the video images based on a map classification scheme (Zitello et al., 2009).

Benthic Grab and Core Sampling

Grab and core sampling techniques collect physical samples of the bottom that can be used to identify and measure bottom characteristics, such as sediment type, organic content, grain size and benthic in-fauna. They are limited by their inability to sample areas with hard substrate (Finkbeiner et al., 2001).

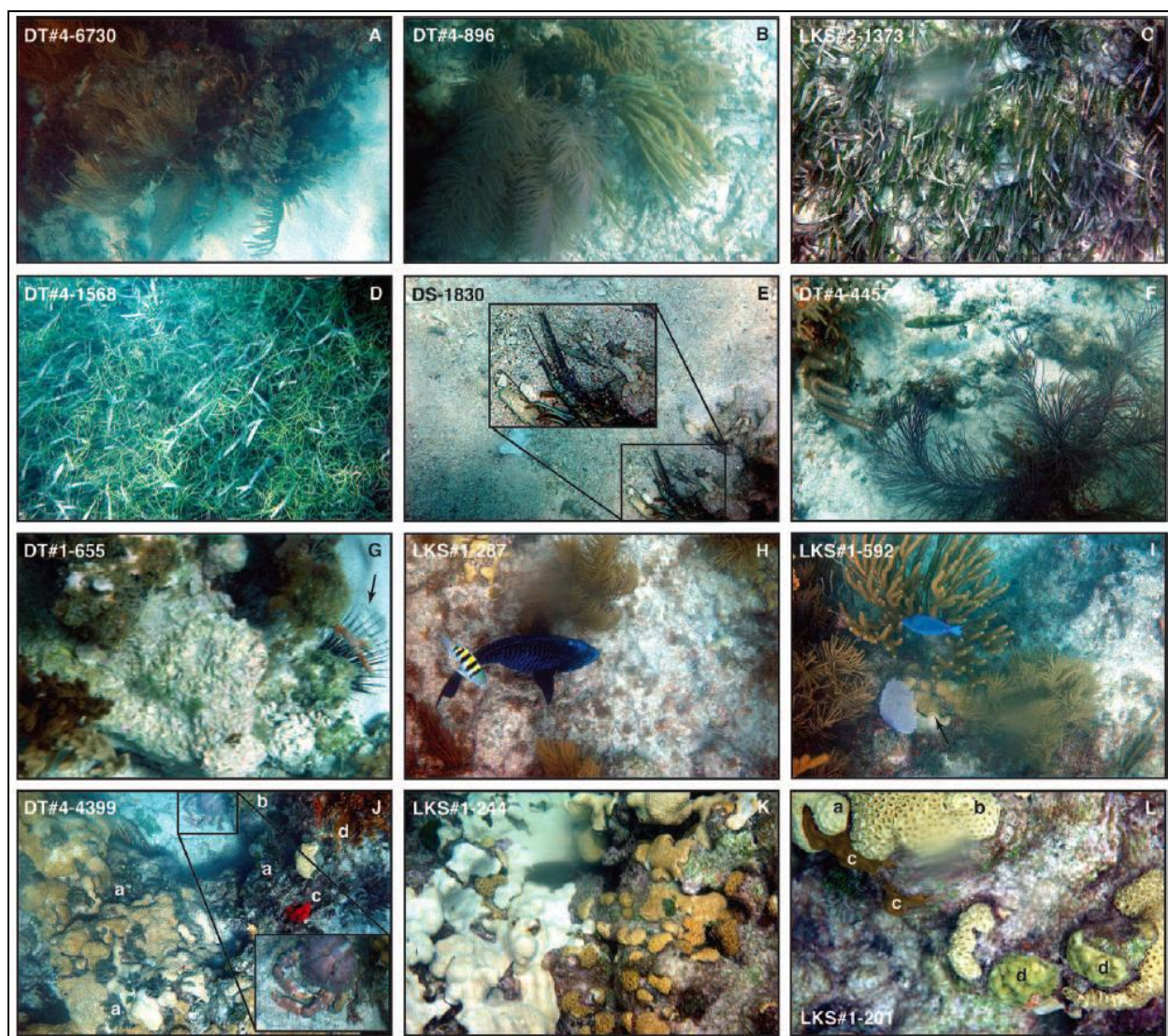


Figure 3. Along-Track Reef Imaging System (ATRIS) imagery from Dry Tortugas National Park and Looe Key Sanctuary, Florida Keys (from Moses et al., 2010b).

Sediment Profiling Imagery

Sediment profiling imagery (SPI) is a technique for producing vertical cross-sectional images of the top layers of the seafloor. The sediment profiling camera (Figure 5) penetrates the seafloor (to a depth of ~20 cm) and photographs a profile of the sediment. The sediment profile provides a context for grab and core sampling and captures structural and biological information (sediment layers, animal burrows, etc.) that grabbing and coring techniques might not preserve (Figure 6). Advantages of sediment profiling technology over grab samples are the permanent record provided by the photography, information about sediment structure, and information about the water-sediment interface. Potential disadvantages are the size and complexity of the units (requiring fixed davits and winches for deployment) and the narrow field of view. Sediment profiling and the grab and core techniques are more powerful when applied in the context of remotely-sensed spatial habitat data (Finkbeiner et al., 2001).



Figure 4. The Seaviewer Sea-Drop 950 drop-camera (pictured) was used by NOAA in benthic mapping projects in St John, U.S. Virgin Islands (from Zitello et al., 2009).

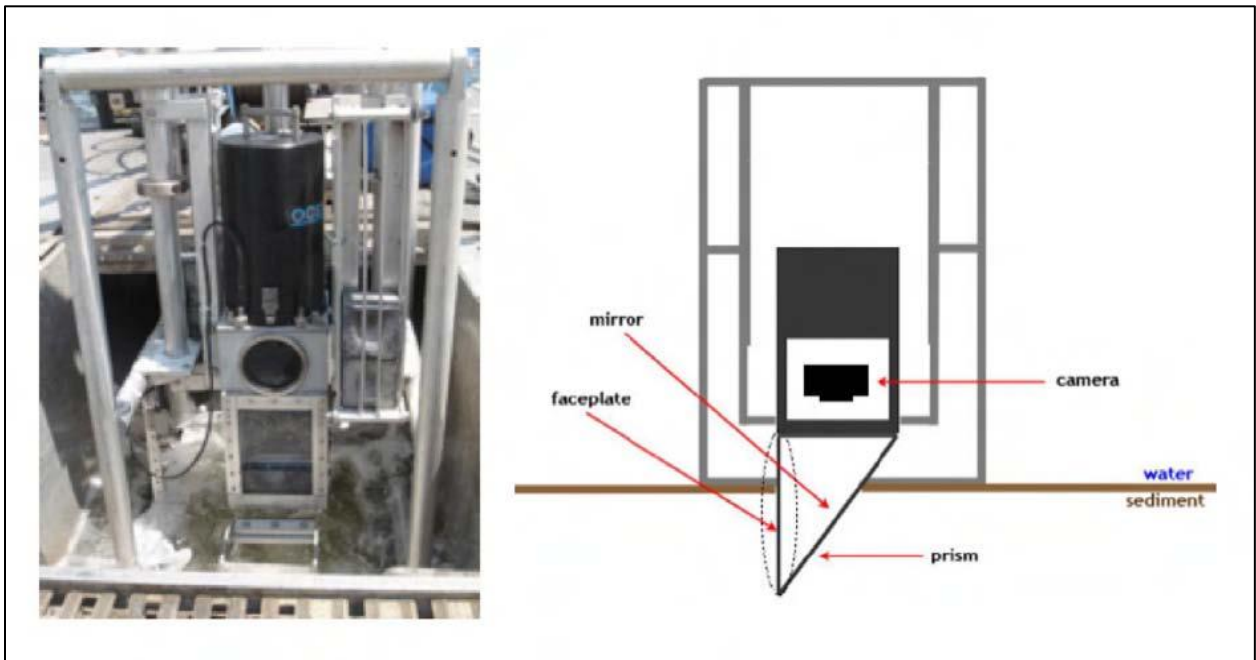


Figure 5. Sediment profiling camera front view and side-view schematic showing deployment in sediment (from Shumchenia and King, 2010).



Figure 6. Three images taken with a sediment profiling camera showing structural and biological information (from Germano & Associates, Inc., www.remots.com/spi_overview.html).

Epibenthic Sled Sampling

An epibenthic sled (Figure 7) is designed to be towed on the sediment surface and includes a net that captures organisms on, or just above, the bottom. Occasionally the sled may dig into the bottom, inadvertently collecting infauna samples and damaging habitat. Such a system can be deployed in depths >5,000 m and can collect rare deep-sea animals that would be difficult to obtain with other methods (Woods Hole Oceanographic Institution, 2013).

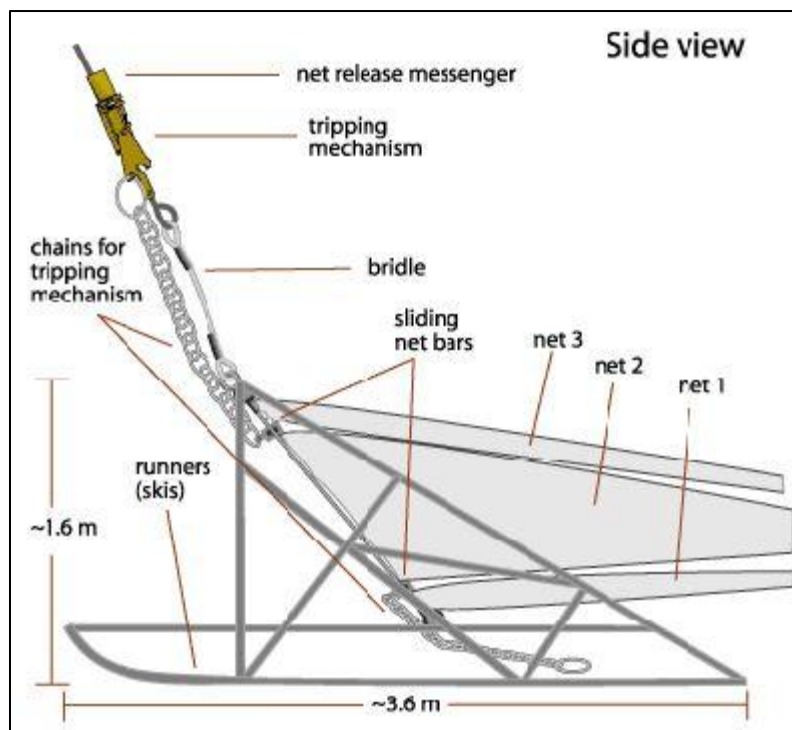


Figure 7. Epibenthic sled schematic (from <http://access.afsc.noaa.gov/icc/illus.cfm?GearAbv=Sled>).

Epibenthic sled samples, sediment grab samples, and SPI systems can provide information about bottom composition and ecology in areas where the water is too turbid for above-bottom image capture.

Remotely Operated Vehicles

A remotely operated vehicle (ROV) is a tethered, unmanned vehicle that allows the vehicle's operator to remain on the surface vessel while the ROV works underwater. The vehicle and operator's controls are connected by a tether containing a group of cables that transmit electrical power, video, and data signals back and forth between the operator and the vehicle. Most ROVs are fitted with at least a video camera and lights. They can be customized with an assortment of sensors and instruments to collect a variety of data, including visual or acoustic imagery, benthic grab samples, and physical and chemical water properties (MTS, 2012).

Autonomous Underwater and Autonomous Surface Vehicles

Autonomous underwater vehicles (AUVs) and autonomous surface vehicles (ASVs) are unmanned vehicles that, like ROVs, are capable of carrying a variety of sensors and equipment for collecting marine data. Unlike ROVs, AUVs and ASVs have no tether and are usually pre-programmed to follow a specific course, collecting data either continuously or at designated locations or time intervals.

The two most common types of AUVs are propeller-driven and buoyancy-driven, also called gliders. The propeller-driven AUVs use battery-powered engines to drive a single stern-mounted propeller and can follow pre-programmed routes and maintain constant depth or altitude if desired. The buoyancy driven gliders rely on inflatable bladders that give the vehicle positive or negative buoyancy and have wings that allow them to glide forward while they rise or sink. There is also a wave-propelled ASV that remains on the surface and uses solar panels to power its instruments (LRI, 2013) (Figure 8). Gliders (buoyancy and wave driven) are better suited for extended missions (multiple months) because they do not rely on batteries for their propulsion system; batteries are only needed to power sensors, data loggers, and the satellite communication systems (McGuinness, 2008).

Significant technological advances are being made in AUV designs. Vehicles are becoming smaller, more sophisticated and more economical. This type of technology is likely to play a more significant role in marine exploration and data collection in coming years⁷.

⁷ Tim Battista, NOAA, personal communication, May 16, 2012.

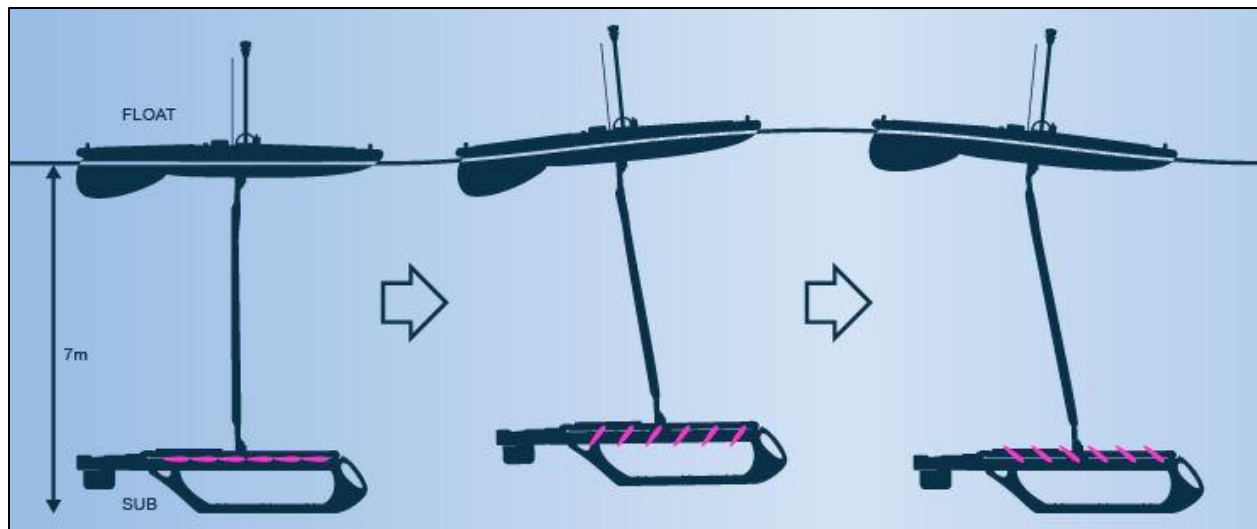


Figure 8. Schematic of the Wave Glider, a wave-propelled autonomous vehicle. Solar panels and batteries on the surface component provide power for instrumentation (from Liquid Robotics, Inc. web site, <http://www.lrog.com/the-wave-glider/how-it-works.html>).

Ecological Classification Scheme

An ecological classification scheme is a system for organizing and assigning consistent names to habitats based on unique combinations of abiotic and biotic ecosystem characteristics (thematic classes). To maximize the usefulness of benthic mapping data, a nationally standardized habitat classification scheme should be used to create maps and reports for national parks. A nationally standardized scheme allows meaningful comparisons of data collected at different parks or at different times in the same park. The ability to compare the same thematic classes allows changes and trends to be detected and monitored. A nationally standardized classification scheme will enable monitoring and trend analysis at the local, regional and national scales.

The Coastal and Marine Ecological Classification Standard (CMECS) was developed by NOAA, NatureServe, the USGS and the U.S. Environmental Protection Agency in cooperation with hundreds of scientists and coastal managers. In 2012, the Federal Geographic Data Committee (FGDC) approved CMECS as a national coastal habitat classification standard (FGDC-STD-018-2012). “As an FGDC standard, it is ‘mandatory’ that all federally funded coastal and marine habitat mapping projects be consistent with CMECS” (FGDC, 2013a). A project may be mapped using a different system, but must also be cross-walked to CMECS units. NPS was involved in the review, testing and validation of the CMECS standard and advocates its use in benthic mapping projects.

CMECS provides a nationally standardized structure for organizing and synthesizing physical, biological and chemical information about coastal and marine ecosystems so they can be identified, characterized, and mapped in a consistent manner (NOAA Coastal Services Center, 2012). The domain of CMECS includes waters from head of tide and the coastal splash zone to the deepest waters of the oceans and Great Lakes. CMECS was developed primarily for use in the territorial waters of the United States, but its underlying structure and concept make it useful in other parts of the marine world. While development of CMECS has been focused on estuarine and marine systems, many of the concepts and units are applicable to the Great Lakes. However, more work is needed to develop a comprehensive list of units for the Great Lakes (FGDC, 2012).

CMECS is flexible enough to be applicable in a wide variety of ecological settings under a wide range of project goals. It is organized into four components (water column, geoform, substrate, biotic) and two settings (biogeographic and aquatic) (Figure 9). Each component is an independent construct that can be used on its own or in combination with other components or settings. Descriptive modifiers (e.g., salinity, energy, turbidity, percent cover) can augment CMECS units to enhance the specificity and detail of classifications and descriptions. Standard modifiers are included, or the user can create non-standard modifiers beyond the lowest tiers of the CMECS components (FGDC, 2012).

More information about CMECS, including a copy of the published standard, can be obtained at <http://www.fgdc.gov/standards/projects/FGDC-standards-projects/cmecs-folder/> and <http://www.csc.noaa.gov/digitalcoast/publications/cmecs>.



Figure 9. Components and settings of Coastal and Marine Ecological Classification Standard (from NOAA Coastal Services Center, 2012).

NPS Benthic Mapping Pilot Projects

Based on the findings of the 2008 SBMP workshop (Moses et al., 2010a), an initial group of parks was identified for benthic mapping pilot projects. The following criteria were used to select the parks (Brunner, 2008):

- geographic diversity,
- ecosystem diversity,
- partner diversity,
- using existing data as much as possible,
- leveraging ongoing partner efforts, and
- projects would meet real park needs and help resolve management questions, such as fishing restrictions, dredging/disposal projects, and identification of potential marine reserve areas.

The pilot projects included parks from Alaska, California, the Great Lakes, Gulf of Mexico, and Caribbean region.

The original design and protocols of the SBMP are detailed in the SBMB Protocols Document (Moses et al., 2010a). Pilot project methods varied depending on existing data, funding, environmental conditions, and the classification system used. Within a single project, multiple technologies might be employed to suit the situation. For example, in St. John, U.S. Virgin Islands, different methods were used in shallow water (where optical data could be used) versus deeper water (where the primary data source was acoustic). When multiple technologies are used within a single park or study area, it is important to use the same classification scheme for each technology so that the resulting datasets can be integrated in a seamless fashion.

From 2008 to 2011, the NPS I&M program funded mapping projects in ocean and coastal parks, but not the SBMP. Following is a brief description of the mapping projects.

FY2008 Projects

Golden Gate National Recreation Area (GOGA)

“The objective of this project was to compile available regional seafloor mapping data for San Francisco Bay [area] and to interpret newly collected data provided through the California State Mapping Program (CSMP) and the United States Geological Survey (USGS) to construct benthic habitat and geologic maps of the submerged lands of the GGNRA [GOGA]” (Greene et al., 2009:1).

The GOGA project is a valuable synthesis of several disparate datasets of varying resolution and quality collected during 10+ years by multiple organizations (NOAA; USGS; California State University, Monterey Bay). Data types include multibeam bathymetry and backscatter, sidescan sonar, single-beam echosounder, and sediment grab samples. Numerous sediment sample datasets (collected between 2004 and 2008) were used as ground-truth to aid in the interpretation of the remotely sensed acoustic data (Greene et al., 2009). While this added to the interpreters’

confidence in their ability to interpret large areas of the seafloor, the report contains the following caveat:

[W]e caution against using our sediment type interpretations as anything more than "best-guess" due to the following issues: characterization of contiguous sediment bodies is a difficult procedure since even small areas can exhibit a wide spectrum of backscatter intensity values that lack distinct boundaries; backscatter intensity can be affected by depth, vegetation, water column conditions, and seafloor relief; and directly observed sediment data, in the form of sediment samples, represents a very small area relative to remotely observed data, requiring broad areas of interpolation. These methods primarily pertain to the area east of the Golden Gate where the quality and resolution of backscatter data was very high. Unfortunately, the majority of backscatter data west of the Golden Gate was considered substandard for making confident interpretations of the sediment type (Greene et al., 2009:15).

Another important tool for interpreting bottom features is the “hillshade” relief renditions of multibeam bathymetry data (Figure 10). Hillshades allow the interpreters to visually identify benthic habitats: “...areas of rock were identified by their often sharply defined edges and high relative relief; these may be contiguous outcrops, isolated portions of outcrop protruding through sediment cover (pinnacles and rocks), or isolated boulders...Broad areas of the seafloor lacking sharp and angular characteristics are considered to be sediment” (Greene et al., 2009:15).

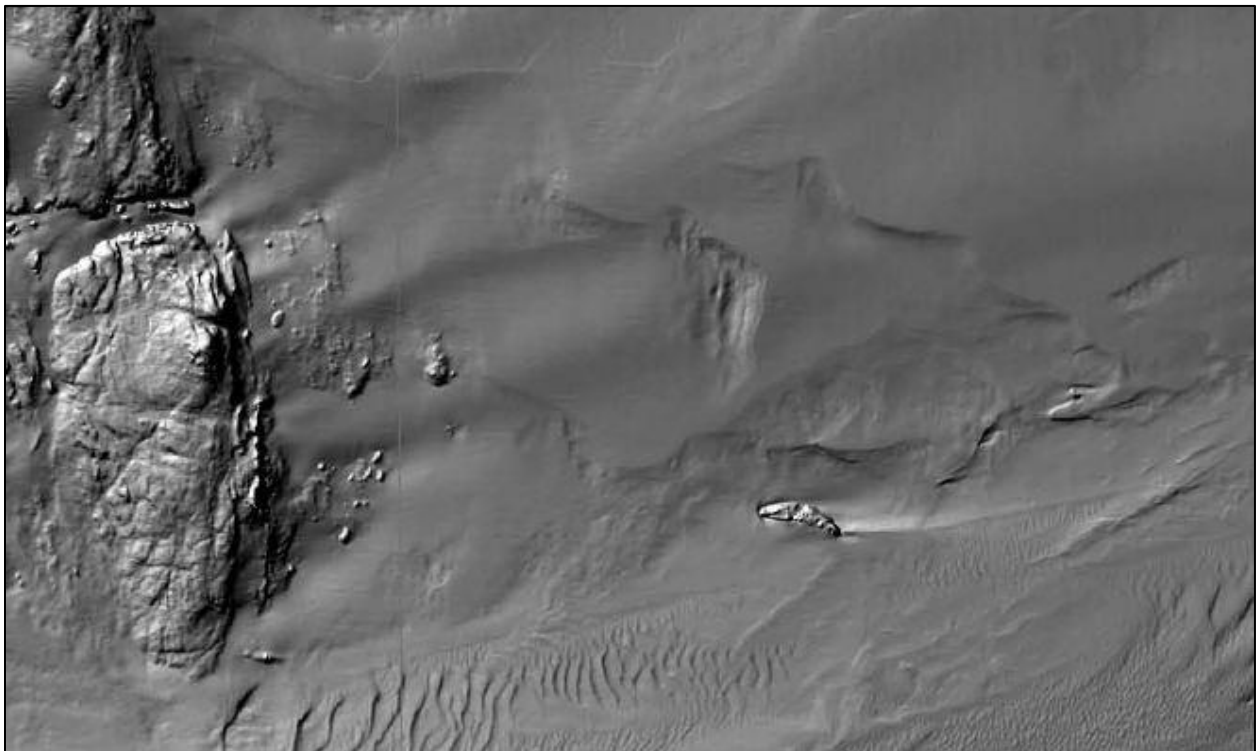


Figure 10. Hillshade image of northern San Francisco Bay seafloor showing characteristic sharp edges and high relief of rock areas on the left side of the image and relatively smooth features of sediment on the right side of the image (from Greene et al., 2009).

Historical anthropogenic data (e.g., shipwrecks, artificial reefs, dredged and dredge spoil locations) can also be an important interpretation tool (Figure 11). Depending on the resolution of the data, the sharp edges and high relative relief of a shipwreck in the middle of a sediment field could be mistaken as a rock outcrop. This highlights the importance of using multiple data sources to identify seafloor features⁸.

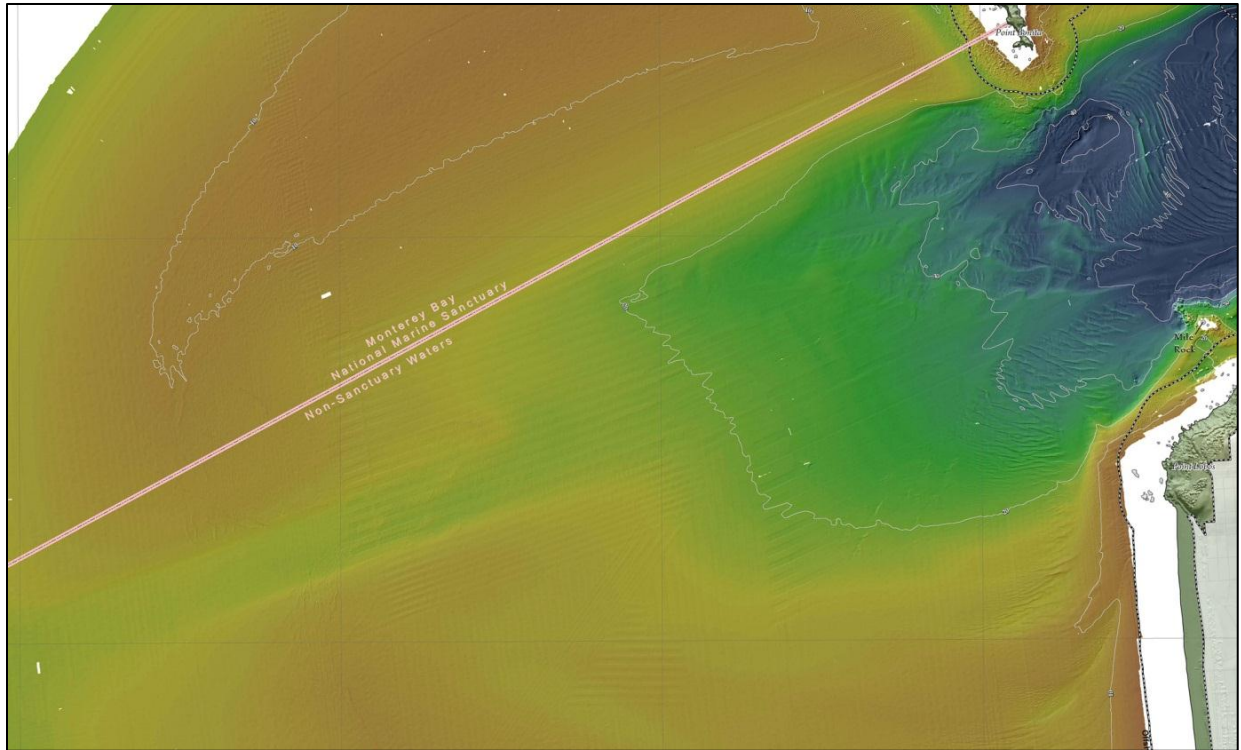


Figure 11. Color bathymetry of the Pacific Ocean off Golden Gate National Recreation Area showing the San Francisco Main Ship Channel leading from the bay to the ocean. It is about 7.9 km long (4.9 mi), 610 m wide (2,000 ft), and 17 m deep (55 ft) (USACE, 2012).

In a stable environment, overlapping datasets can be used to corroborate or ground-truth each other. Strong ocean currents in the study area “create a dynamic, sedimentary environment with major bedforms that often shift in position and shape...[Figure 12]... This dynamic seafloor activity precludes combining data collected at different times into a single substrate or benthic map” (Greene et al., 2009). The disparate datasets were used to fill gaps and verify stable features in less dynamic areas.

The lack of data for submerged areas within GOGA was a significant challenge. Most of the submerged area is in the nearshore or “white zone,” which is difficult to map because of shallow, turbid water and powerful waves and currents. Due to the shallow, high energy conditions, access by ship or boat is dangerous, difficult, or impossible. Turbid water and clouds or fog make scheduling of aerial and satellite-based optical data collection problematic. The white zone gets its name because it lacks data and appears as white (or blank) areas on preliminary maps (Figure 13). Benthic habitat information for the white zone was interpolated from data collected in adjacent areas (e.g., terrestrial geology maps and marine benthic acoustic data).

⁸ Charlie Endris, Moss Landing Marine Laboratories, personal communication, June 6, 2013.

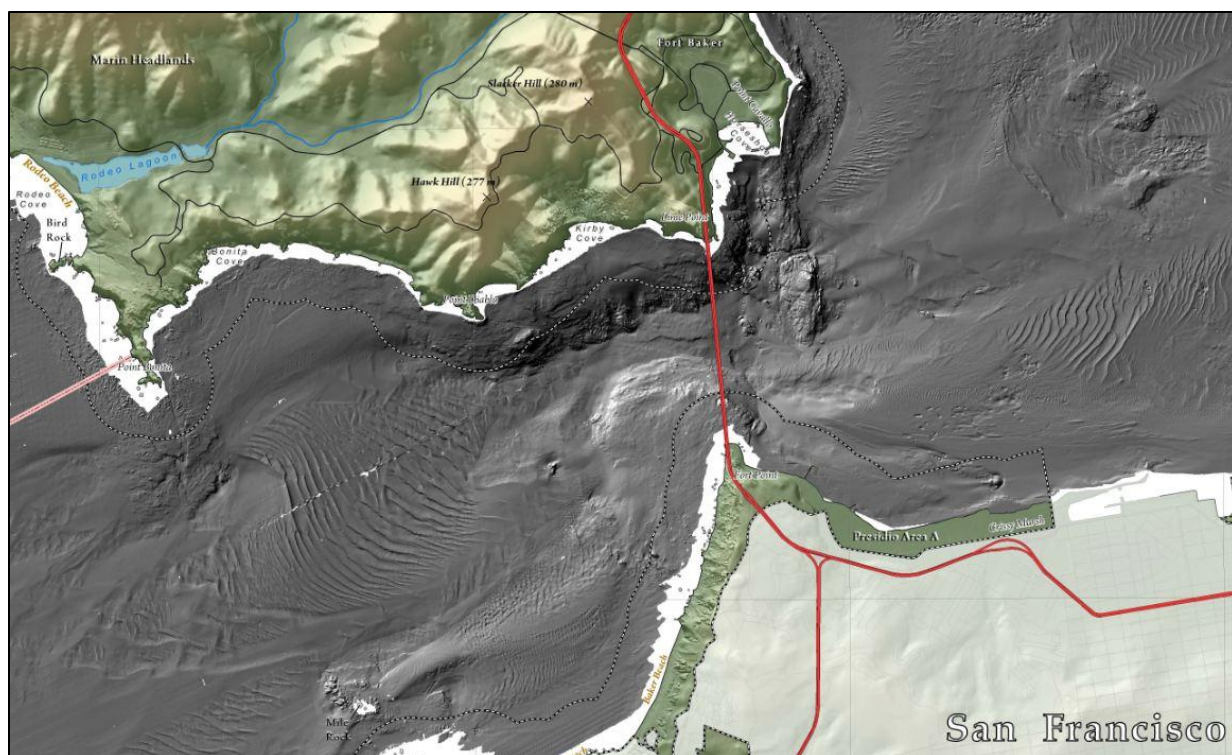


Figure 12. Hillshade image showing sand waves in the entrance to San Francisco Bay. Sand waves indicate strong currents that create a dynamic sedimentary environment (from Greene et al., 2009).

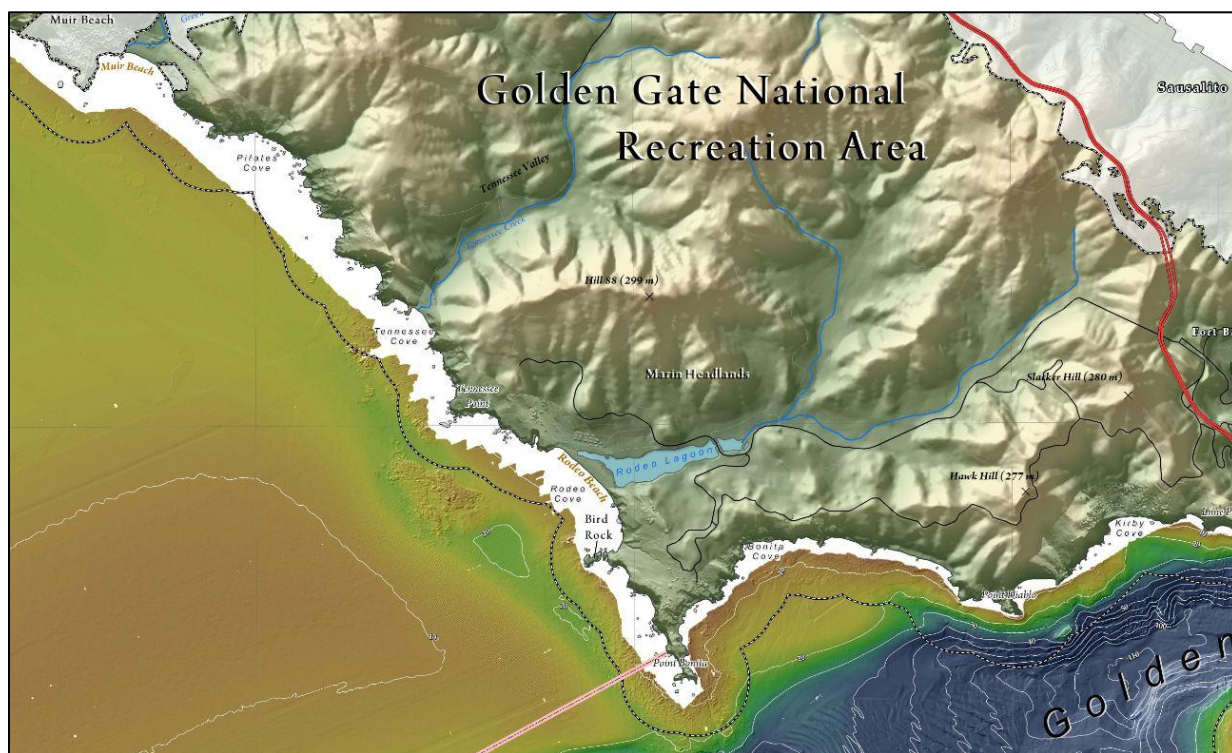


Figure 13. Preliminary bathymetry map showing the white zone in Golden Gate National Recreation Area (GOGA). Note that the white zone in this image includes approximately half of the offshore area within the GOGA boundary (dotted line) (from Greene et al., 2009).

Lidar flights and personal watercraft (Jet Ski) fitted with sonar equipment are potential data collection techniques in some shallow-water areas where conventional data collection is not feasible, but unpredictable and rarely favorable environmental conditions require rapid mobilization on short notice. Although rapid mobilization is feasible for deploying personal watercraft, it is more challenging and expensive for a lidar flight. Successful lidar collection depends on good visibility (in air and water) and good flying conditions. Attempts to collect new lidar data for GOGA were unsuccessful; flights were cancelled on two occasions due to rain. Environmental conditions also thwarted efforts to collect new single-beam sonar data via personal watercraft. However, single-beam bathymetric data previously collected by USGS using personal watercraft (Barnard, et al., 2007) were used to interpret areas along Ocean Beach and along the southern part of the shoreline from the Golden Gate westward in water depths of 0-5 m (0-16 ft) (Greene et al., 2009).

The GOGA project made good use of existing data and the report explained the caveats of integrating disparate datasets. Unfortunately, most of the submerged areas of GOGA lacked data. Existing data from surrounding areas were integrated and interpreted, and the white zone was interpolated appropriately from these data.

Gulf Islands National Seashore (GUIS)

The 2005 hurricane season was especially destructive in the northern Gulf of Mexico (NGOM). Hurricanes Dennis (July), Katrina (August), and Rita (September) made landfall between Louisiana and Florida. Following the hurricanes, the USGS established the Northern Gulf of Mexico Ecosystem Change and Hazard Susceptibility project (NGOM-ECHS). The project goals were to “understand the evolution of coastal ecosystems on the northern gulf coast [sic], the impact of human activities on these ecosystems, and the vulnerability of ecosystems and human communities to more frequent and more intense hurricanes in the future” (USGS, 2013) through regional scale interdisciplinary scientific investigations.

In response to the devastation of the 2005 hurricane season, Congress passed Public Law 109-148 that established the Mississippi Coastal Improvements Program (MsCIP). Headed by the US Army Corps of Engineers (USACE), MsCIP is a multi-agency planning effort to reduce hurricane and storm damage, prevent saltwater intrusion, promote fish and wildlife preservation, and prevent shoreline erosion (NPS, 2011).

As the manager of GUIS, NPS had been working with the state of Mississippi and the U.S. Army Corps of Engineers to provide recommendations to the MsCIP. Several barrier island renourishment projects were under consideration. The lack of data for bathymetry, sediment type, and biota made it difficult to develop recommendations. More benthic substrate and habitat data were needed not only to inform the recommendations to MsCIP, but to help manage the natural and cultural resources of GUIS.

During the summers of 2008 and 2009, USGS collected sidescan interferometric swath-bathymetry and associated backscatter data within GUIS boundaries as part of NGOM-ECHS. Substrate data were collected concomitantly during a sub-bottom profiling survey (Lavoie et al., in press). While the NGOM project goal was to survey benthic substrate types near East and West Ship, Horn, and Petit Bois islands, data were collected in the broader context of the

NGOM-ECHS goal of understanding the evolution and vulnerability of regional ecosystems to hurricane impacts.

The NGOM-ECHS project was an opportunity for NPS to partner with USGS to obtain benthic habitat data “to develop a comprehensive map of the benthic marine habitats within the GUIS to give park managers the ability to develop strategies for coastal and ocean-resource management, and to aid decision makers in evaluating conservation priorities” (Lavoie et al., in press).

Unfortunately, the goals of the two projects were not as well aligned as originally thought. The USGS survey lines were approximately 200 m (656 ft) apart and the gaps between the data tracks were greater than the swaths where data were collected (Figure 14). While the track spacing may be appropriate for broad characterization of substrates, it is not appropriate for developing a benthic habitat map. To achieve continuous habitat characterization from the data, large areas had to be interpolated. The data gaps made it difficult to accurately delineate habitat types, and increased the chance of missing small habitat patches or substrate anomalies.

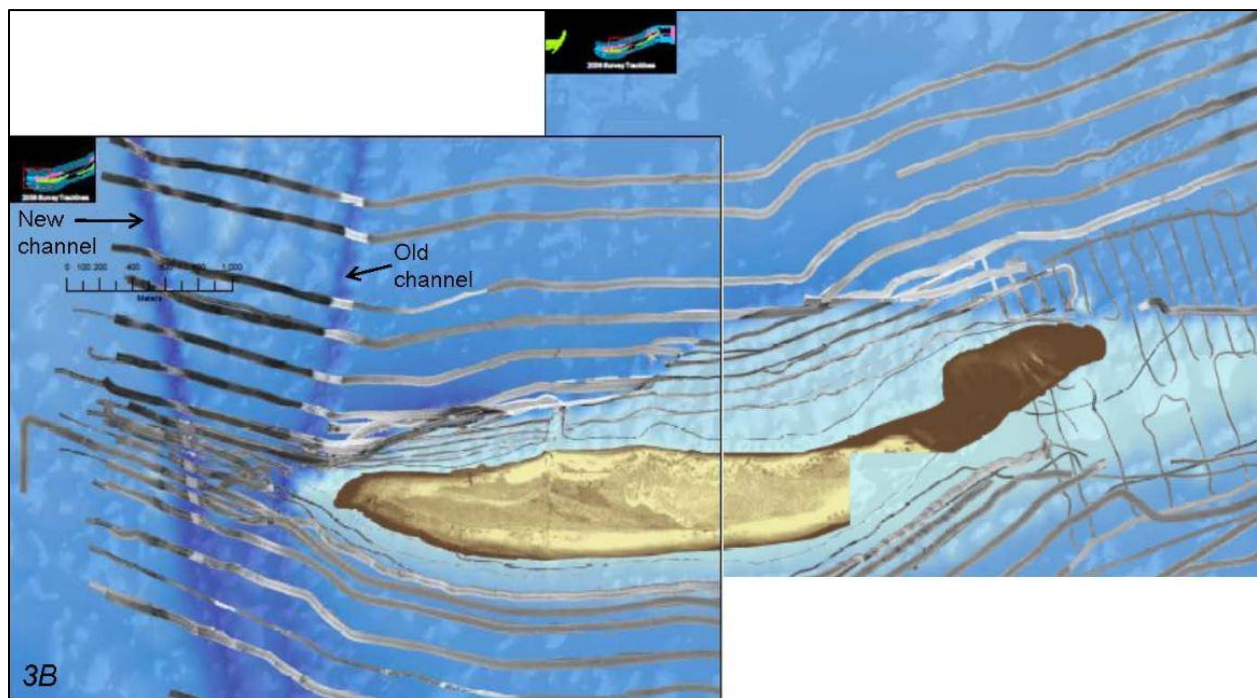


Figure 14. Examples of backscatter returns (thin stripes) from West ship Island. The light returns from the shipping channels represent fine-grained mud, and the dark returns between the old and new shipping channels are coarse to medium sands. Note the spacing of the data tracks and the large areas between the tracks (blue) that lack backscatter data (from Lavoie et al., in press).

An initial attempt was made to classify the data using a supervised approach. However, the large data gaps did not support this method. Instead, habitat boundaries were manually drawn and edited in ArcGIS “based on visual interpretation of backscatter intensity and [the] presence of geofoms.” This required the analyst to approximate habitat boundaries in large areas between the data tracks. In areas shallower than 2 m (6.6 ft), seagrass habitat data were added from an

existing dataset. Other areas of seagrass or organic bottom material were interpreted from the backscatter data (Lavoie et al., in press).

In March 2010, ground-truth data (sediment samples and bottom photographs) were collected at 132 sites. Sediment samples were analyzed for particle size and used to verify interpretations of the backscatter data (Lavoie et al., in press).

The sediment analyses indicate that sand is the predominant bottom type around the islands, and that particle size generally becomes finer as distance from the islands increases. Features mapped as geologic structures may be sand waves; they are found in relatively high-energy areas south of the islands, but not in the more protected low-energy areas north of the islands. It is likely that some sand wave features were not mapped since isolated indications in the backscatter returns were ignored. Continuous (or more closely-spaced) data would likely reveal more areas of sand waves and other bedforms (Lavoie et al., in press).

The PIs encountered some problems related to data processing. Though they had extensive experience with bathymetry and coastal lidar data collection and processing, they had never processed sidescan interferometric swath-bathymetry and the associated backscatter data. The project was delayed while they received specialized training to process the data.

The attempt to partner with another agency on an existing project can increase efficiencies and reduce costs. However, a successful partnership must have compatible goals. It is critical to ensure that the data fit the project goals and that the PIs have the expertise necessary to process and interpret the data.

Muir Inlet, Glacier Bay National Park and Preserve (GLBA)

Seafloor geology and potential benthic habitats were mapped in Muir Inlet, one of the two major northern tributaries of Glacier Bay, in Glacier Bay National Park and Preserve, Alaska. Muir Inlet (locally known as the East Arm) is approximately 41 km (25 mi) long and 1-4 km (0.5-2.5 mi) wide, and has recently experienced rapid deglaciation. Between 1886 and 1968, Muir Glacier retreated 33 km (21 mi) (Field, 1975). Retreat continues, but as the glacier retreated from its tidewater setting to near the head of the fjord, the rate of retreat slowed. Rapid glacial retreat (producing large sediment and melt water fluxes), combined with strong tidal currents, resulted in a dynamic estuarine and benthic ecosystem in the upper fjord. Sediment accumulation data show that the lower fjord is less dynamic than the upper fjord. The morphology of Muir Inlet is characteristic of a glacial fjord; it includes a shallow sill at the mouth, steep walls, and multiple deep basins separated by transverse sills and morainal banks (Figure 15) (Trusel et al., 2010).

The primary data source for benthic habitat and seafloor substrate mapping in Muir Inlet was multibeam sonar data collected in 2004 at depths ranging from just below the surface to >300 m (984 ft). The dataset includes simultaneously collected bathymetric and co-registered backscatter data (Trusel et al., 2010). Backscatter data provide information on seafloor shape, rugosity, and induration from which bottom composition can be inferred.

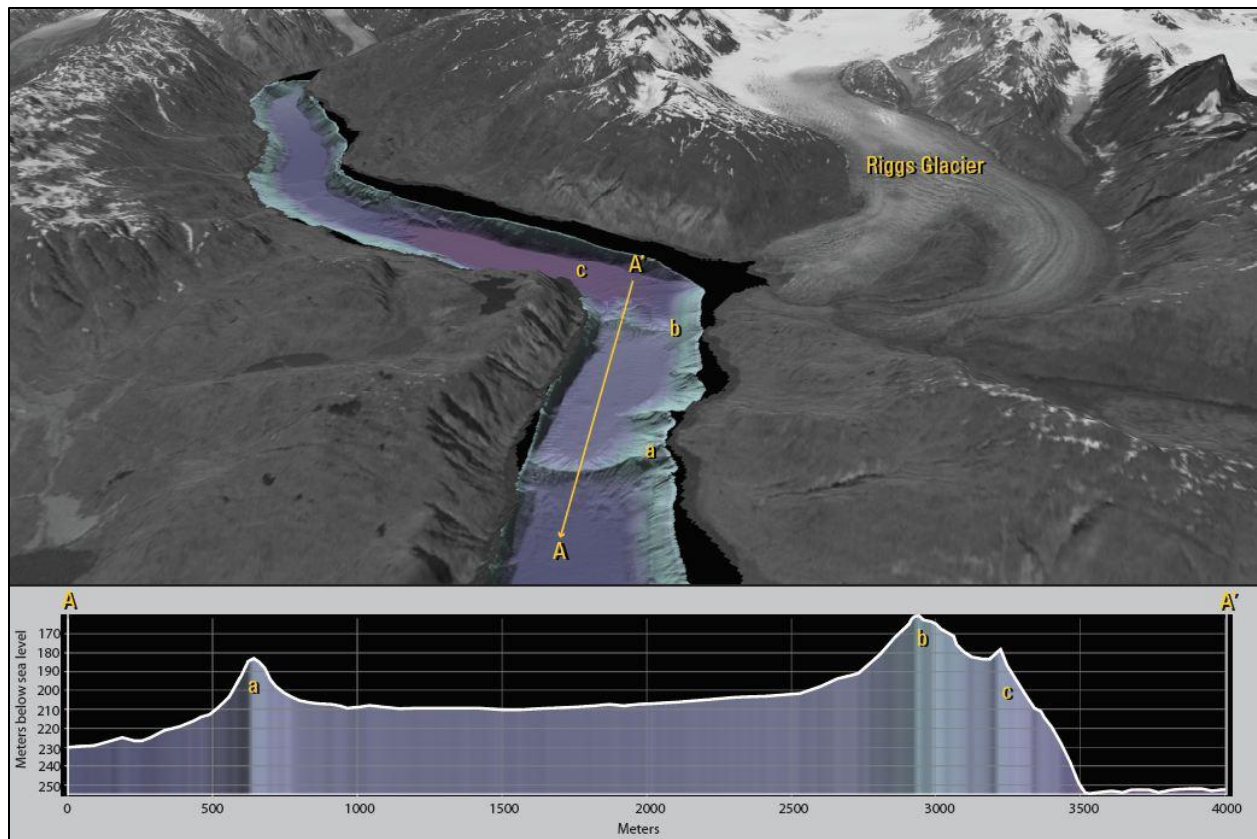


Figure 15. Perspective view of upper Muir Inlet and its associated seafloor profile showing two bedrock-cored morainal banks (a, b). The sills have high profiles and separate Muir Inlet into distinct low-relief sedimentary basins where sediment pools between the sills. Vertical exaggeration is 1.5x in the perspective view and 9x in the profile view (from Trusel et al., 2010).

Ground-truth information was originally collected for other projects and includes USGS seafloor video observations, sediment samples and cores, seismic reflection profiles, and seafloor dive observations. The video observations were collected for benthic habitat mapping in Glacier Bay proper and were not extensively collected in Muir Inlet. Knowledge of glaciomarine processes in the fjord environment was critical in the interpretation of multibeam backscatter data and the production of the potential benthic habitat maps (Trusel et al., 2010).

The Coastal and Marine Ecological Classification Standard (CMECS), Version III (Madden and others, 2008) ecological classification scheme was used to classify seafloor habitats. A supervised manual classification approach was used to delineate and classify benthic habitat features based on multibeam backscatter intensity data, two derivative products (seafloor rugosity and slope) (Figure 16), limited ground-truth data, and knowledge of local glaciomarine processes.

Based on the large glaciomarine sediment flux in the system, unconsolidated bottom types (mud, gravel, cobble, or mixed sediments) were expected. Mud covers about 90% of the seafloor in Muir Inlet; bedrock covers about 6% (Table 1).

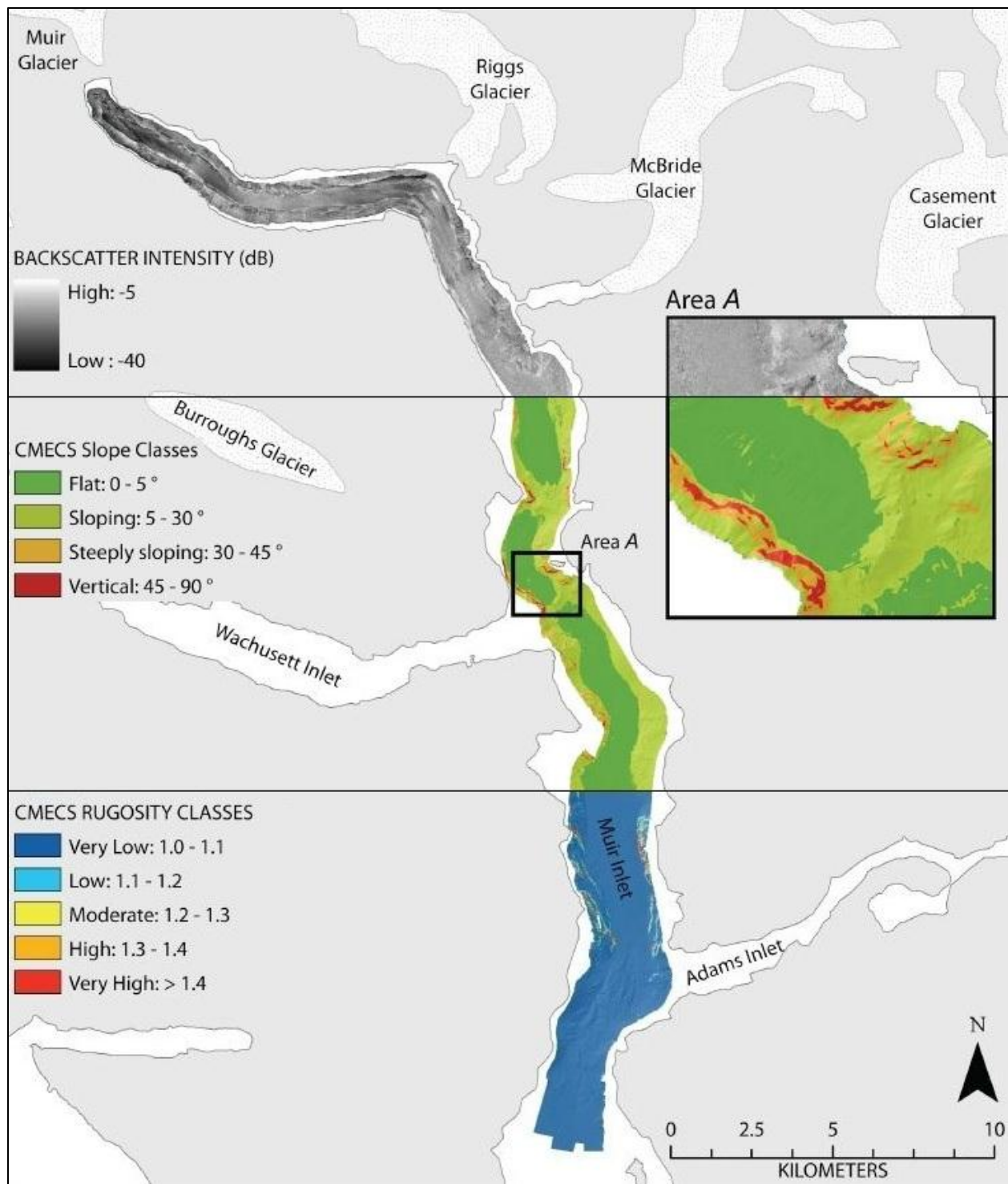


Figure 16. Composite map showing examples of rugosity, slope, and backscatter intensity data from Muir Inlet. The composite map was made from portions of three maps in Trusel et al., 2010.

Table 1. Substrate distribution for Muir Inlet, Alaska (from Trusel et al., 2010)

CMECS Class	CMECS Subclass	Percent of Total Area	Area (km ²)
Unconsolidated Bottom	Mud	88.7	64.6
	Mixed sediments	3.3	2.4
	Cobble/gravel	0.4	0.3
Rock Bottom	Boulder/rubble	1.4	1.0
	Bedrock	6.2	4.5

The geoforms of Muir Inlet are wall (40%), floor (38.7%), moraine (15.5%), and delta (5.8%). The high relative proportion of walls and floors is characteristic of glacial fjord morphology. The transverse sills are classified as moraines (per CMECS). Seismic data imply that some of the sills have bedrock cores and others are composed of discontinuous, hummocky and mounded glacial material. Backscatter data indicate all of the sills are covered with a layer of mud (Trusel et al., 2010).

A primary challenge to benthic habitat mapping in Glacier Bay is the difficulty in obtaining ground-truth data due to water depth (>300 m; 984 ft), cold water temperatures, and the expense and logistics of operating in a remote location.

This project made good use of available data and knowledge of local environmental conditions and processes to produce a dataset that is mostly interpolated. Assumptions and methods were well documented.

Virgin Islands National Park (VIIS) and Virgin Islands Coral Reef National Monument (VICR)

Virgin Islands National Park includes 2,281 ha (5,637 ac) of submerged federal lands and conserves a rich, but fragile, coral reef ecosystem off the coast of St. John, U.S. Virgin Islands. Virgin Islands Coral Reef National Monument includes 5,149 ha (12,722 ac) of federal submerged lands adjacent to VIIS. Both parks contain some of the most biologically rich and economically important coral ecosystems in U.S. waters and support a complex system of coral reefs, shoreline mangrove forests, and seagrass beds (Costa et al. 2009).

Due to the range of water depths, different methods of data collection and benthic habitat mapping were used for shallow (<30 m; <98 ft) versus moderate-to-deep (>30 m; >98 ft) waters in St. John. The primary data source for the shallow-water habitat maps was optical imagery (color digital orthophotography and IKONOS multispectral satellite imagery). In the Caribbean, optical imagery can detect bottom features to water depths of about 30 m (98 ft). The primary method of habitat delineation was traditional heads-up digitizing at a scale of 1:2,000 using ArcGIS 9.3 and the Habitat Digitizer Extension. Images were sometimes manipulated using brightness, contrast, and color stretches to enhance the features of interest and facilitate habitat delineation. Ancillary datasets (e.g., previous habitat classifications, nautical charts, different dates of imagery) were sometimes used to augment the habitat delineation process (Zitello et al., 2009).

Acoustic multibeam sonar was the primary data source for deeper waters where insufficient light penetration prohibits the acquisition of optical imagery of bottom features. Depth, seafloor

rugosity, and induration were derived from the multibeam sonar data. Benthic habitats were mapped using semi-automated classification and visual interpretation of acoustic imagery (Costa et al., 2009).

Methods for Shallow-Water Mapping

Benthic habitat maps for the shallow areas of VIIS and VICR were created by visually interpreting satellite and aerial imagery. NOAA's Biogeography Branch uses a six-step workflow for their benthic mapping projects. The workflow can be adapted to match the specific needs and methods of a particular project. The following six-step workflow was used for shallow-water mapping at VIIS and VICR (Zitello et al., 2009):

1. Imagery Acquisition – Color orthophotography and IKONOS satellite imagery were acquired and georeferenced to ensure acceptable spatial accuracy in the mapping product.
2. Habitat Boundary Delineation – A first draft of the benthic habitat map was generated by delineating all features that could be identified by visual inspection of the remotely sensed imagery. During the creation of the first draft, the interpreter placed discrete points on the map in locations that were difficult to classify and that warranted further field investigation. These sites were labeled as “ground validation” positions.
3. Ground Validation – NOAA field scientists explored the ground validation locations with a combination of underwater video, free diving, snorkeling, and surface observations. This information was analyzed and the initial maps were edited to generate a second draft map improved by the field observations.
4. Expert Review – The second draft map was reviewed by local marine biologists, coral reef scientists and resource managers at a one-day workshop in Cruz Bay, St. John. Comments were integrated into the map products to generate a final draft map.
5. Accuracy Assessment – An independent team of NOAA scientists conducted field investigations at pre-defined locations to assess the classification accuracy of the final draft map. Locations were generated with a stratified random sampling design that allowed for a statistically rigorous assessment of map accuracy.
6. Final Products Creation – A final benthic habitat map for St. John was generated by correcting inaccuracies revealed by the accuracy assessment. All associated datasets, including GIS files, field video, and metadata, were packaged and provided to project partners and the public.

Methods for Moderate-Depth Mapping

A similar six-step workflow was used to map the moderate-depth areas. But because the methods were somewhat experimental and more complex than those used for the shallow-water areas, the six-step process was modified. Instead of conducting expert review in Step 4, the moderate-depth workflow included automated and semi-automated classification methods to generate habitat classes. The six-step workflow used for the moderate-depth mapping at VIIS-VICR (Costa et al., 2009) is described below and is followed by a more thorough description of the habitat boundary delineation and accuracy assessment steps:

1. Imagery Acquisition and Processing – High-resolution acoustic imagery was collected during two years and used to map the full geographic extent of the VICR's southern

boundaries. Several metrics were derived from the depth imagery that described the complexity of the seafloor in different ways. Principal components analysis was then used to reduce the redundancy of information contained in these metrics.

2. **Habitat Boundary Delineation** – A first draft benthic habitat map was generated using edge detection algorithms to delineate features on the seafloor that had discrete acoustic signatures. Two types of ground validation points were identified and marked on the first draft maps. The first type identified features with known acoustic signatures and the second type identified features with unknown signatures. The locations of these points were visited in the field to confirm and identify the associated habitats.
3. **Ground Validation** – Underwater video was collected along 13 transects using a remotely operated vehicle (ROV), and at 117 discrete points using a manually operated drop camera. The resulting GPS and video information was processed, analyzed and used to train the classification algorithm that was used to generate the second draft map.
4. **Habitat Classification** – A CART-like (Classification and Regression Tree) algorithm was used to classify each habitat feature delineated by the edge-detection algorithms described in step 2. To simplify this classification process, coral reef habitat features, and soft bottom and rhodolith habitat features were classified separately. The classification algorithm separated these two habitat feature types into five categories: major and detailed geomorphological structure, major and detailed biological cover, and live coral classes. The two resulting classifications were merged together and manually edited to create a final seamless habitat map.
5. **Accuracy Assessment** – Accuracy assessment sites were generated using a stratified random sampling design (based on detailed structure type) that allowed for a statistically rigorous assessment of map accuracy. Underwater video was collected at 299 sites using a manually operated drop camera.
6. **Final Product Creation** – The information generated during the accuracy assessment was used to correct and refine the draft maps and produce the final benthic habitat map. All associated datasets, including GIS files, field video, and metadata were packaged and provided to project partners.

Habitat Boundary Delineation

To increase efficiency and repeatability of their benthic mapping projects, the Biogeography Branch used a combination of object- and pixel-based classification methods to delineate and classify benthic habitat features. This project was the first attempt by the Biogeography Branch to use a semi-automated approach to create a benthic habitat map from acoustic data.

After data acquisition, one of the first steps was to create a seamless bathymetric surface from multibeam acoustic datasets acquired in 2004-2005. To characterize the complexity of the shape and structure of the ocean bottom, eight metrics were derived from the merged bathymetric surface: mean depth, standard deviation of depth, curvature, plan curvature, profile curvature, rugosity, slope, and slope of slope. A single eight-band image was created from the eight metrics.

The complexity of this eight-band image was reduced by applying principal components analysis (PCA). The first three principal components of the PCA transformation were combined to create

a three-band image that eliminated redundant data in the eight-band image and contained most of the information that described the complexity and structure of the seafloor. Edge detection algorithms were then applied to the three-band PCA image to delineate habitat features. Coral reef habitat features, as well as soft bottom and rhodolith habitat features, were exported as two separate shapefiles. The shapefiles were then visually inspected and manually edited.

Accuracy Assessment

Two missions collected “ground validation” (GV) data: one in 2005 that deployed still and video cameras on a remotely operated vehicle (ROV) and one in 2009 that used a drop camera. Underwater video and still images were collected at the GV locations to verify or assign habitat types to the previously delineated habitat polygons. Locations for these GV points and transects were manually selected to: 1) explore features in the imagery with unknown or confusing acoustic signatures, or 2) confirm that the habitat type correlated with a particular acoustic signature remained consistent throughout the entire study area (Costa et al., 2009).

By referring to the underwater and still images collected by the ROV and drop camera, it was possible to assign habitat types to the GV points and transects. They were then converted into training polygons that were used to train the classification algorithm to create a second draft habitat map. To simplify the classification process, coral reef habitats were classified separately from the soft bottom and rhodolith habitats.

Accuracy error matrices were computed for five attributes: major geomorphological structure, detailed geomorphological structure, major biological cover, detailed biological cover, and percent coral cover. Adjusted overall accuracy⁹ for four of the five attributes was above 88% (Table 2). Accuracy for detailed biological cover was 74%, which is below the suggested accuracy threshold of 80% (Moses et al., 2010a). There are several possible explanations for this result. The poor quality of the backscatter intensity imagery in some areas made it difficult to accurately map biological cover. Second, the semi-automated classification technique may be better at identifying signatures for structure than for cover. Finally, the use of density classes may have negatively affected the accuracy. Density classes are often difficult to assess and minor differences in density could have been interpreted differently by different analysts. For example, if an area had 85% actual algae cover, it might have been erroneously assigned to the 90-100%

Table 2. Summary of accuracy assessment results for moderate-depth benthic habitat mapping in Virgin Islands National Park and Virgin Islands Coral Reef National Monument

Attribute	Overall Accuracy (%)
Major geomorphological structure	95.7
Detailed geomorphological structure	88.7
Major biological cover	95.0
Detailed biological cover	74.0
Percent coral cover	88.3

⁹ The overall accuracy (number of correct classifications divided by total accuracy assessment samples) for each class is adjusted by removing bias introduced by differential sampling rates inherent in stratified sampling. For example, although *Rhodoliths* composed 77% of the map area, only 44% of the target points were allocated for this habitat. Conversely, *Aggregated Patch Reefs* composed only 3% of the map area, but received 13% of the allocated target sample points. The bias was removed using the method of Card (1982) (Costa et al., 2009:42).

algae class during the initial classification and to the 50-90% algae during the accuracy assessment. This type of classification error would affect the accuracy assessment, but is arguably a less significant error than a misclassification of discrete classes (e.g., algae vs. coral) (Costa et al., 2009).

Additional data processing included visual quality control, merging the two classified images, filtering them to remove polygons smaller than the minimum mapping unit (1,000 m²) and smoothing the polygons to remove the jagged edges remaining after the raster to vector conversion. Final quality control measures included topological and attribute error checking.

Results

Shallow water areas were evenly dominated by coral reef and hard-bottom structure (50% of the area mapped) and unconsolidated sediments (50%). Sand (43%), pavement¹⁰ (16%), rhodoliths¹¹ (9%) and aggregate reef (7%) (Figure 17) were the dominant bottom features. Patch reefs covered 3.3% of the area. Algae were the major biological cover (74%); about half of the algae-



Figure 17. Aggregate reef (left) in Privateer Bay, St. John, U.S. Virgin Islands, and map with red polygon outlining aggregate reef on orthophotograph (right) (Zitello et al., 2009).

dominated area was 90-100% covered by turf algae. The rest of the area had seagrass (15%) or no biological cover (9%) (Zitello et al., 2009).

Moderate-depth areas were dominated by unconsolidated sediments (87% of the area mapped); coral reef and hard-bottom structure covered the rest of the area (13%). Rhodoliths (77%) (Figure 18), sand (8%) and pavement (6%) were the dominant bottom features. Algae were the major biological cover (93%) comprising numerous types of turf, fleshy, filamentous and crustose coralline species; 7% of the area had no biological cover. Patch reefs covered 5.4% of the area. The majority (98%) of moderate-depth areas had 0-10% live corals; 2% of the moderate depth area had coral cover $\geq 10\%$ (Costa et al., 2009).

¹⁰ Pavement is flat, low-relief carbonate rock covered with algae, hard coral, gorgonians, zooanthids and other sessile invertebrates that partially obscure the surface (Zitello et al. 2009).

¹¹ Rhodoliths are aggregations of unattached, cylindrical, discoid, or irregular-shaped calcareous nodules about 6 cm in diameter (Zitello et al. 2009).

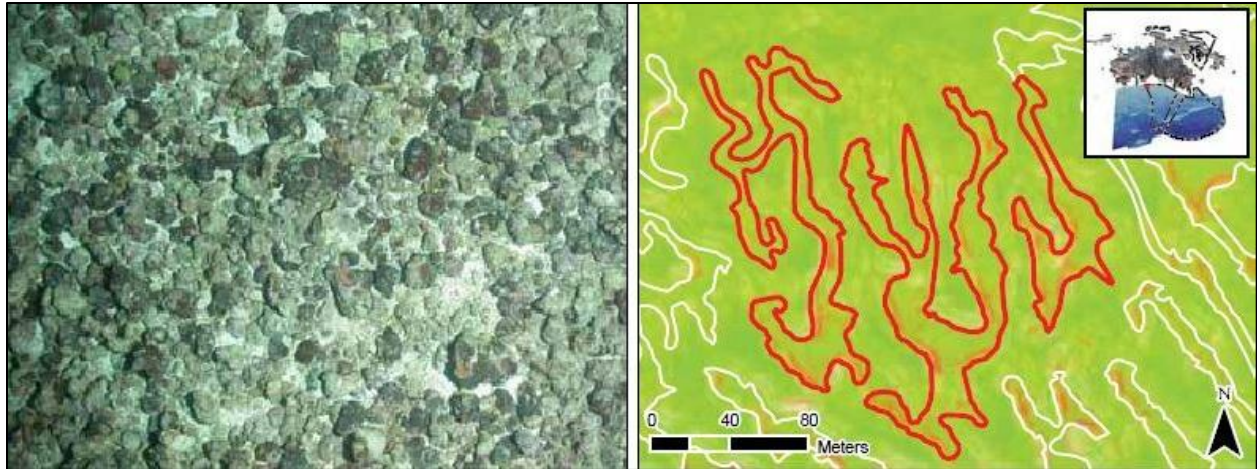


Figure 18. Rhodoliths (left) in St. John, U.S. Virgin Islands, and map with red polygon outlining rhodoliths on acoustic image (right) (Costa et al., 2009).

The semi-automated approach increased the repeatability of the project and reduced the amount of manual editing required to delineate habitat features. However, it still required a significant amount of manual editing and a level of remote sensing expertise and additional software that most parks do not have. The NOAA team combined the results of different technologies (optical and acoustic data) for the different environments (optically shallow and deep) in the study area, and included rigorous ground-truthing and accuracy assessment techniques. Deliverables (imagery, underwater video, GIS data, and metadata), maps, and a final report were thorough and delivered on time. This highly successful project can be used to guide future mapping efforts.

FY2009 Projects

Buck Island Reef National Monument (BUIS)

Buck Island Reef National Monument (BUIS) is located just north of eastern St. Croix, in the U.S. Virgin Islands (Figure 19). The monument includes nearly 19,000 ac (77 km²) of marine area surrounding the 172-ac (0.7 km²) Buck Island. It protects a diverse ecosystem containing coral reefs, seagrass beds, pavement, boulders, rhodoliths, and areas of unconsolidated sediment (sand and mud) with a depth range of 0-1830 m (0-6,000 ft) (Costa et al., 2012).

Mapping at BUIS was conducted by NOAA's Biogeography Branch. The six-step process used for BUIS is outlined below (Costa et al., 2012):

1. Imagery Acquisition – The first step in map creation was the acquisition and processing of high-resolution, remotely-sensed imagery. Aerial orthophotographs, lidar, and acoustic data were collected for the majority of BUIS.
2. Habitat Boundary Delineation – A draft benthic habitat map was generated using edge-detection algorithms to delineate habitat features clearly visible in the orthophotographs, lidar, and acoustic remotely-sensed imagery.

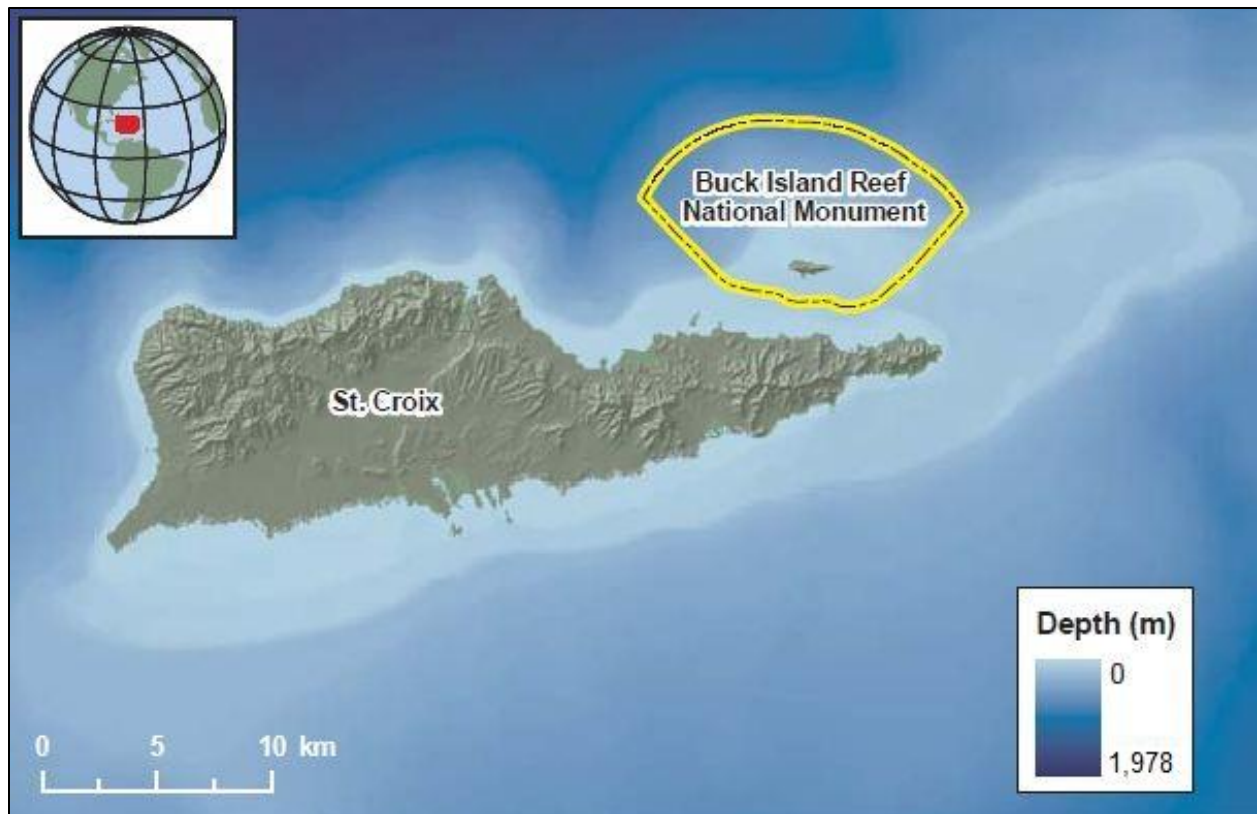


Figure 19. Buck Island Reef National Monument, U.S. Virgin Islands (adapted from Costa et al., 2012).

3. Ground Validation – Habitat features in the map with representative or with unknown spectral or acoustic signatures were explored using underwater cameras to identify unknown habitats and to confirm that the signature of known habitats remained consistent throughout the study area. Initial maps were edited to generate a second draft map.
4. Expert Review – The second draft map was reviewed online by local marine biologists, scientists, and resource managers to qualitatively assess thematic accuracy of the shallow-water map.
5. Accuracy Assessment – After incorporating comments from the expert review, thematic accuracy of the draft shallow-water habitat map was assessed using a random stratified sampling plan. Quantitative accuracy assessment was not conducted for the moderate and deep-water habitat maps.
6. Final Product Creation – A final benthic habitat map was generated by correcting inaccuracies identified during the accuracy assessment and edge-matching the shallow, moderate, and deep-water maps.

The workflow for BUIS was similar to VIIS-VICR, but was complicated by the extreme range of water depths and the number of sensors used. Three remote sensing technologies and six sensors were used to collect data: aerial orthophotos, lidar, and sonar (four missions using different sensors) (Figure 20). Data were collected at different spatial resolutions by several federal agencies, academic institutions, and private companies from 2004-2011 (Costa et al., 2012).

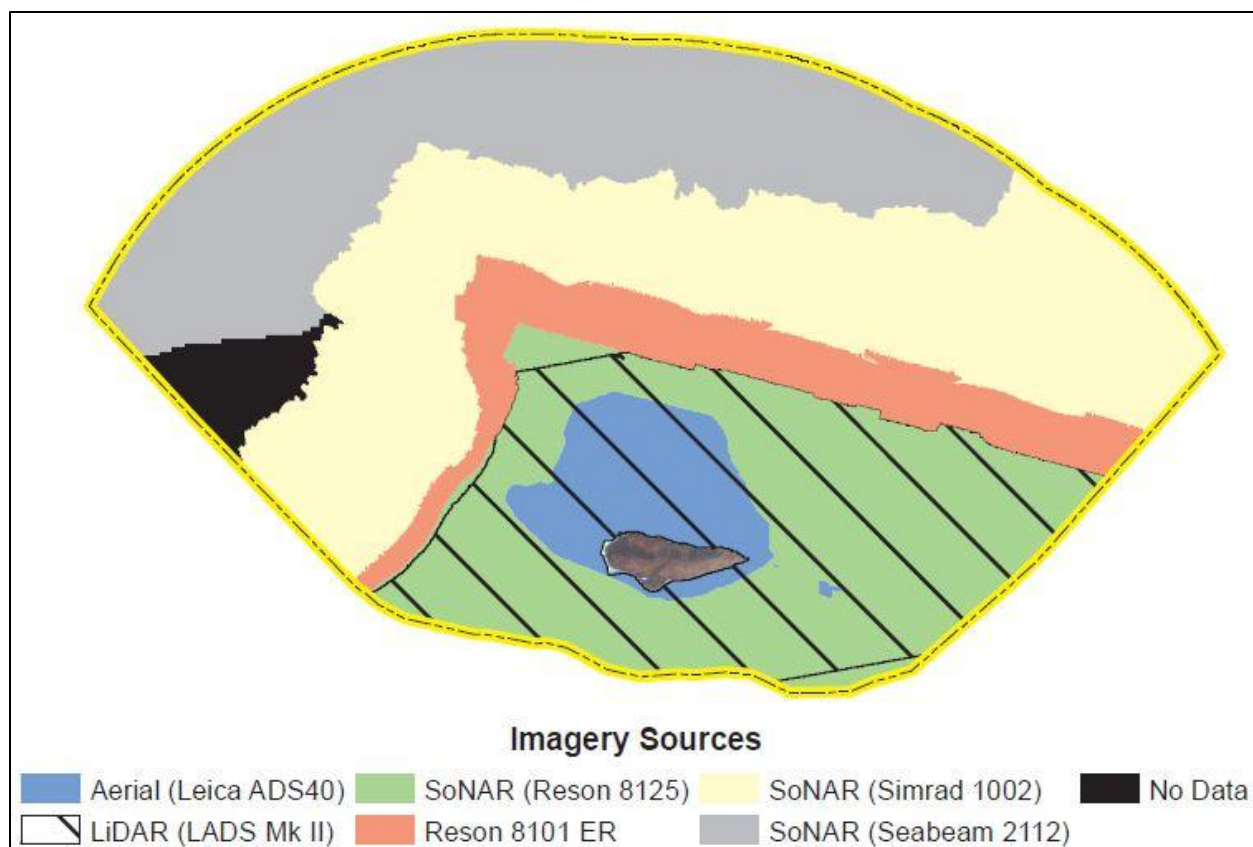


Figure 20. Buck Island Reef National Monument showing areas mapped with aerial photography, lidar, and sonar, and list of six sensors used (from Costa et al., 2012).

The study area was divided into five regions based primarily on depth and the spatial extents of the sensors used: aerial, shallow, moderate shelf, moderate, and deep. A semi-automatic delineation process involving pixel- and object-based algorithms and PCA analysis (similar to that used for VIIS-VICR) was used for initial habitat delineation. After habitats in each of the five regions were delineated, subjected to quality control, and edge-matched, the habitat datasets with the same MMU (i.e., aerial/shallow and moderate shelf/moderate) were merged. Three seamless benthic habitat maps, each with a different MMU, were created with the following depth zones: shallow ($0 \leq 50$ m; $0 \leq 164$ ft), moderate ($51 \leq 1,000$ m; $167 \leq 3,280$ ft) and deep water ($1,001 \leq 1,830$ m; $3,284 \leq 6,004$ ft) (Table 3) (Costa et al., 2012).

Table 3. Survey regions, source imagery resolution, minimum mapping units (MMU) and depth zones for Buck Island Reef National Monument benthic mapping project (from Costa et al., 2012).

Depth Zone	Survey Region	Source Imagery Resolution (m-ft)	MMU ($\text{m}^2\text{-ft}^2$)
Shallow ($0 \leq 50$ m; $0 \leq 164$ ft)	Aerial	0.35--1.15	100--1,076
	Shallow	1--3.3	100--1,076
Moderate ($51 \leq 1,000$ m; $167 \leq 3,280$ ft)	Moderate Shelf	10--33	1,000--10,764
	Moderate	10--33	1,000--10,764
Deep ($1,001 \leq 1,830$ m; $3,284 \leq 6,004$ ft)	Deep	50--164	5,000--53,820

A ground validation (GV) mission was not conducted for this project because the Biogeography Branch had previously collected data in support of the Coral Reef Ecosystem Monitoring Program and deeper hydrographic surveys from 2005-2011 via scuba and ROV transects, and drop camera sites. In the accuracy assessment phase, a small number of GV points were added in areas that were not sufficiently covered by previous efforts (Costa et al., 2012).

The shallow areas of BUIS had been mapped before, but this was the first time that areas deeper than 30 m (108 ft) had been mapped. The resulting data and maps are a baseline to which future mapping efforts can be compared to detect changes or trends in habitat composition and distribution.

An independent accuracy assessment was conducted for the shallow zone based on underwater video collected at 350 sites. No accuracy assessment was conducted for the moderate or deep zones because of the difficulty in accessing these habitats using traditional underwater sampling techniques (Costa et al., 2012).

For the shallow zone, accuracy error matrices were computed for five attributes: major geomorphological structure, detailed geomorphological structure, major biological cover, detailed biological cover, and percent coral cover. Adjusted overall accuracy for all five attributes (Table 4) was above the accuracy threshold of 80% suggested by Moses et al., 2010a.

Table 4. Summary of accuracy assessment results for shallow water benthic habitat mapping in Buck Island Reef National Monument (from Costa et al., 2012)

Attribute	Overall Accuracy (%)
Major geomorphological structure	94.4
Detailed geomorphological structure	85.2
Major biological cover	88.8
Detailed biological cover	81.4
Percent coral cover	90.1

Due to the different depths, ecology, and effects of different MMUs on habitat mapping, summary analyses were divided into two regions (Figure 21). The shelf region is shallower (mostly <30 m; 108 ft), has a smaller MMU, and more diverse geological patterns. The escarpment region is deeper (mostly >500 m; 1,640 ft), has larger MMUs, and large-scale geological patterns (Figure 22). The shelf region is dominated by coral reef and hard-bottom habitats (65%), which are concentrated mostly north and east of Buck Island. Pavement is the dominant detailed structure type, accounting for 66% of all hard-bottom habitats on the shelf. Unconsolidated sediment covers much of Buck Channel to the south of the island and large swaths in the deeper areas of the shelf region (Costa et al., 2012).

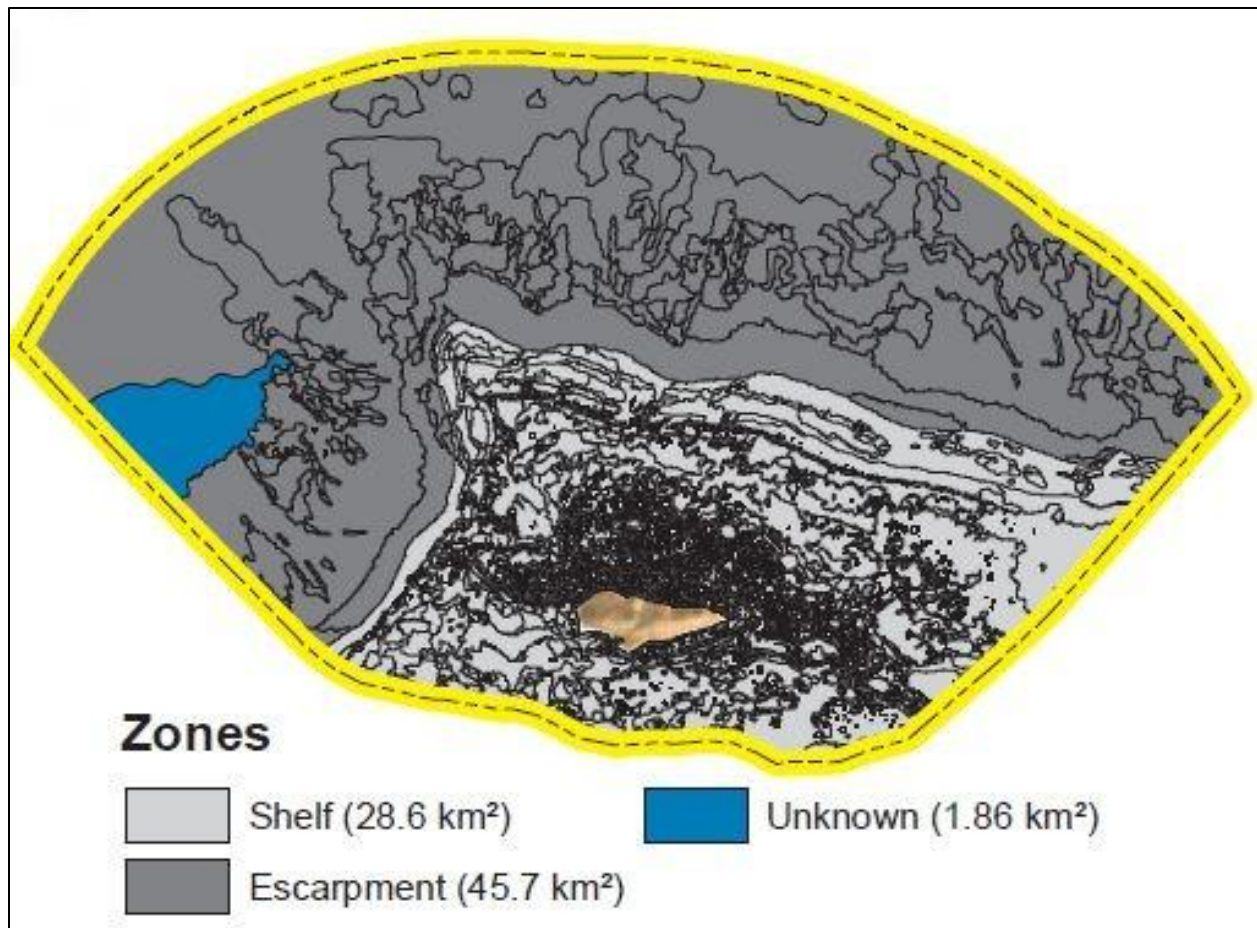


Figure 21. Final Buck Island Reef National Monument habitat map divided into two summary zones: shelf and escarpment. Buck Island and a marine area that was not classified due to a lack of data (blue area in western BUIS) were not considered in the summary statistics (from Costa et al., 2012).

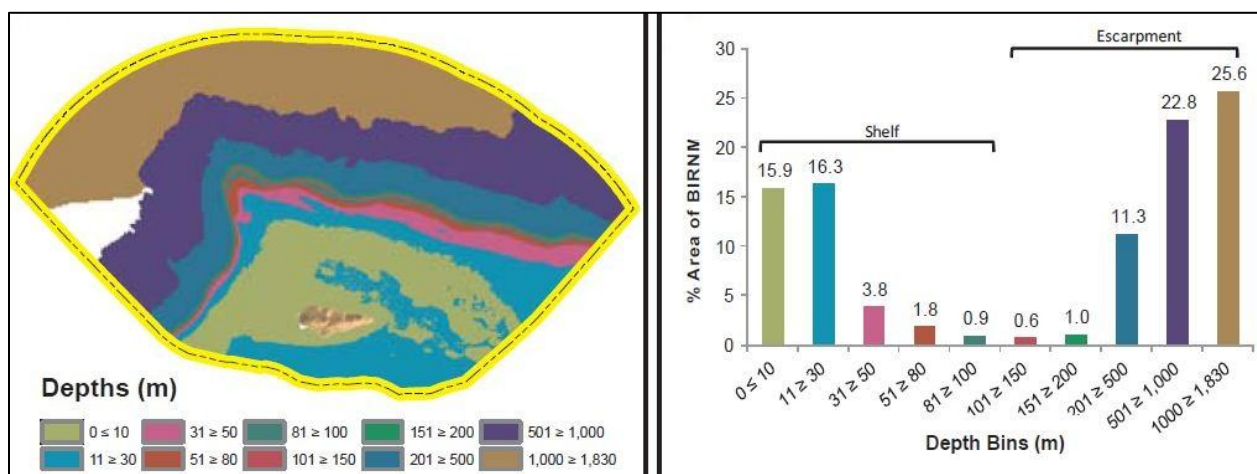


Figure 22. The shelf and escarpment zones were treated separately due to different depths, ecology, and minimum mapping units. Most of the shelf zone is 0-30 m (0-108 ft) deep and most of the escarpment zone is 500-1,830 m (1,640-6,004 ft) (from Costa et al., 2012).

The escarpment region is dominated by unconsolidated sediment consisting of fine-grained mud (51%) transitioning into sand (11%) in the shallower parts of this zone. Rock/boulder habitat (37%) is scattered throughout the escarpment region (Costa et al., 2012).

Deliverables include a final report (Costa et al., 2012), data acquisition reports, imagery, and habitat maps, which can all be downloaded from the NPS Integrated Resource Management Applications (IRMA) website (<https://irma.nps.gov/App/Reference/Profile/2184431>). NOAA also developed an interactive, web-based map application called Buck Island BIOMapper (<http://ccma.nos.noaa.gov/explorer/biomapper/biomapper.html?id=BUIS>), where the deliverables can be accessed and explored.

FY2010 Projects

West Arm of Glacier Bay, Glacier Bay National Park and Preserve (GLBA)

Mapping the West Arm of Glacier Bay complemented that of Muir Inlet (see FY08 Projects). Both areas are recently-deglaciated fjords in the Glacier Bay system. The morphology of the West Arm is typical of a glacial fjord – a shallow sill at the mouth, steeply sloping walls, and multiple deep basins separated by transverse sills and morainal banks (Hodson et al., in press).

High-resolution multibeam sonar data were collected by NOAA during bathymetric surveys in 2010. Bathymetry and backscatter data were gridded at 16 m (55 ft) horizontal resolution that cover about 93% of the West Arm from just below sea level to over 400 m (1,312 ft) depth (Hodson et al., in press).

Ground-truthing data were collected in 2010 by towed video sled equipped with forward- and downward- looking video cameras, lights, altimeter, and a pressure (depth) sensor. An ROV equipped with video cameras was used in areas where sled video transects were incomplete. Bottom grab samples from Cowan et al., 1994 (used in the Muir Inlet Study) and Cai 1994 were also used for ground-truthing (Hodson et al., in press).

Seafloor habitats were classified using a supervised manual classification of seafloor substrate based on knowledge from ground-truthing and two derivative bathymetric properties – seafloor rugosity and slope. Multibeam backscatter supplemented the primary data sets in locations where surficial geology was ambiguous.

Due to the low quality of the backscatter data in the West Arm, it was not possible to use backscatter intensity to infer substrate distribution (as was done in Muir Inlet). Instead, ground-truthed data collected during the study and previous NOAA cruises were used to characterize substrate distribution in the West Arm.

A preliminary map of surficial geology based on slope, geoforms, and ground-truthing observations was produced as the template for manual classification. The dominant substrate in the West Arm is mud, which covers about 72% of the seafloor. Bedrock (7%), sand and mixed sediments (4%), cobble/gravel (2%), boulder/rubble (<1%), and unclassified areas (14%) make up the rest (Hodson et al., in press).

The primary geoforms of the West Arm are fjord wall, rock outcrop, basin floor, delta /fan, and moraine (Figure 23). The high relative proportion of walls, floors, and moraines is characteristic

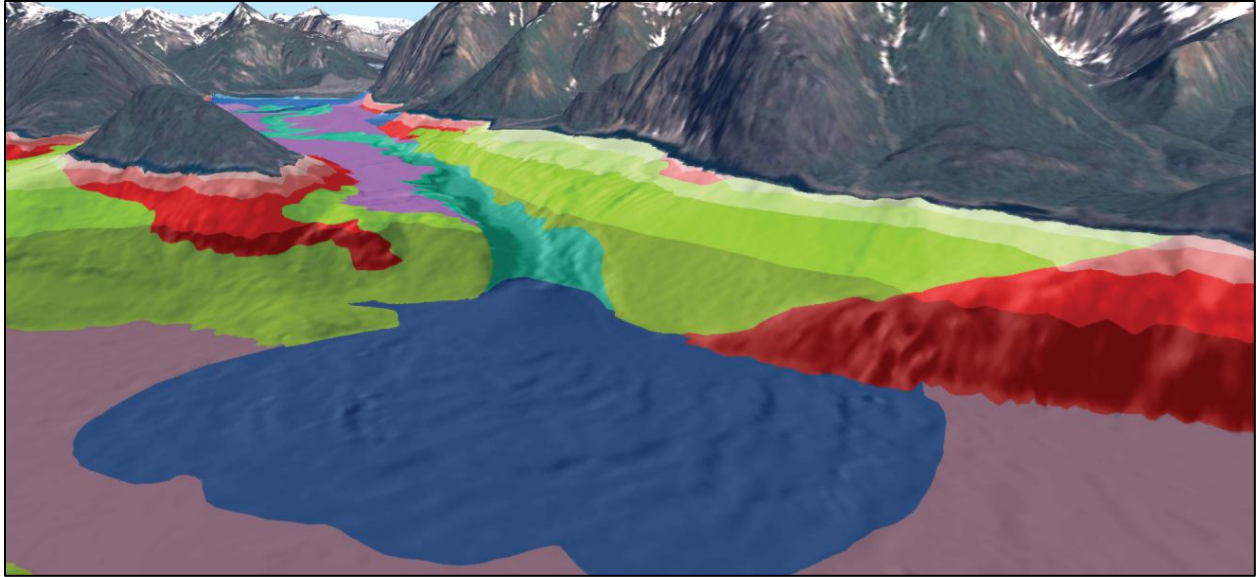


Figure 23. Perspective view of geofoms of Queen Inlet, Glacier Bay National Park & Preserve looking north over a submarine fan (dark blue) at the mouth of the inlet, which is a large hanging valley intersecting the main stem of the West Arm. The fan is fed by a 10-km (6.2 mi) submarine channel (light blue) incised into the fjord (purple). The moraine is coded from light green (shallow) to dark green (deep). Rock walls and outcrops are coded from pink to dark red. Vertical exaggeration is 1.5x (from Hodson et al., in press).

of glacial fjord morphology. Numerous deltas originating from fluvial and glacial-fluvial processes exist along the fjord walls (Hodson et al., in press).

The report was submitted to USGS for publication in 2012.

Point Reyes National Seashore (PORE)

Although the terrestrial and intertidal habitats of PORE have been described and mapped, little work has been done in the deep-water and nearshore habitats. Erdey-Herdon (2007) mapped some benthic habitat, but this is the first comprehensive benthic mapping of PORE. The study area is larger than the PORE boundaries and provides valuable regional context (Figure 24). Although data coverage in the “white zone” (nearshore, shallow, high energy zone) was better than in GOGA, it was not complete and some white zone interpolation was required.

Several datasets collected between 1998 and 2009 by different groups using different sensors and techniques were used to compile the maps. Data sources include MBES bathymetry and backscatter, interferometric bathymetry and sidescan, single-beam bathymetry, lidar, seafloor video collected by ROV and towed camera sled, sediment samples, coastal biophysical shoreline inventory, and kelp canopy data. Data for the terrestrial areas (orthoimagery, landcover, and geology) were incorporated in the final maps.

The PIs used their experience from the GOGA benthic mapping project to produce the report and map series. The methods, challenges, and deliverables for the two projects were very similar, including the caveat about the uncertainty of interpreting large areas of acoustic data based on sediment samples.

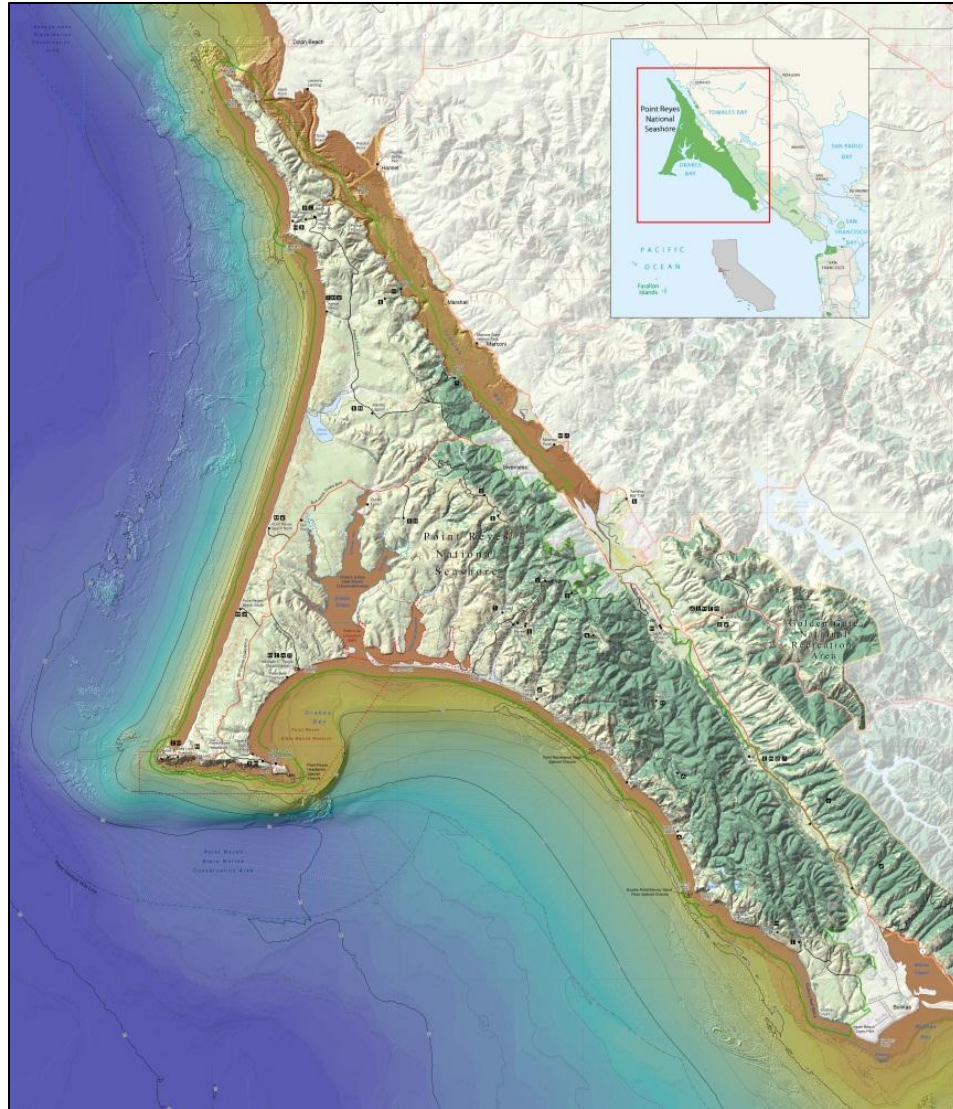


Figure 24. Location map of Point Reyes National Seashore, showing the park boundary (green area in inset) and extent of data coverage (adapted from Greene et al., 2011).

The Benthic Marine Potential Habitat Classification Scheme, developed by Greene and others (1999, 2007; Greene et al., 2011) was used to classify benthic habitats. Much of this classification scheme was incorporated into the final version of CMECS.

Thirty-nine habitat types were defined; 11 in estuaries and 28 on the continental shelf. The estuaries are >99% unconsolidated sediment and less than 1% hard substrate. The shelf area is 80% unconsolidated sediment and 16% hard substrate (mostly sedimentary rock). For the entire mapped area, 16% is hard substrates, 81% soft, and 3% mixed (Greene et al., 2011) (Figure 25).

Much of the offshore area of PORE is shaped by high-energy waves and currents. These areas have dynamic bedforms, such as sediment waves, mobile sand sheets, and dunes (Figure 26). “Dynamic bedforms... are considered potential foraging habitat for juvenile lingcod and possibly migratory fishes (Beaudreau, 2005), as well as for forage fish such as Pacific sand lance.” (Greene et al., 2011:16).

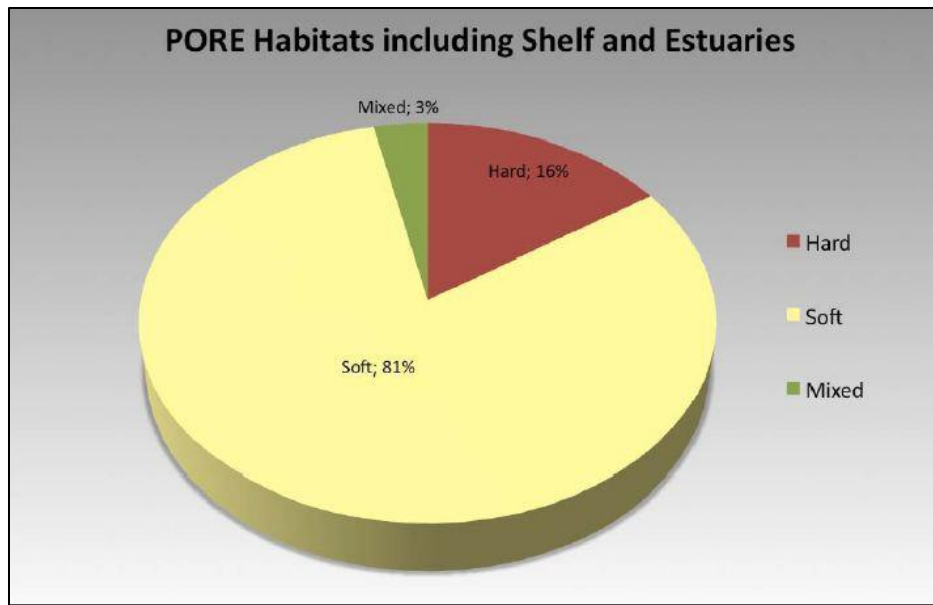


Figure 25. Habitats for Point Reyes National Seashore and surrounding area (from Greene et al., 2011)



Figure 26. Perspective view looking northeast towards Point Reyes Headlands. The colored bathymetric image shows dynamic bedforms of mobile sand sheets and dunes (center foreground) that are swept by bottom currents around Point Reyes Headlands. Also note the bedrock outcrop in the left foreground. Striations on the seafloor are artifacts from the roll of the survey vessel (from Greene et al., 2011).

Exposed hard rock makes up approximately 16% of the total mapped area and occurs predominantly on the shelf. Approximately 66% of the hard substrate (10% of total mapped area) are folded and faulted sedimentary rock and 33% (5% of total) are granitic basement rock. Both hard substrate types provide habitat for adult rockfish and lingcod (Greene et al., 2011).

The largest concentration of granitic rock occurs in the northern part of the mapped area from Elephant Rock north past Tomales Bay to the northern limit of the mapped area (Figure 27). Smaller granitic outcrops occur along the southern margin of Point Reyes Headland. From Elephant Rock south to Point Reyes, the nearshore zone is mostly soft, dynamic substrate, while offshore (outside park boundaries), extensive areas of sedimentary bedrock are exposed, creating

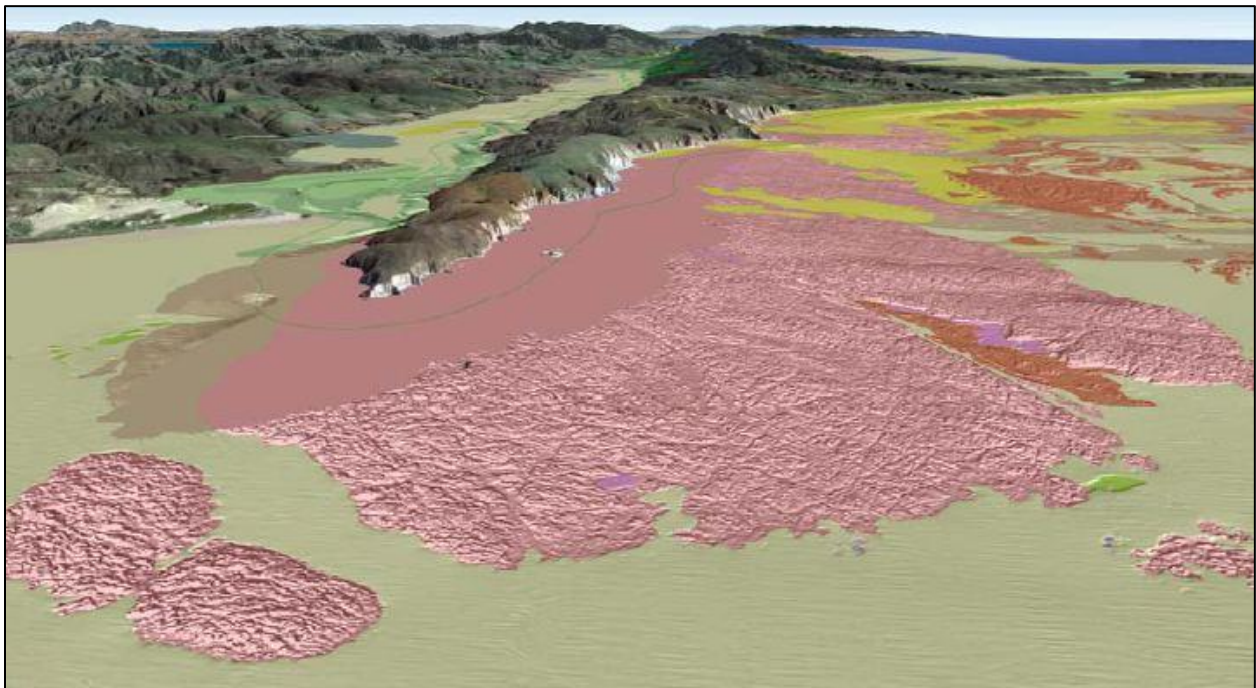


Figure 27. Perspective view looking southeast towards Tomales Point and Tomales Bay (center background). The view features the largest concentration of granitic outcrops (pink) in the mapped area. Smooth nearshore areas (white zone) lack multibeam echo sounder data and have been interpolated (from Greene et al., 2011).

potential rockfish and lingcod habitat along this entire stretch of coast (Greene et al., 2011). A concentration of sedimentary rock outcrops is found in the southern part of the mapped area, within and outside park boundaries, from Double Point to Bolinas Bay (Figure 28). Hard-bottom substrates are interspersed with dynamic, soft-bottom substrates creating an interesting mix of habitats suitable for adult rockfish, juvenile lingcod, and other forage fish (Greene et al., 2011).

Deliverables for this project include imagery, GIS data and metadata, a final report, six 1:48,000 scale maps, and a sheet of perspective views of areas of special interest. The perspective views (Figures 26-28) facilitate visualization of the distribution of benthic habitats and their relationship to the surrounding landscape. This successful project can be used to guide future mapping efforts.

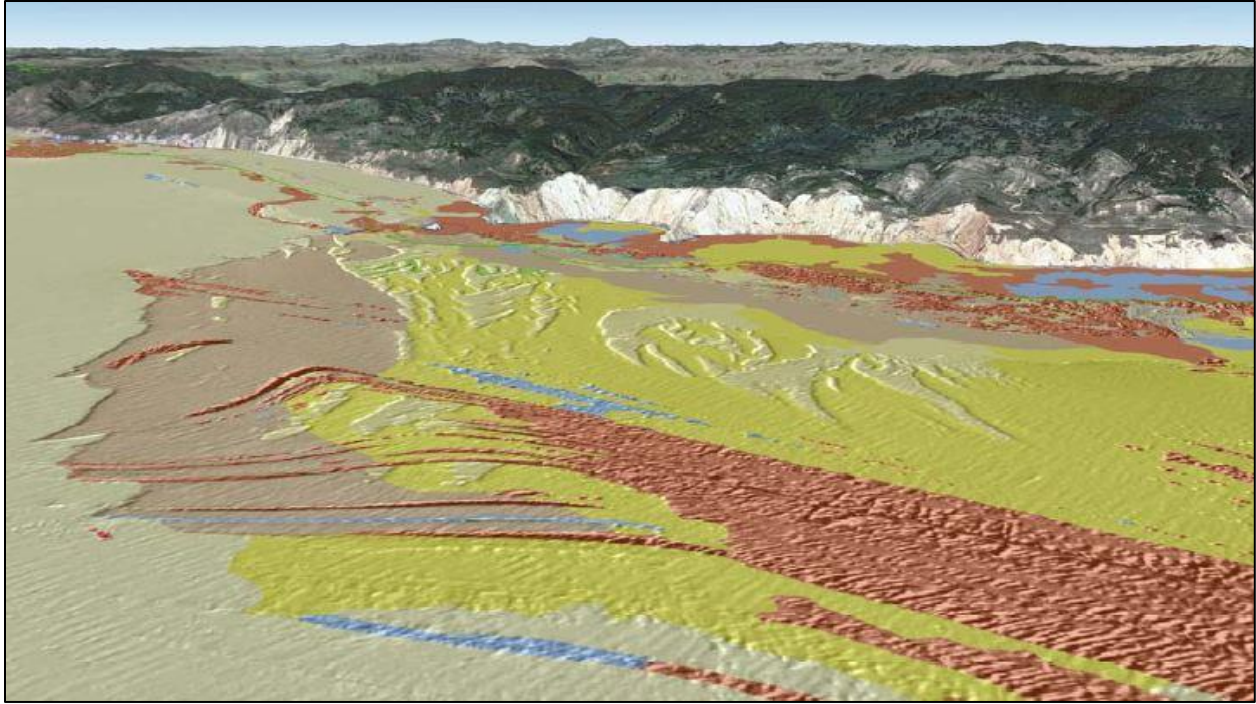


Figure 28. Perspective view looking north towards Double Point. This view shows a variety of habitat types, including a concentration of differentially eroded sedimentary rock outcrops (brown and blue), and dynamic bedforms made of sand, mud and gravel (tans and green) (from Greene et al., 2011).

San Juan Island National Historical Park (SAJH)

The project was coordinated by Dr. Gary Greene, who also coordinated the GOGA and PORE projects. The objectives of the project were to: 1) compile existing regional seafloor mapping data in and around the American and English Camp units of SAJH (Figure 29), 2) interpret MBES data collected by the Canadian Hydrographic Service, and 3) construct benthic habitat maps for SAJH. Since shallow-water nearshore and intertidal areas are difficult to map using conventional boat-based acoustic instruments, another goal was to investigate and develop a nearshore mapping protocol that could be used at other NPS coastal parks. The technique is based on the combined use of: 1) terrestrial lidar, 2) geo-referenced air photographs (collected during low tides), 3) bottom sediment grab samples, and 4) nearshore underwater video (collected during high tides).

MBES bathymetry and backscatter data were collected in 2010 by the Canadian Hydrographic Service using two instruments: one for waters >50 m (>164 ft) deep and another for waters <50 m (<164 ft) deep. In most areas, data tracks captured 100% of the seafloor with 100% overlap, providing 200% coverage. The newly collected MBES bathymetry data were processed to create raster images with a horizontal resolution of 1-2 m (3.3-6.6 ft); backscatter intensities were processed to a resolution of 1 m (3.3 ft). The images were displayed in a GIS and backscatter intensities were used to identify and delineate substrate type and sedimentary texture. Rock outcrops were identified using bathymetry and backscatter data. The interpretations were ground-truthed by video collected via towed sled. Interpretations were done at 1:1,000 or greater and the results were mapped at 1:5,200 or 1:2,200. Previously collected and interpreted MBES data were compiled and incorporated into the final maps. Lidar data (collected in 2009) were interpreted



Figure 29. San Juan Island National Historical Park (modified from Harper's Ferry Map Center: <http://www.nps.gov/hfc/cfm/carto-detail.cfm?Alpha=SAJH>).

and used to delineate features in a manner consistent with the MBES interpretation, which facilitated subsequent integration with the other datasets (Greene et al., 2013).

Sediment samples, single-beam bathymetry and other data collected and interpreted by the USGS were used to extend the maps at English Camp into deep-water areas of Westcott Bay (Grossman et al., 2007). Sediment samples were categorized as mud, muddy sand, sand, and sandy gravel based on grain size. Acoustic data and sediment samples were used to delineate seafloor substrate and habitat types within areas identified as soft induration (Greene et al., 2013).

Aerial imagery was acquired by means of a simple system that used a small, private plane with a wing-mounted, remotely-controlled camera (Figure 30). The camera was mounted to be as vertical as possible during flight, and images were acquired in 2010 and 2011 within 30 min of low tide. Flight path locations were recorded with a GPS unit, and the camera and GPS clocks were synchronized, which provided the general location of each image. The images were georectified using ground control points (GCPs) primarily from 2008 USGS orthoimagery (0.15-m [0.5-ft] spatial resolution), with additional points from 2006 USGS orthoimagery (0.5-m [1.6 ft] spatial resolution). The georectified aerial imagery was used to fill the data gaps in the white zone (Figure 31).



Figure 30. Wing-mounted, remotely-controlled aerial camera system.

Georectification, sometimes referred to as “rubber sheeting,” removes much of the imagery’s distortion caused by camera orientation and some of the distortion caused by topographic relief. Successful georectification requires multiple GCPs that can be recognized in the imagery, have known geographic coordinates, and are distributed throughout the image. Orthorectification is a more robust process than georectification. In addition to GCPs, orthorectification requires a digital elevation model (DEM) and camera lens specifications. The DEM allows a more thorough correction of topographic distortion, and the camera information is necessary to remove distortions caused by the camera lens. An orthophoto combines the image characteristics of a photograph with the geometric qualities of a map, allowing the analyst to delineate spatially accurate boundaries of features in the imagery. In areas with low topographic relief, such as SAJH, the spatial differences between an orthophoto and a well-georectified photo can be minimal.

Habitat boundaries in the white zone were delineated in a GIS by manually digitizing features visible in the aerial imagery. Habitat types were assigned to the delineated features and ground-truthed using underwater video and sediment grab samples. Habitat boundaries from all data sources were then combined in a GIS and processed into a continuous habitat map of the marine-terrestrial transition zone (Greene et al., 2013).

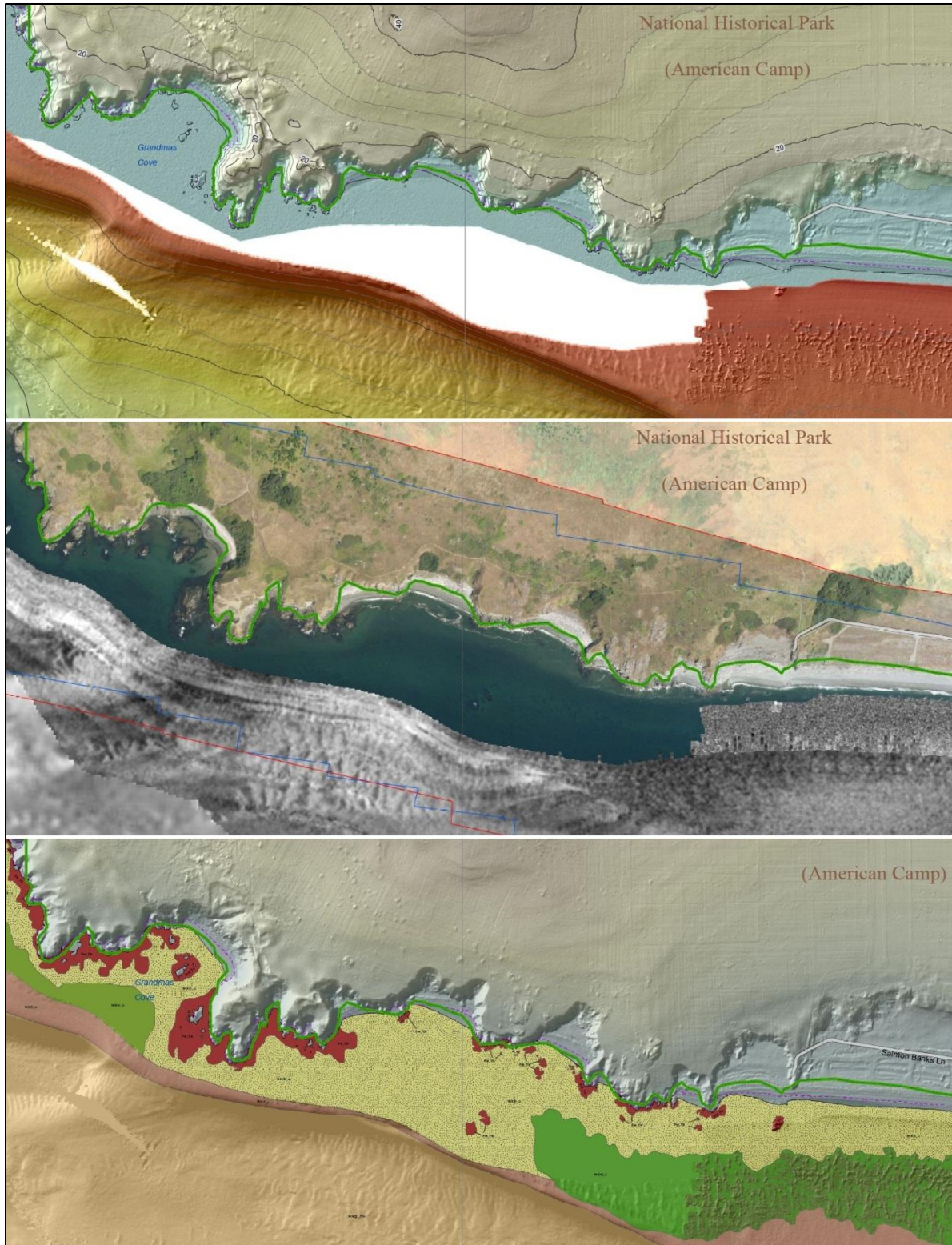


Figure 31. Examples from the American Camp “Bathymetry & Lidar” map (top), “Backscatter & Airphoto” map (middle), and “Habitat” map (bottom). The top image shows the lack of data for the white zone. The middle image is a combination of acoustic backscatter imagery and aerial photography that provides complete coverage in the white zone. The bottom image is the final habitat classification, interpreted from multiple datasets, with no data gaps.

A “high water line” was included in the “Bathymetry & Lidar” and “Habitat” maps (Figure 32). The line was determined by correlating the wrack line visible in the imagery with an elevation value in the lidar data. NAVD88 elevation values for the wrack line in several locations were averaged, and the average value was used for the high water line on the maps¹². For English Camp the high water line is 1.8 m (5.9 ft), and for American Camp the value is 2.4 m (7.9 ft) (above MSL NAVD88) (Maher et al., 2012). The American Camp coast is more exposed to wind and waves than English Camp, which could explain the different high water line elevations at the two sites, since wind and waves may push debris higher than the high tide level.



Figure 32. High water line shown as dashed magenta line on maps (adapted from Greene et al., 2013)

In the American Camp area, 28 potential habitat types were mapped in a total area of just over 12 km² (4.6 mi²). The dominant habitat type (~72% of mapped area) was soft, unconsolidated sediment. Other soft habitat types included beach sediment of sand, pebbles and cobble (~0.1%) and vegetated (primarily eelgrass [*Zostera marina*] at ~18% of total mapped area). Hard substrate (hard rock exposures, hard pinnacles and boulders) composed ~10% of the mapped area, and mixed soft over hard substrate covered approximately ~0.2% of the mapped area (Maher et al., 2012).

In the English Camp area, 15 potential habitat types were mapped in a total area of almost 13 km² (5.0 mi²). This area was also dominated by unconsolidated sediment (~99% of total mapped area), including three vegetation types (eelgrass [*Z. marina*], sea lettuce [*Ulva lactuca*], and sand with unknown vegetation) which covered ~3.7% of mapped area. Intertidal flats and channels made up ~11% of the mapped area. Hard substrate, including hard pinnacles, boulders and anthropogenic features (e.g., jetties, riprap, and oyster lines), made up approximately 1% of the mapped area (Maher et al., 2012).

In English Camp and American Camp, highly fractured bedrock, pinnacles, and boulders can provide excellent habitat for rockfish (*Sebastes* spp.), and sandy areas can provide habitat for the

¹² Norman Maher, Moss Landing Marine Laboratories, personal communication, June 11, 2013.

Pacific sand lance (*Ammodytes hexapterus*). Eelgrass beds stabilize sediment and provide foraging and refuge habitat for fish and waterfowl (Maher et al., 2012). Habitats in both areas were classified using the Benthic Marine Potential Habitat Classification Scheme developed by Greene and others (Greene et al., 2007) and incorporated into CMECS.

The use of aerial photography or satellite imagery to interpret benthic habitat types is an effective method to map the shallow, nearshore white zone (see FY2008 Virgin Islands projects) as long as favorable environmental conditions can be met. The inexpensive system devised for collecting aerial photographs for the SAJH project is a practical method that facilitated rapid deployment once environmental conditions were met. The method was especially practical and efficient in a relatively small park, such as SAJH. In a large park, it would be difficult to complete all the necessary flight lines within 30 minutes of low tide, so multiple flights involving multiple tide cycles with favorable environmental conditions would be required. Another disadvantage of using aerial photography in a large park is the small footprint of each image and the additional effort required to collect, rectify and process the imagery. High-resolution satellite imagery would be a viable data source in larger parks, as long as the spatial resolution met project objectives.

The keys to success of the methods used in the SAJH project are 1) favorable environmental conditions (clear, calm water, low tide, good sun angle, and good flight conditions), and 2) datasets that are accurately georeferenced to the same coordinate system. Accurate georeferencing allows spatial integration of disparate datasets.

FY2011 Projects

Channel Islands National Park (CHIS)

A Task Agreement is in place for a five-year project (August 2011 - July 2016) to construct marine benthic habitat and geology maps for CHIS. Dr. Gary Greene is on the mapping team, bringing his extensive experience and proven track record in producing benthic maps for the National Park Service. Phase 1 of the project is compiling existing data and collecting new data in areas monitored by CHIS. Phase 2 will acquire new data for the areas not included in Phase 1.

Overview of the Mapping Process and Guidelines for Benthic Mapping Projects

This section contains guidelines and a general workflow that can be applied to NPS benthic mapping projects. More specific protocols (e.g., minimum mapping unit; inclusion of adjacent, non-NPS lands in study area; thematic detail; mapping priorities; etc.) should be based on the needs of a particular project.

Partnerships

The NPS has neither the funding nor expertise to initiate and maintain an effective, self-equipped benthic mapping program. Due to programmatic priorities and the current budget climate, it is unlikely that such a program would be developed in the foreseeable future. To conduct successful, cost-effective benthic mapping projects, NPS should partner with experienced agencies and groups (e.g., NOAA, USGS, Moss Landing Marine Laboratories, etc.) that have equipment (e.g., boats, acoustic instruments) and benthic mapping expertise. If partnerships are cost-share agreements or add-ons to an existing project, it is important to reach consensus on objectives and protocols at the beginning of the project, and to communicate periodically about mapping progress and priorities.

Literature Review and Gap Analysis

An initial step in a benthic mapping project is to locate and review existing surveys and datasets relevant to the project, and to identify gaps in mapping and inventory data. Data gaps can be geographic (e.g., a physical portion of the study area lacks data), thematic (e.g., bathymetry data exist, but there no data for biotic cover), or a combination of the two (Moses et al., 2010a).

In 2012, NOAA conducted a gap analysis for the eight coral reef national parks and monuments¹³. The objectives were to identify and synthesize available biological, physical, and socioeconomic data sets relevant to marine resource management into a common GIS geodatabase framework and identify information gaps. Existing data holdings varied among parks, but most parks had at least some data for the major thematic resources (Table 5). Significant data gaps included oceanographic currents, vertebrate and invertebrate recruitment, coral reef growth and recruitment, and recreational fishing and diving pressure.

The NPS Northeast Region conducted a similar data analysis for marine and estuarine resources for 10 coastal parks. The project provides a thorough review of existing data, but does not provide the data. The report (*Priority Data on Marine and Estuarine Resources within Northeastern National Parks: Inventory and Acquisition Needs*) will be published in the Natural Resource Report series in 2013.

¹³ The project deliverables included a mapping portal where data can be displayed:

http://ccma.nos.noaa.gov/explorer/gapanalysis/gap_analysis.html.

The final report and data can be accessed on the NPS Integrated Resource Management Applications (IRMA) Portal: <https://irma.nps.gov/App/Reference/Profile/2186848>.

Table 5. Existing data holdings for major thematic resource groups for eight coral-reef national parks and monuments. SARI = Salt River Bay National Historical Park and Ecological Preserve; BUIS = Buck Island Reef National Monument; STJO = Virgin Islands National Park and Virgin Islands Coral Reef National Monument on St. Johns (STJO); KALA = Kalaupapa National Historical Park; KAHO = Kaloko-Honokohau National Historical Park; WAPA = War in the Pacific National Historical Park; NPSA = National Park of American Samoa. X = park has data, but not necessarily complete data (Dorfman and Battista 2012).

RESOURCES	SARI	BUIS	STJO	KALA	KAHO	WAPA	NPSA
Park Boundary	X	X	X	X	X	X	X
Shoreline	X	X	X	X	X	X	X
Bathymetry	X	X	X	X	X	X	X
Imagery	X	X	X	X	X	X	X
Socioeconomic Data (ESI)	X	X	X	X	X	X	X
Water Quality Monitoring	X	X	X			X	X
Fish Monitoring	X	X	X	X		X	X
Macroinvertebrate Monitoring		X	X	X			
Coral Monitoring	X	X	X	X		X	X
Shoreline Characterization (ESI)	X	X	X	X	X	X	X
Impervious Surface (CCAP)	X	X	X	X	X	X	
Landcover	X	X	X	X	X	X	X
Hydrology	X		X	X		X	X
Benthic Habitat Mapping	X	X	X	X	X	X	X
Digital Elevation Model	X	X	X	X	X	X	X

Scoping Meeting

Meetings held prior to mapping should include (at a minimum) natural and cultural resource managers, park physical and biological scientists, and external collaborators involved in the mapping process (e.g., technical experts; cooperating Federal, State and academic organizations; etc.). Discussions should clarify the goals of the mapping project, the extent of the area to be mapped, the minimum mapping unit to be used, data gaps and how they will be addressed, the classification scheme to be used, and park-specific management or resource issues that should be considered. Objectives, methods, accuracy thresholds, timelines, and deliverables should be clearly defined in writing.

Data Collection

Prevailing local environmental conditions figure prominently when evaluating data collection technologies (e.g., optical, acoustic, bottom sampling) and planning data collection missions. In some areas, local conditions will necessitate use of multiple technologies, as in the Virgin Islands pilot projects, where aerial and satellite imagery were the primary data sources for shallow-water habitat delineation and acoustic data were used in deeper areas. Additional environmental conditions to consider include water clarity, bottom contrast, surface conditions (chop, reflectivity, strong wind, waves, and currents), tidal range, cloud cover, fog, and rain. Many of these conditions have local seasonal trends that should be considered when planning a mission. It is also important to consider the relative ease of access to an area. For example, in particularly

remote or isolated areas, it is possible that unmanned aircraft, AUVs, and ASVs may lower mobilization and operational costs in the future.¹⁴

Data Post-processing

Post-processing data can be one of the most labor-intensive and expensive steps in the benthic mapping process. Post-processing includes any manipulation of the original remotely sensed data files to convert them into more usable formats. Some technologies, such as satellite imagery and aerial photography, may require relatively little post-processing, whereas most acoustic techniques demand intensive and complex post-processing to derive a quality product. Bathymetric and sidescan post-processing typically requires a 3:1 time ratio to data collection (NOAA Biogeography Branch, St. Croix Work Plan, 2009).

Data Interpretation (Classification)

The post-processed data are classified into discrete thematic categories, such as habitat types or bottom roughness, by three basic approaches: supervised, unsupervised, and visual interpretation. Supervised and unsupervised techniques rely on computer algorithms to segregate the data into discrete classes; visual interpretation is a manual technique that relies on human judgment to segregate the data.

In the supervised approach, representative samples are defined for each class. The parameters contained in the samples (e.g., a discrete range of reflected acoustic or visible values) are used to train a computer program to assign each pixel (or group of pixels) in the source data to one of the pre-defined classes.

The unsupervised approach segregates the pixels into a predetermined number of classes where all the pixels in any given class are more like each other than they are to pixels in another class. These classes must then be interpreted and assigned a class name.

In the visual interpretation approach, an analyst examines the image data and manually defines homogenous polygons (Zitello et al., 2009). Depending on the size and complexity of a dataset, visual interpretation can be labor intensive.

Hybrid techniques that use combinations of the three basic approaches are often used. The more automated the process, the more repeatable it is and the less observer bias that is introduced. Depending on the complexity of the data and on the thematic specificity of the classification goals, there is almost always some degree of human judgment and manual editing involved.

Validation of Draft Classification (Ground-truthing)

The ability to interpret remotely sensed benthic data (e.g., lidar, satellite imagery, acoustic backscatter) is significantly enhanced by detailed *in situ* data, such as physical samples (sediment) or visual samples (video, still photos, diver observations) of the seafloor. *In situ* data are commonly referred to as ground-truth data. Positive identification of substrate and features at sample points or transects can be used to interpret larger areas of the remotely sensed data that lack ground-truth information.

¹⁴ Bryan Costa, NOAA Biogeography Branch, personal communication, April 16, 2013

Sampling techniques vary in effectiveness depending on the substrate type, ease of access, and goals of the project. For example, it is difficult or impossible to obtain grab samples from hard substrates, such as bedrock, boulders, or cobble, and visual samples are more appropriate. If a project goal is to map infauna and epifauna, grab, dredge, or trawl samples would be required.

Ground-truth data collection should be carefully planned with project goals and classification scheme in mind. Attempts should be made to collect ground-truth samples representative of each class to be depicted in the final map. If no *a priori* knowledge of the study area exists, systematically collected ground-truth data may miss some targeted map classes and/or discover unexpected classes. Initial classification attempts often identify areas of uncertain type. The missed, unexpected, and uncertain areas are prime targets for follow-up ground-truth data collection.

In dynamic benthic environments (e.g., soft substrate with strong currents), efforts should be made to collect ground-truth data as near as possible to the time of primary data collection. The longer the interval between the two data collections, the greater the likelihood that conditions will change and the ground-truth data will no longer represent the remotely-sensed data.

Revision of Draft Maps

The ground-truth information gained in the validation process can be used to revise the draft maps. Improvements in thematic and geospatial accuracy are likely. After revisions, the draft maps should be reviewed by subject matter experts and potential users knowledgeable about the area not directly involved in the mapping process.

Expert Review of Data, Draft Maps and Report

NPS staff should be involved in the review process as well as others from diverse backgrounds, including other government agencies, non-government organizations, and academic institutions, as appropriate. Expert reviewers should be given at least a month to review the revised draft maps and report inaccuracies, omissions, etc. After revisions have been completed, a map accuracy assessment can be conducted.

Map Accuracy Assessment

In addition to verification and interpretation of imagery and draft maps, ground-truth data can be used to assess the accuracy of the final classified map. This step involves a substantial amount of work, but adds significant value to the final product. It gives users an objective measure of the accuracy of the map and may point out strengths and weaknesses in specific map classes.

Most of the NPS benthic mapping pilot projects acquired some form of ground-truth data (either existing or newly collected) that improved image interpretation, but only the projects conducted by NOAA's Biogeography Branch (BUIIS, VIIS, VICR) included a thorough map accuracy assessment by an independent team, not involved in the original classification work. This method reduces bias in the accuracy assessment.

An accuracy assessment is conducted by comparing random sample points on the classified maps to the corresponding points on the seafloor. Sample points should be stratified by map class to insure inclusion of an appropriate number of points from each class. When assessing map accuracy, there are two main types of accuracy: thematic and geospatial.

Thematic accuracy describes how well a classified area on the map describes what is actually on the bottom. If the classified map identifies an area as coral reef and field verification identifies the area as sandy substrate, the thematic accuracy of the map in that area is poor (Table 6). Overall thematic accuracy will vary from project to project, but should be at least 80% (Moses et al., 2010a). A simple classification scheme with a small number of easily distinguished classes is likely to produce a map with high thematic accuracy, while maps with many classes and maps with similar classes will likely have lower thematic accuracy. This idea is further discussed in the [Thematic Considerations](#) section.

Table 6. Error matrix for major geomorphological and coral cover classes from shallow-water mapping at Virgin Islands National Park and Virgin Islands Coral Reef National Monument (from Zitello et al., 2009). Thematic accuracy (P_o) was 86%.

		Accuracy Assessment (i)				User's Accuracy (%)
		Softbottom, Coral <10%	Softbottom, Coral 10% - <50%	Hardbottom, Coral <10%	Hardbottom, Coral 10% - <50%	
Map data (j)	Softbottom, Coral <10%	171		6		177 96.6%
	Softbottom, Coral 10% - <50%			3		3 0.0%
	Hardbottom, Coral <10%	9		172	24	205 83.9%
	Hardbottom, Coral 10% - <50%			26	64	90 71.1%
$n_{i.}$		179	0	207	88	$n=475$
Producer's Accuracy (%)		95.0%	n/a	83.1%	72.7%	$P_o = 85.7\%$
						$T_e = 0.809 \pm 0.042$

Geospatial accuracy refers to the positional accuracy of features on the map. Geospatial accuracy directly affects thematic accuracy. For example, if a map feature has poor geospatial accuracy (i.e., is offset from its true location), field verification could indicate that an area is incorrectly classified, when in fact it is correctly classified, but incorrectly located on the map.

Map accuracy requirements are likely to vary, depending on project goals, but Moses et al. (2010b:53-54) recommend that NPS benthic mapping projects adhere to the following USGS geospatial accuracy standards when possible:

Horizontal Accuracy - The USGS national map accuracy standard is that no more than 10 percent of randomly selected validation points should be misplaced by more than 1/50 of an inch on a 1:20,000 scale map (USGS, 1999). This translates to no more than 10 percent of test points being in error by more than 400 inches (10.2 m) on the ground. At coarse MMUs (e.g., 30 m, or 1 acre), precision must be less than 50 percent of the MMU.

Vertical Accuracy - The USGS national map accuracy standard is that no more than 10 percent of randomly selected validation points should be in error by more than half the contour interval (USGS, 1999). This translates to no more

than 10 percent of test points being in error by more than half of the vertical resolution of the instrument. For some lidar measurements in shallow clear water, a hypothetical acceptable error would be for less than 10 percent of validation points to be vertically incorrect by more than approximately 7 cm.

Final Products

After thematic and geospatial accuracy assessments have been completed, the final maps, metadata, and report can be prepared. Metadata should conform to the standards of the Federal Geographic Data Committee (FGDC), a national interagency committee that promotes the coordinated development, use, and sharing of geospatial data (FGDC, 2013b). Following are suggested deliverables, adapted from the SBMP Protocols Document (Moses et al., 2010b):

Publicly available online resources. Sharing information collected for each park unit is important. The final report and zipped data files should be archived in the Integrated Resource Management Application (IRMA, <https://irma.nps.gov>), a centralized NPS data repository. Online resources should include:

- Final Report
- Downloadable GIS files (e.g., geodatabases, shapefiles, raster data, FGDC-compliant metadata, map document files) for the project feature classes and maps (e.g., park boundaries, bathymetry, benthic cover, etc.)
- Downloadable maps formatted for display in Google Earth® (i.e., KML and KMZ formats)
- Submerged cultural resources data, carefully screened and approved to exclude sensitive or non-public content

Bound report. This is intended for alternative access to, or distribution of, information related to the benthic systems for a given park unit. This includes at a minimum:

- Study area geologic and ecologic framework
- Discussion of regional and local physical oceanography
- Methods and data collection
- Results
- Accuracy assessment
- Maps, figures, or lists representing every data layer available for the park unit.
- Links to online resources

Portable media with report and printable maps. Portable media (e.g. external hard drive, thumb drive, etc.) with digital resources is a useful archive of benthic-mapping products and includes at a minimum:

- All GIS and map data (e.g., geodatabases, shapefiles, raster data, metadata, map document files)

- PDF or equivalent digital format of the final report
- Large format (24 x 36 in or greater) ready-to-print PDF files (or equivalent) of each map in the final report with sufficient detail to be enlarged to that scale

Special Challenges and Considerations

Shallow Water and “White Zone”

Significant challenges to mapping shallow-water habitats include “variable currents, turbidity, challenging wave conditions, large temperature and salinity fluctuations (which can affect sensors and readings), limited clearance for mapping vessels, and navigational hazards that may limit vessel access or operation” (Hart et al., 2010:3). Paradoxically, even in calm waters without waves and currents, seafloor mapping with ship-based acoustic technologies in shallow water is more expensive and less efficient than in deep water due to the effect of shallow depths on the swath widths of acoustic instruments. The closer the sensor is to the seafloor, the narrower the swath width. Collecting narrow swaths of data requires more track lines, more time to achieve required coverage, and more time to process the data, all resulting in greater expense.

The white zone is the high-energy, nearshore zone that is typically difficult to map. Along exposed coasts it is roughly equivalent to the surf zone, although deeper draft vessels expand the offshore boundary of the white zone. It gets its name because it lacks data and is depicted as white (blank) areas on preliminary maps. Benthic habitat information for these areas can be interpolated from data collected in adjacent areas (e.g., terrestrial geology maps and marine benthic data).

One approach to mapping the white zone that has potential (but limited success in practice) is personal watercraft (Jet Ski) (MacMahan, 2001; Ruggiero et al., 2005). They can be used to deploy acoustic instruments in the shallow, high-energy surf zone where larger vessels cannot safely navigate. Their shallow draft and maneuverability give them advantages compared to larger vessels. Their powerful propulsion gives them advantages in strong currents compared to AUVs and ASVs. And their rapid deployment capabilities and low operating costs also allow them to take advantage of short periods of favorable environmental conditions. Nonetheless, even personal watercraft cannot safely access the surf zone during unfavorable environmental conditions (e.g., large waves, dangerous currents), so mapping the seafloor in the white zone remains a significant challenge.

Aerial lidar is another potential method for collecting bathymetric data in the nearshore zone. But turbid waters and the presence of clouds or fog limit opportunities for successful lidar data collection. Scheduling a lidar collection mission can be expensive and logistically challenging in areas with persistent rain or fog, where the aircraft, lidar equipment, and personnel would have to be reserved for an unspecified period and ready to deploy at short notice. Current research on turbidity-penetrating lidar looks promising, but is not yet operational.¹⁵

Intertidal Zone

Like any benthic mapping project, the best solution(s) to mapping intertidal areas will be dictated by mapping objectives, size of area to be mapped, and local environmental conditions. Mapping in the intertidal zone is especially challenging because of the tidal regime that transforms the zone from a slightly submerged to a fully-exposed area in a matter of hours.

There are three general approaches to mapping intertidal areas:

¹⁵ Tim Battista, NOAA, personal communication, May 16, 2012

- aerial or satellite-based sensors (e.g., lidar, visible imagery),
- water- or vessel-based sensors (e.g., interferometry, sidescan sonar), and
- land-based sensors (e.g., ground-based lidar).

The advantages, disadvantages, and limitations of the first two options have been discussed in the context of subtidal benthic mapping and provide potential solutions to intertidal mapping.

The third option, ground-based lidar, is a potential method for mapping the bottom structure of intertidal areas at low tide. Ground-based systems are especially useful for mapping geological features, such as sea caves and vertical cliffs that are difficult to capture with an aerial system (Storlazzi et al., 2007). Ground-based lidar systems are small, mobile, and easy to deploy, but limited by the effective operational range. Ground-based lidar systems can be classified by their operational range (Penn State, 2012):

- Short-range systems operate at ranges of 50-100 m (164-328 ft) with panoramic scanning, and are often used to map building interiors or small objects;
- Medium-range systems operate at distances of 150-250 m (492-820 ft), that achieve millimeter accuracy in high-definition surveying and 3D modeling applications, such as bridge and dam monitoring; and
- Long-range systems can measure at distances of up to 1 km (0.62 mi) and are frequently used in open-pit mining and topographic survey applications.

Depending on the size of the area, medium- and long-range systems would be appropriate for mapping the bottom structure of intertidal areas and creating a detailed digital elevation model. For areas larger than the effective operational range of the system, the equipment must be set up at multiple locations. Where coastal roads or beaches allow a vehicle to drive along a strip of intertidal zone, vehicle-mounted scenarios are possible. Rapid static laser scanning is a process where the vehicle-mounted instrument is quickly and efficiently moved from one scanning station to the next. Mobile mapping systems allow data to be collected from a moving vehicle, similar to an airborne system.

Ground-based lidar systems “can co-acquire true-color digital photos which are directly geo-referenced to the lidar returns to produce a highly detailed 3D representation of the surveyed area” (WSI, 2012). The resulting models have typically been used in engineering applications (e.g., building and road measurements, terrain change in mining operations, post-earthquake, etc.), but could be used to delineate intertidal ecotones or habitat boundaries.

Vertical Datum¹⁶

The National Geodetic Survey (NGS) defines, maintains, and provides access to the National Spatial Reference System (NSRS). The foundations of the NSRS are the horizontal and vertical datums, currently the North American Datum of 1983 (NAD83) and the North American Vertical Datum of 1988 (NAVD88). The NSRS and its datums are periodically revised as new technology and methods allow more precise and updated geodetic models.

¹⁶ See <http://www.ngs.noaa.gov/datums/vertical/VerticalDatums.shtml> for an explanation of vertical datums.

When the vertical component of spatial data is important (e.g., bathymetry, lidar, geodetic monumentation), metadata must include thorough documentation of the vertical datum (and its version or “realization”). If GPS is used to derive orthometric heights, it is important to include the reference ellipsoid¹⁷ (and epoch) and geoid¹⁸ that were used to obtain orthometric (NAVD88) heights¹⁹. Complete spatial metadata ensure the ability to update the spatial coordinates of a dataset as changes are made to the NSRS. Use of the latest geoid model to produce orthometric heights is recommended.

Collecting bathymetric data from a vessel in a marine or estuarine environment can present challenges related to tidal height variation. As the vessel rises or falls with the tide, tidal height variation is introduced into the depth data. If the amount of tidal variation is significant for a particular project, there are several ways to address it.

Some systems use GPS and inertial motion units to “level” this tidal fluctuation, either in real time or via post-processing. The GPS receiver records the vessel’s vertical position as height above ellipsoid (HAE). This information is added to the depth readings to yield depth in HAE. In this case, the ellipsoid is the constant “zero surface” to which all depth readings are referenced. Although this provides a consistent reference frame, the ellipsoidal model is an idealized model of the shape of the earth and does not necessarily describe the relationship of local water levels to local marine or terrestrial features. Referencing the data to a geoid model gets closer to real world relationships, but the “zero surface” reference is still based on a global or regional model, not local measurements.

Another way to address the tidal variation in a bathymetry dataset - without using global models - is to reference the depth data to a local tidal datum (e.g., mean low water [MLW], mean high water [MHW], etc.). This requires a local tide station that is collecting and recording water level data during the bathymetry data collection mission. If bathymetry data are referenced to local tidal heights, the specific tide station that provided the local tidal heights must be documented. The tidal epoch (expressed in a range of 19 years) and local tidal datum to which the newly collected data are referenced must also be documented. The particular tidal datum used is not as important as accurate documentation. As long as all metadata and the original dataset are preserved, the data can be re-referenced to a different tidal datum as needed for other projects.

To seamlessly integrate multiple datasets that are referenced to different vertical datums, all datasets must be converted to a common vertical reference system. VDatum²⁰ is a software tool designed by NOAA to vertically transform geospatial data between various tidal, orthometric, and ellipsoidal datums into a common vertical datum. A consistent vertical datum is important in

¹⁷ An ellipsoid is an idealized geocentric model of the shape of the earth that accounts for the relative flattening at the poles and elongation along the equator (imagine a slightly flattened kickball). GPS receivers calculate coordinates relative to the ellipsoidal model.

¹⁸ A geoid is “a hypothetical surface that corresponds to mean sea level and extends at the same level under the continents” (Collinsdictionary.com). When we say Denver, Colorado is 5280 feet “above mean sea level,” we are actually saying that it is 5280 feet above the surface of the geoidal model. A geoidal model takes into account the variations in Earth’s gravitational field. On a global scale the geoidal surface is lumpier than an ellipsoid; on a local scale the surface of the geoid is flat and level.

¹⁹ See Appendix 2 for an explanation of the relationship between ellipsoidal, geoidal and orthometric heights.

²⁰ See <http://vdatum.noaa.gov/>.

many coastal applications, including inundation modeling and the creation of seamless topographic/bathymetric datasets²¹.

Mapping Considerations

Determine Data Collection Technologies

In addition to environmental conditions, the type, extent, quality, and temporal relevance of existing datasets will help determine the most appropriate data collection technologies (e.g., aerial photography, multibeam sonar, lidar, etc.). This is why the initial data gap analysis is crucial. Once data gaps are identified and appropriate technologies are determined, strategies can be initiated to pursue partnerships and secure the funding necessary for new data acquisitions.

Costs

The costs of producing benthic habitat maps vary with technology and mapping location. Generally, optical imagery in shallow, clear waters is the least expensive, while acoustic imagery is the most expensive (Table 7).

Table 7. Approximate costs of benthic habitat mapping by remote sensing methods. Estimates are based on 2010 data. NOAA = National Oceanic and Atmospheric Administration; USGS = U.S. Geological Survey; km = kilometer; Lidar = light detection and ranging. To estimate costs per square mile, multiply cost per square kilometer by 2.59.

Technology	USGS	NOAA
Optical imagery	\$250-\$350 ^a /km ²	\$300 ^b /km ²
Lidar (aircraft based)	\$1,100/km ²	\$375/km ² at 5-m resolution \$2,000/km ² at 2-m resolution
Multibeam sonar (ship-based)	\$2,000-\$8,000/km ²	\$1,500-\$5,000/km ²

^asatellite and airborne imagery

^bhigh-resolution satellite imagery

Spatial Considerations

Several spatially-related questions should be answered to determine mapping objectives. What is the spatial extent of the project? Should the study area include a buffer; if so, how large should it be? Are there other agencies or organizations with marine holdings in the buffer area that you could partner with? What is the minimum size of features that need to be mapped?

Mapping objectives and available technologies determine the appropriate data type, spatial resolution, extent of new data collections, and the appropriate minimum mapping unit (MMU). The optimum MMU captures all features defined in the mapping objectives at minimal cost. If the MMU is too small, time and money are wasted on data collection and analysis. If the MMU is too large, small or fragmented habitat units can be missed or underrepresented in the classified habitat map; habitat diversity could also be underestimated. The MMU should be smaller than the smallest target feature and larger than the spatial resolution (pixel size) of the source imagery.

²¹ See Smith and Gallagher, 2011 (<https://irma.nps.gov/App/Reference/Profile/2194167>) for a discussion of and guidelines for obtaining accurate coastal elevation data.

Thematic Considerations

Use of a nationally standardized ecosystem/habitat classification scheme is important to enable monitoring and trend analysis at local, regional, and national scales.

Key benthic and marine features that need to be represented on the final maps (e.g., coral, seagrass, kelp, rock, sediment type, cultural features) should be identified early in the planning process. The required level of thematic specificity should be defined. For example, using CMECS, an oyster bed could be defined as any of the following (progressing from general to specific): faunal bed, sessile epifauna, mollusk reef, oyster bed. For a given project, is it enough to know that an area is a faunal bed, or do project goals require it be more specifically defined as a mollusk reef or an oyster bed?

The NPS Ocean and Coastal Resources Branch recommends using CMECS for benthic mapping projects. Because it is a Federal Geographic Data Committee standard, federal agencies and federally-funded coastal and marine habitat mapping projects are required to be consistent with CMECS²². At a minimum, the project must report in CMECS units; if habitats are characterized in a different system, they should be cross-walked to CMECS terminology.

Temporal Considerations

Seasonal and interannual events, such as currents, storms, earthquakes, tsunamis, etc., can affect bathymetry and benthic habitat structure and composition. It is important to remember, especially in dynamic benthic environments, that a habitat map is a snapshot of the conditions that existed when the data were collected. Opportunities for collecting new data in the wake of habitat-changing events should be pursued. To document trends and changes in benthic habitat, periodic data collection on a 5-10 year cycle is encouraged.

²² <http://www.fgdc.gov/standards/projects/FGDC-standards-projects/cmeecs-folder/cmeecs-index-page> and <http://www.csc.noaa.gov/digitalcoast/publications/cmeecs>

Conclusions and Lessons Learned

- Partner with agencies and programs that are established experts in marine benthic mapping (e.g., NOAA, USGS, Moss Landing Marine Laboratories). The technology and expertise needed to collect and process benthic data (e.g., lidar, bathymetry, interferometric and sidescan sonar), and the platforms to deploy them, are expensive and continually evolving. It would take a significant financial commitment from the NPS to purchase and maintain the remote sensing equipment and support vessels necessary for a servicewide program.
- Partner with researchers that have a track record working with specific technologies and data types. The differences between technologies, data types, and processing techniques used for benthic mapping can be significant. Just because a team is familiar with one type of data acquisition and processing (e.g., lidar) does not mean that those skills will transfer to another type of data (e.g., multibeam sonar). Technologies are evolving rapidly and each data type has a learning curve associated with it. There is also a certain blend of art and science involved in collecting and interpreting many of the specialized data types. Experience is key.
- Be specific about deliverables in the partnership documentation (Interagency Agreement, Memorandum of Understanding, etc.). Make sure that these documents address classification scheme to be used, map scale, minimum mapping unit, file formats (including FGDC-compliant metadata), acceptable amount of data interpolation, acceptable amount of ‘unknown’ category reported, accuracy assessments, and thresholds, etc. Get detailed information regarding data collection specifications and documentation (vertical datum, acoustic data track line width and spacing, image resolution, etc.).
- Be aware of the available benthic mapping technologies and match them to local environmental conditions. In situations where multiple technologies are needed, researchers need a plan to integrate the various datasets.
- Request two cost estimates based on use of existing data and acquisition of new data. In many cases, much valuable information can be gained by synthesizing existing datasets. This should be the first step for financial efficacy; it will be helpful for identifying and pricing future data acquisition, which can fill gaps in existing datasets (e.g., bathymetry or imagery) or suggest the collection of a new type of data (e.g., biotic cover).
- Use a nationally standardized ecological classification scheme to permit comparison of different data sets (within the same park and among different parks) and allow changes and trends to be detected, compared, and monitored at the park, regional, or national level. At a minimum, the project must report in CMECS units; if habitats are characterized in a different system, they should be cross-walked to CMECS terminology.
- Schedule a review period between the collection/interpretation of the data and the delivery of the final maps. If possible, it should include a meeting between map makers and map users and should be scheduled so that the users have adequate time to review the draft maps and suggest and approve any changes.

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Appendices

Appendix 1. Mapping Checklist

Adapted from the SBMP Protocols Document (Moses, et al., 2010b):

The recommended series of steps in an optimal order. Additional steps may be included, and the order of steps may be rearranged as long as those changes do not significantly decrease the effectiveness of the mapping process.

- Determine the need - What is the primary reason for mapping?
 - What is the objective of the map (for example, management of oyster reefs)?
 - What area *needs* to be mapped, and why? What areas would be nice to map if possible, and why?
 - What tools and instruments are needed? Can multiple surveys be combined for efficiency?
- Gap analysis - Create a list of missing map information (for example, bathymetry) and a map of where various spatial data exist or are needed.
- Scoping meeting - Hold a meeting to orient key personnel to the mapping plan.
- New data collection - Maximize efficiency and minimize expense by opportunistically combining surveys.
 - Bathymetry
 - Biotic cover
 - Geoform
 - Surficial geology
- Data processing - Retain a copy of the full-resolution raw data for later reprocessing with improved techniques.
- Data interpretation - initial mapping and classification (draft map)
- Validation of the draft map - field validation, proxy validation, and expert review
- Revision of the draft map
- Expert review
- Publication - in digital format and hard copy

Appendix 2. Relationship Between Terrestrial and Tidal Datums

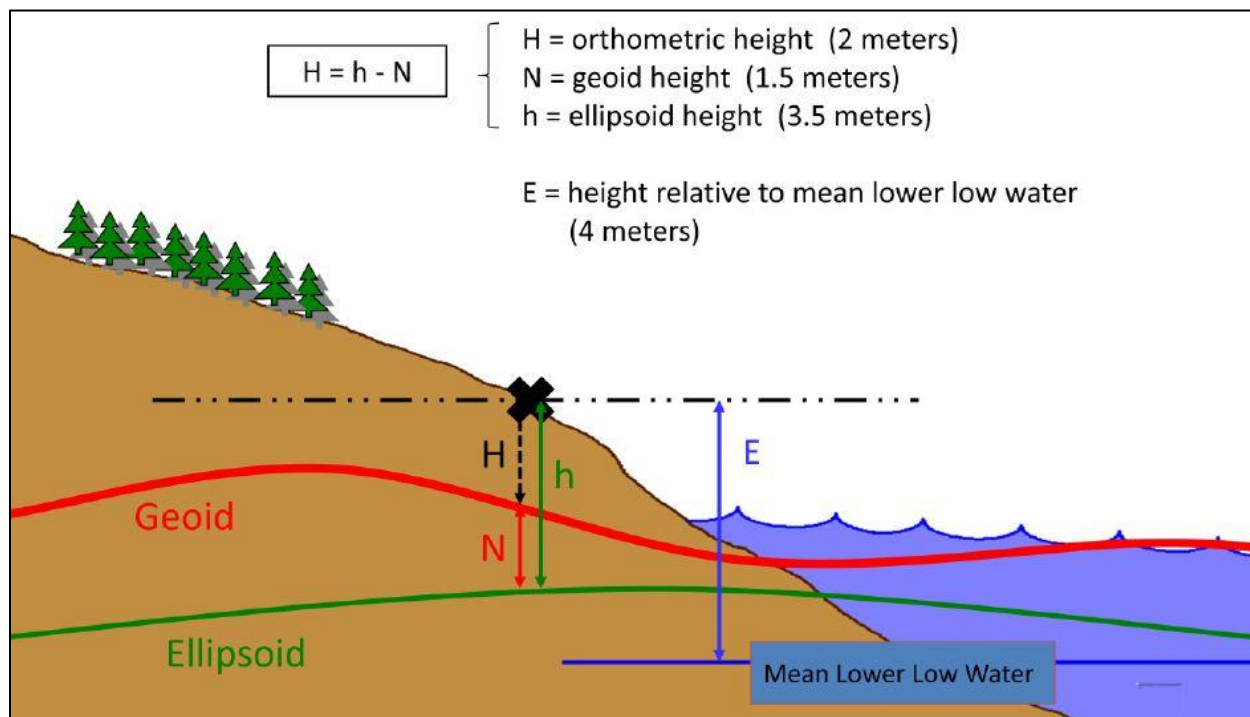


Figure 33. The relationship between terrestrial and tidal datums (from Smith and Gallagher, 2011).

- 1) Green line - When we use GPS to determine a position and elevation, that coordinate is relative to the ellipsoid. In this diagram, point “X” is distance “h” units above the ellipsoid.
- 2) The red line is the geoid which is an equipotential surface of the Earth's gravity field which best fits, in a least squares sense, global mean sea level. It is measured using gravity data. Point “X” is “H” units above the geoid. This distance is an orthometric height and what we colloquially, although not quite accurately, refer to as an elevation above mean sea level.
- 3) The equation illustrates how ellipsoid and orthometric heights are related algebraically. The value N is the geoid height and it allows us to calculate H using an ellipsoid height measured with GPS and a current geoid model as defined by NOAA’s National Geodetic Survey.
- 4) While the geoid represents, in a sense, global mean sea level, neither the ellipsoid nor orthometric height gives us any information about “X”’s position relative to local water levels. To account for local water levels, local tidal datums are defined based on local water level observations over long periods of time.
- 5) These datums include Mean High Water (MHW), Mean Tide Level (MTL), Mean Low Water (MLW) and others. The blue line on this diagram was drawn to represent MLLW, and it shows that “X” is distance “E” above MLLW.

The Department of the Interior protects and manages the nation's natural resources and cultural heritage; provides scientific and other information about those resources; and honors its special responsibilities to American Indians, Alaska Natives, and affiliated Island Communities.

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