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Mapping Shallow Coastal Ecosystems: A Case Study of a Rhode Island Lagoon

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ABSTRACT

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In order to effectively study, manage, conserve, and sustain shallow-subtidal ecosystems, a spatial inventory of the basic resources and habitats is essential. Because of the complexities of shallow-subtidal substrates, benthic communities, geology, geomorphology, and water column attributes, few standard protocols are fully articulated and tested that describe the mapping and inventory processes and accompanying interpretations. In this paper, we describe a systematic approach to map Rhode Island's shallow-subtidal coastal lagoon ecosystems, by using, integrating, and reconciling multiple data sets to identify the geology, soils, biological communities, and environments that, collectively, define each shallow-subtidal habitat. We constructed maps for these lagoons *via* a deliberate, step by step approach. Acoustics and geostatistical modeling were used to create a bathymetric map. These data were analyzed to identify submerged landforms and geologic boundaries. Geologic interpretations were verified with video and grab samples. Soils were sampled, characterized, and mapped within the context of the landscape and geologic boundaries. Biological components and distributions were investigated using acoustics, grab samples, video, and sediment profile images. Data sets were cross-referenced and ground-truthed to test for inconsistencies. Maps and geospatial data, with Federal Geographic Data Committee (FGDC)-compliant metadata, were finalized after reconciling data set inconsistencies and made available on the Internet. These data allow for classification in the revised Coastal and Marine Ecological Classification Standard (CMECS). With these maps, we explored potential relationships among and between physical and biological parameters. In some cases, we discovered a clear match between habitat measures; in others, however, relationships were more difficult to distinguish and require further investigation.

ADDITIONAL INDEX WORDS: *Bathymetry, subaqueous soils, depositional environments, side-scan sonar, sediment profile imagery, sediment cores, geology, biological communities, submerged habitats, CMECS, data integration.*

INTRODUCTION

Shallow, near-shore temperate marine ecosystems represent one of the most important and environmentally sensitive coastal habitats in the world (Gönenç and Wolflin, 2005). These ecosystems provide essential habitat for birds, finfish, and shellfish; support complex communities of benthic organisms; deliver diverse ecosystem services; and provide considerable

social, economic, and aesthetic value to human populations (Wilson and Farber, 2008). Within the next decade, nearly three-fourths of the U.S. population is expected to live within 100 km of the coast (Beach, 2002). This high population density, together with its associated commerce, pollution, and development, will put significant stress on these coastal and near-shore ecosystems. Furthermore, global climate change is expected to have profound impacts on coastal ecosystems through sea level rise, warming of air and sea, and increased storminess (Anthony *et al.*, 2009). With 10% of the world's population living in coastal landscapes occurring at elevations of 10 m or less (McGranahan, Balk, and Anderson, 2007), understanding many of the environmental changes expected

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from global climate change is critical to understanding the sustainability of coastal resources. Resource management and conservation plans that are needed for these areas depend upon spatially explicit inventories of physical properties and habitats as fundamental information (Cicin-Sain and Knecht, 1998). There are, however, few standard procedures for mapping shallow coastal ecosystems.

Mapping benthic habitats in shallow coasts and estuaries is a complex undertaking. Sharp boundaries as well as fine-scale gradients of water depth, physical energy, sediment types, salinity, and other factors create distinctive and complex spatial patterns of near-shore substrates that provide habitat for plants and animals (Diaz, Solan, and Valente, 2004). Traditional mapping protocols and technologies that were primarily established for terrestrial or deep-water environments do not always work effectively in shallow marine habitats. For example, side-scan sonar is a primary tool for mapping coastal waters; however, it is not often used in extremely shallow areas (<3–5 m) because of the difficulty of towing large instruments behind watercraft in shallow depths. Some surveys map these areas using autonomous underwater or surface vehicles; however, the cost of these instruments can be prohibitive. Acoustic imagery of benthic habitats has been reliably used to map biological features in hard bottom conditions such as coral reef, mussel, and oyster habitats (Kendall *et al.*, 2005; Kenny *et al.*, 2003; Taylor, 2001). However, soft-sediment environments, the most widespread marine habitats on earth (Zajac, 2008), are much more difficult to map for biological organisms using acoustic techniques (Anderson *et al.*, 2008; Brown and Collier, 2008; Hewitt *et al.*, 2004).

Although numerous schemes have been proposed for classifying estuarine and marine benthic habitats (*e.g.*, Cowardin *et al.*, 1979; Greene *et al.*, 1999; Madden *et al.*, 2010; Nitsche *et al.*, 2004; Valentine, Todd, and Kostylev, 2005); see Diaz, Solan, and Valente (2004) for a review; there is no consensus at present on a standardized nomenclature for naming and defining submerged coastal habitats. The most comprehensive system is the Coastal and Marine Ecological Classification Standard (CMECS) developed by the National Oceanic and Atmospheric Administration (NOAA) as part of their effort to solidify a national classification system for estuarine and marine habitats (FGDC SWG, 2010). The mapping protocol we describe here includes the basic datasets needed to classify shallow ecosystems using CMECS and illustrates methods for data synthesis and interpretation.

Since there are few standardized procedures for mapping shallow coastal temperate habitats, it is not surprising that there is a lack of standardized descriptive maps that are comparable over multiple mapping sites, across different jurisdictional borders, and encompassing multiple scales. In the pedological realm, the National Cooperative Soil Survey (NCSS) has maintained standards for mapping U.S. soil resources for over 50 years (Soil Survey Staff, 1951). Over the last decade, soil scientists have shown that substrates in shallow water (<5 m typically) can be effectively and economically characterized, classified, and mapped as soils following existing (albeit slightly modified) NCSS procedures (Bradley and Stolt, 2003; Demas and Rabenhorst, 2001; Osher

and Flannagan, 2007). Following the lead of the NCSS, and recognizing the need for shallow-water benthic habitat resource maps, the MapCoast Partnership (MapCoast.org) began developing standard methods and procedures for making such maps. MapCoast consists of a consortium of marine ecologists, geologists, soil scientists, biologists, and mapping scientists from a variety of academic institutions and public agencies (August and Costa-Pierce, 2007). In this paper, we describe an approach developed by MapCoast to map shallow coastal habitats in an inclusive and systematic manner that is transferable across a wide range of geographic regions and mapping scales. Our protocol involves use, integration, and reconciliation of multiple data sets to identify the properties, conditions, biological communities, and environments that, combined, define each shallow-subtidal habitat.

The goals of MapCoast are to provide resource managers, coastal decision makers, and scientists the basic spatial information needed to support resource inventories and conservation planning of nearshore marine ecosystems. Critical to the MapCoast initiative is the efficient dissemination of geospatial data describing coastal ecosystems; hence, an important part of our project is the development of digital data products and interpretive tools that can be distributed to a diverse group of data consumers *via* the Internet.

METHODS

Mapping Approach

We used an array of tools (Table 1) to sample and describe these different components of shallow coastal habitats in Rhode Island. The most recent digital orthophotography available was used as base maps to visualize all locations of our sampling and studies. Locations of all spatial data points were identified using differentially corrected global positioning systems (DGPS). We developed our maps by following a deliberate plan, which consisted of the following steps: (1) develop a bathymetric map using single beam acoustics and geostatistical modeling; (2) initially identify submerged landforms and landscape units using orthophotographs and bathymetric maps; (3) more clearly define landforms and landscape units and develop geologic boundaries using acoustic surveys; (4) verify acoustic geologic facies interpretations with underwater video and grab samples; (5) develop initial soil distribution maps through reconnaissance soil investigations within landscape and geologic facies boundaries; (6) characterize and classify representative soils; (7) characterize the biological components using grab samples, video, and sediment profile images (SPI); (8) test for inconsistencies in the data sets (bathymetry, geology, soils, and biological community) by cross-referencing and ground-truthing; (9) finalize maps after reconciling inconsistencies (differing interpretations) among data sets; and (10) develop Federal Geographic Data Committee (FGDC) compliant metadata for completed datasets and make them readily available on the Internet.

Study Area

Our mapping protocols were developed in the coastal lagoons (salt ponds) of southern Rhode Island (Figure 1). These shallow

Table 1. List of tools used and the data derived from each tool.

Data Metric	Tools	Citations
Depth/elevation	Echosounder; geodetic GPS; LIDAR; orthophotography	Guenther (2007); Huff and Noll (2007); Scherzinger, Hutton, and Mostafa (2007)
Shallow-water (<5m) subtidal landform identification	Side-scan sonar; orthophotography; contour map (GIS modeling)	Valentine, Todd, and Kostylev (2005); Kendall <i>et al.</i> (2005); Bradley and Stolt (2003); Maune <i>et al.</i> (2007)
Facies	Side-scan sonar; underwater video; grab samplers (augers or bucket sampler); vibracorer; orthophotography	Valentine, Todd, and Kostylev (2005); Goff, Olson, and Duncan (2000)
Subaqueous soil type (subsurface abiotic composition)	Vibracorer; augers; Macaulay peat sampler	Lanesky <i>et al.</i> (1979); Demas and Rabenhorst (1998); Bradley and Stolt (2003); Osher and Flannagan (2007)
Biological community	SPI; Side-scan sonar; grab samplers; underwater video	Guarinello (2009); Cicchetti <i>et al.</i> (2006)

lagoons (mean depth of 1.6 m) are separated from the open ocean by barrier spits that range from 1 to 8 km long and 0.8 to 3.5 km wide (Boothroyd, Friedrich, and McGinn, 1985). Ocean waters enter the ponds through jettied inlets (breachways) made permanent during the last century, predominantly in the 1950s and 1960s. Flushing rates for the ponds range from 1 to 5 days (Hougham and Moran, 2007). Freshwater input is primarily from groundwater, with little entering the systems from rivers or streams (Nowicki and Gold, 2008). Salinity values are close to those of open ocean (29–32 psu, Hougham and Moran, 2007). Land use adjacent to the ponds ranges from nearly pristine undeveloped natural habitats to dense residential development. All lagoons are popular destinations for recreational boaters and anglers; shellfish aquaculture is a common practice; and the inlet into Point Judith Pond has Rhode Island's largest commercial fishing port (Galilee, Rhode Island). Here, we present our data from Quonochontaug Pond, Rhode Island (71°43'30"W, 41°20'24"N), as an example of our habitat mapping protocols and procedures.

Bathymetry

A bathymetric data acquisition and processing protocol was developed to create a seamless grid of topography and bathymetry (topobathy). We used single beam echosounders because of their utility in extremely shallow environments. Topographic elevations were measured using a geodetic GPS (Trimble 4700), and mass points of elevation were obtained using photogrammetric methods and were provided by the Rhode Island Department of Transportation. When available, we used light detection and ranging (LIDAR) data from the NOAA Coastal Services Center (CSC) or the Army Corps of Engineers.

Bathymetric data in waters where depth was more than 0.5 m were obtained using a ship-based single beam fathometer (*e.g.*, Garmin 240 Blue) with positional data recorded by a DGPS receiver. Fathometer track lines were run both parallel and perpendicular in order to achieve the most comprehensive bathymetric data set. We obtained geodetic GPS elevations in

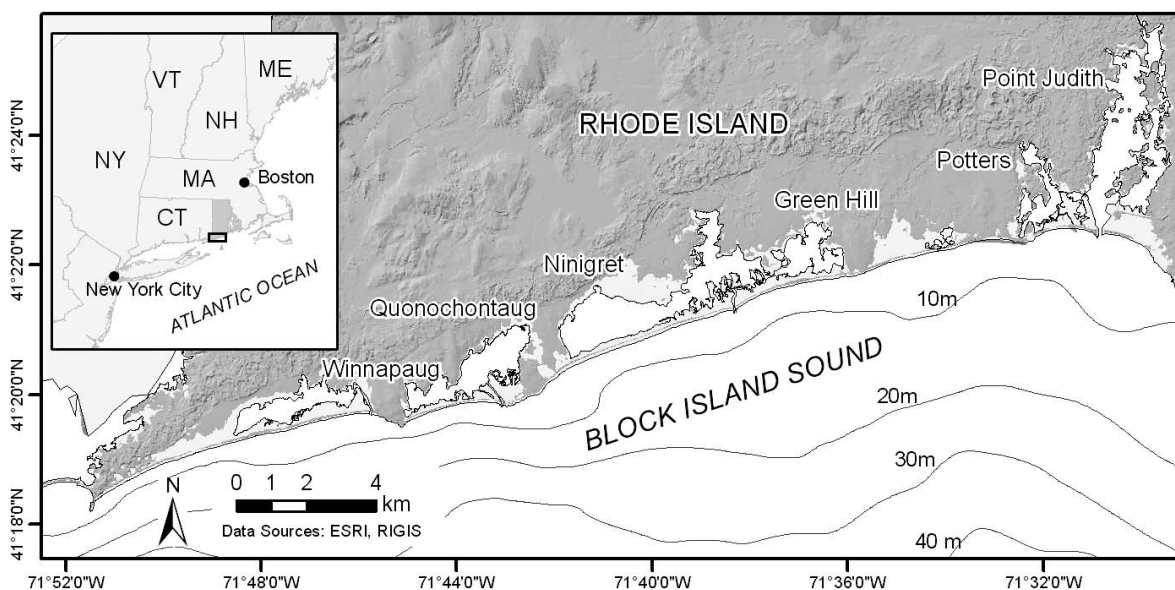


Figure 1. The coastal lagoons of the south shore of Rhode Island.

areas too shallow to traverse by boat (<1 m). To tide correct all bathymetry data, we used Hypack 2.12A Gold software with tidal flux data from two to three tide gauges established in the ponds. A water level logger (Solinst Levelogger Gold, corrected for barometric pressure with a Solinst Barrologger) collected tidal fluctuations every 6 minutes. Topographic and bathymetric data were collected and corrected relative to the North American Vertical Datum of 1988 (NAVD88) by using a geodetic GPS. This was done in one of two ways: (1) by measuring the elevation and location of the tide gauges or (2) by continuously measuring the elevation of the transducer during data collection.

All mass point data (fathometer soundings and GPS elevations) were entered into a triangular irregular network (TIN) interpolation model using ArcGIS 9.3 software (ESRI, 2009). A hard breakline of the land–sea border was imposed on the model using the wet/dry line obtained from 2004 digital orthophotography (0.61 m pixel size). The resulting TIN was converted to an ArcInfo grid with a 4.6-m pixel size and smoothed using a three-pixel radius average to produce bathymetric contour maps. We chose a TIN algorithm for our interpolation because of its conservative nature, ability to integrate mass points from different sources, and ability to include breakline features in the final model (Jordan, 2007).

Using geographic information system (GIS) spatial analysis tools, we assessed the accuracy of the bathymetry grids by randomly withholding approximately 10% of the mass points used to build the TIN model. We measured the difference in elevation between the final (unsmoothed) grid that was created with the subset of bathymetric data and the validation points to derive an estimate of the vertical error of the final topobathy grid.

Landscape Units

Landforms were identified through interpretation of the orthophotography and bathymetric maps. We further divided these delineations into landscape units based upon water depth, slope, and geographic position. Coves, submerged beaches, shoals, washover fans, flood-tidal deltas, and inlets are examples of landscape units we identified that are commonly found in many of the coastal lagoons along the east coast of the United States. These are commonly found in coastal lagoons such as Quonochontaug Pond (Figure 2). For further examples and definitions of landforms and landscape units, see Fisher and Simpson (1979); Boothroyd, Friedrich, and McGinn (1985); Davis (1994); and NCSS (2005).

Geologic Facies

We used side-scan sonar to collect acoustic data and interpreted the side-scan images based upon the texture and intensity of the returning signal. Spatially recognizable areas with different backscatter patterns represented side-scan sonar facies. In traditional geologic mapping, facies are bodies of sediment or rock with characteristics discernable in the field or laboratory, including color, particle size, sorting, structure, and biologic content, among others (Walker, 1992). Side-scan sonar facies are simply the geologic facies in which information

about particle size, sorting, structure, and living organisms are interpreted from the strength and texture of the returning sonar signal: the harder the bottom, the stronger the return signal and the darker the side-scan sonar record (using an inverse color scheme). As a result, we mapped facies based on the relative signal strength, with boundaries representing our interpretation of differences in grain size.

Benthic geologic habitats were interpreted and identified by ground-truthing side-scan facies with underwater video imagery, digital orthophotographs, sediment samples, bathymetry, SPI, and sediment core data, as well as with existing or estimated tidal current, wind, and wave information. We used the “traditional” high-resolution towed side-scan sonar towfish to collect acoustic data for identifying geologic facies. We manually digitized the seafloor (bottom tracked) to set the actual towfish height above the seafloor, allowing the images to be slant range corrected. Slant range corrected data represent a true linear representation of the side-scan information across the track of the record (Fish and Carr, 1990). The sonar, operated at a frequency of 500 kHz (390 kHz actual), was linked to SonarWiz scan acquisition software (CTI, 2011). The total swath width was 112 m (56 m on each side of the towfish). Survey lines were spaced every 75 m, with additional survey lines parallel to the shoreline of basins and coves. Data were collected in water as shallow as 0.5 m. Raw sonar data were processed using Sonar Web software (CTI, 2005). Data were spatially located using the DGPS signal embedded in the digital side-scan files and the spatial offset was accounted for between the GPS antenna and side-scan towfish. Navigation data were smoothed using the software-supplied smoothing function, removing spikes and outliers in the raw GPS data. The mosaics were checked for consistency in gain and contrast, and we applied a time-varied gain correction to account for the differences in intensity between returning signals across the mosaic (Fish and Carr, 1990). We used the same analog gain settings to collect all raw data; however, occasionally files that were plotted alongside each other had different coloration for the same apparent sonar facies and either the contrast or the time-varied gain was adjusted to bring the colors into balance. These differences do not impede interpretation and are caused by changes in towfish altitude, changes in slope of the lagoon bottom, or slight changes in grain size, particularly small increases in the percentage of shells and shell fragments (Goff, Olson, and Duncan, 2000). For maximum contrast, final side-scan mosaics were displayed in a “Klein” color scheme (an inverse medium yellow-orange color ramp (Ostnes, Abbot, and Lavander, 2004)). The final mosaic pixel size was <30 cm.

Facies boundaries were digitized onto the digital mosaic in a GIS, with a scale of 1 : 1000 (Figure 3). At this scale, boundaries between side-scan facies were discernable, and, because of pixel size, a larger scale did not improve interpretation or line placement. Polygons were coded based on their side-scan facies, and the area and perimeter of each polygon calculated using GIS software. Minimum polygon size was 300 m².

Grain size, bed roughness, vegetation, and slope can influence the intensity of the side-scan sonar signal (Kendall *et al.*, 2005; Nitsche *et al.*, 2004; Valentine, Todd, and Kostylev, 2005). Side-scan facies were ground-truthed by collecting

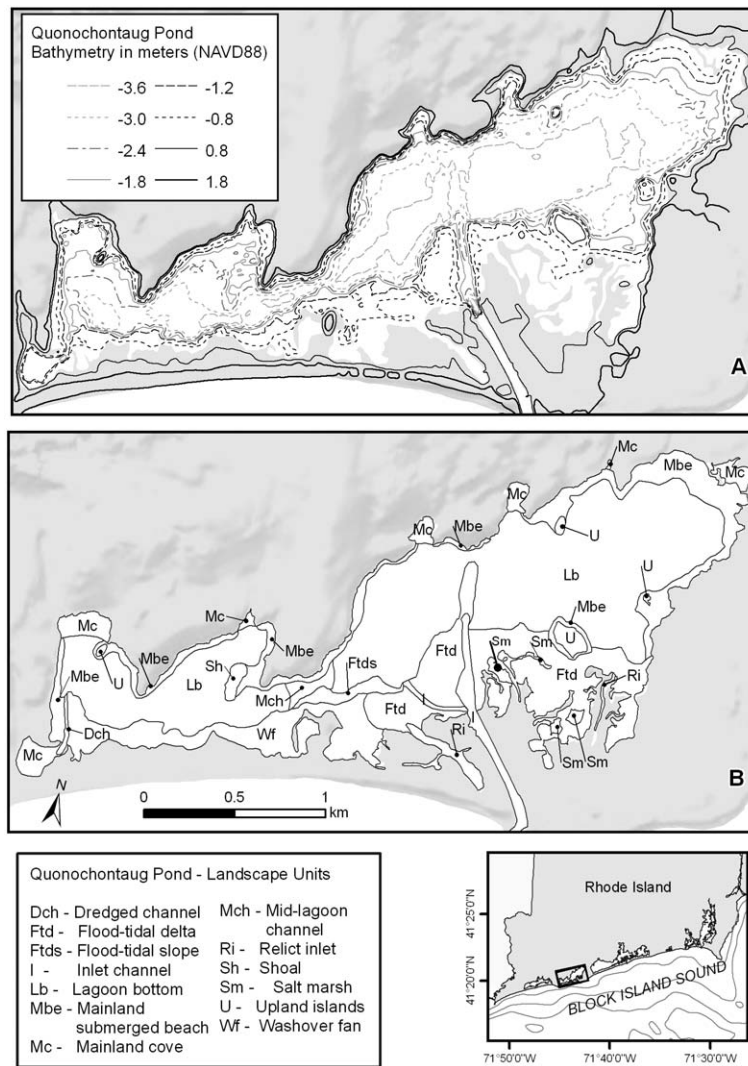


Figure 2. (A) The topobathy contours lines and (B) landscape units for Quonochontaug Pond, Rhode Island.

surface samples and underwater video imagery. We collected surface samples of the top 10–15 cm from each of the side-scan facies using a bucket-style sampler. Sample locations were selected from each of the side-scan facies, and we navigated to

these points using a DGPS. We analyzed samples using standard sieve and pipette techniques (Folk, 1980).

Underwater video imagery was collected in the study sites using a commercially available color underwater camera

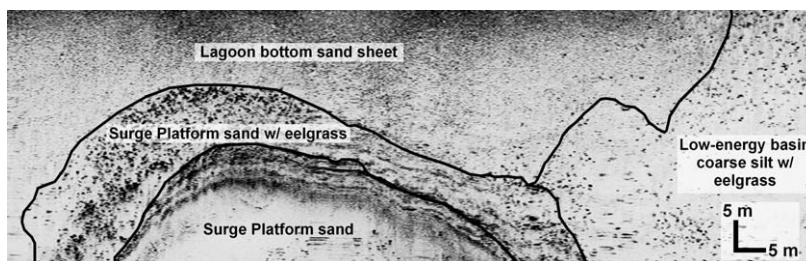


Figure 3. Interpreted side-scan sonar image from southwest Quonochontaug Pond.

(SeaViewer, Tampa, Florida). We determined spatial information including latitude, longitude, and approximate drift speed and time using a DGPS and imprinted (watermarked) in real time. Underwater laser pointers spaced at 10 cm provided reference for the video. Videos were viewed in the lab, and the still-frame images were used to provide a representative view of each sampling location.

The extent of the benthic geologic habitats (depositional environments) were interpreted by comparing the side-scan sonar facies identified with information from surface sediment samples, underwater video imagery, and pertinent information on tidal currents and wave energy. The extent of the depositional environments in shallow waters (<2 m) was often based on side-scan sonar data, supplemented with high-resolution (<1:5000) digital orthophotographs with pixel size <1 m and low-angle oblique aerial photographs. This imagery allows for identification of the presence/absence and type of submerged aquatic vegetation (SAV) or macroalgae present and identification of boulders and bedrock outcrops in areas too shallow for safe navigation.

Subaqueous Soils

We began our mapping of subaqueous soils within the framework of the initial geology, landform, and landscape unit maps. These boundaries were used because such delineations provide the first approximation of soil spatial distributions and offer an objective delineation of subaqueous soil–landscape units (Bradley and Stolt, 2003; Osher and Flannagan, 2007). We sampled soils and delineated the various soil types within each landscape unit based on similar physical and morphologic properties (Soil Survey Staff, 1993). Typically, field sampling was conducted from a modified 5.8-m pontoon boat with an opening (60 × 60 cm moon pool) in the middle of the forward deck that provided access to the water below for sampling subaqueous soils. Areas too shallow for boat navigation were sampled on foot. Reconnaissance field tools included a Macaulay peat sampler, bucket auger, and tile probe (with extensions). Peat samplers worked best in organic soil materials or mineral materials with a low bearing capacity (*i.e.*, fluid or very fluid; high *n* value). A Macaulay peat sampler collected soil materials to 3 m below the soil–water interface without difficulty.

In areas where low *n* value (*i.e.*, nonfluid) mineral soils dominate, a bucket auger was used to sample the upper ~75 cm of the soil. We used tile probes to find the depth to bedrock (or similar consolidated or semiconsolidated materials). Percentages of boulders and large stones were estimated by aerial photo interpretation and by conducting a single transect across map unit boundaries using the tile probe for submerged boulders. Established procedures were followed to describe soils, including standard morphological properties such as color texture and horizonation (Schoeneberger *et al.*, 2002). Based on physical and morphological properties, we classified and delineated soils within landscape unit boundaries (Soil Survey Staff, 2010). When more than one soil type was identified within a landscape unit (if the mapping scale allowed), we further divided the soil–landscape unit into dominant soil types. Obvious features identified from orthophotography such as glacial outcrops and

mainland coves were delineated at resolutions <0.25 ha, but the majority of subaqueous soil map units were larger than 0.5 ha.

In representative areas within each soil map unit, a vibracorer (Lanesky *et al.*, 1979) was used to collect relatively undisturbed samples of the upper 1–2 m of soil for detailed description and laboratory analysis. Cores were extracted using a 2.5-ton electric winch attached to a tripod mounted over the moon pool in our pontoon boat. Once removed, we dewatered, trimmed, labeled, and sealed the cores on the boat. Immediately after returning from the field, the cores were placed in a refrigerator. Cores were described, sampled, and analyzed for a range of parameters including particle size distribution, electrical conductivity, sulfide, organic carbon, calcium carbonate, and metal contents (Bradley and Stolt, 2003; Bradley and Stolt, 2006; Soil Survey Laboratory Staff, 2004). Based on physical, chemical, and morphological characteristics, all soil cores were classified to the family-class level according to Soil Taxonomy (Soil Survey Staff, 2010). We used Natural Resources Conservation Service (NRCS) soil series range in characteristics to define soil types to the series level and assigned a map unit symbol indicating soil type and water depth class (<1, 1–2, 2–3, and >3 m). We consulted side-scan sonar backscatter images for evidence of surface stones and boulders or shell reefs and, if necessary, further adjusted the map unit. Those map units having considerable surface stones or boulders were identified in the map unit symbol; see Soil Survey Staff (1993) for the criterion we followed. We “heads-up” delineated and digitized soil mapping units into a GIS using 2004 true color digital orthophotography as a base map. Generally, we used a scale of 1:2500 with a minimum mapping unit of 0.5 ha for digitization. Map units were named for the predominant soil type (series) found with the delineated areas. Soils that were similar to those for which the mapping unit was named but were too small to map (inclusions) were noted in map unit descriptions.

Biological Community Mapping

We implemented a suite of techniques (Table 1) to map epibenthic and subbenthic (infaunal) biological communities. Multivariate statistics were used to determine whether or not biological communities were compositionally different among acoustic, geologic, and soils units. This approach assumed that landscape-level features are the driving force behind biological variability in the study area. Since a detailed description of biological community patterns is beyond the scope of this paper, our discussion is restricted to landscape-level biological community characteristics. Detailed descriptions of the procedures used to map eelgrass and the finer scale dynamics of the benthic biological habitat in Quonochontaug Pond are found in Guarinello (2009). In general, we primarily focused on mapping the distribution of eelgrass (*Zostera marina*) because it is widely recognized as an important estuarine and marine habitat (Duarte *et al.*, 2008; Hinchey *et al.*, 2008), is often used as an indicator of habitat quality (Dennison *et al.*, 1993; Stevenson, Staver, and Staver, 1993), and can be reliably described with acoustic data (Lefebvre *et al.*, 2009). To delineate the areal extent of eelgrass beds, we identified initial eelgrass distributions visually from a speckled pattern in

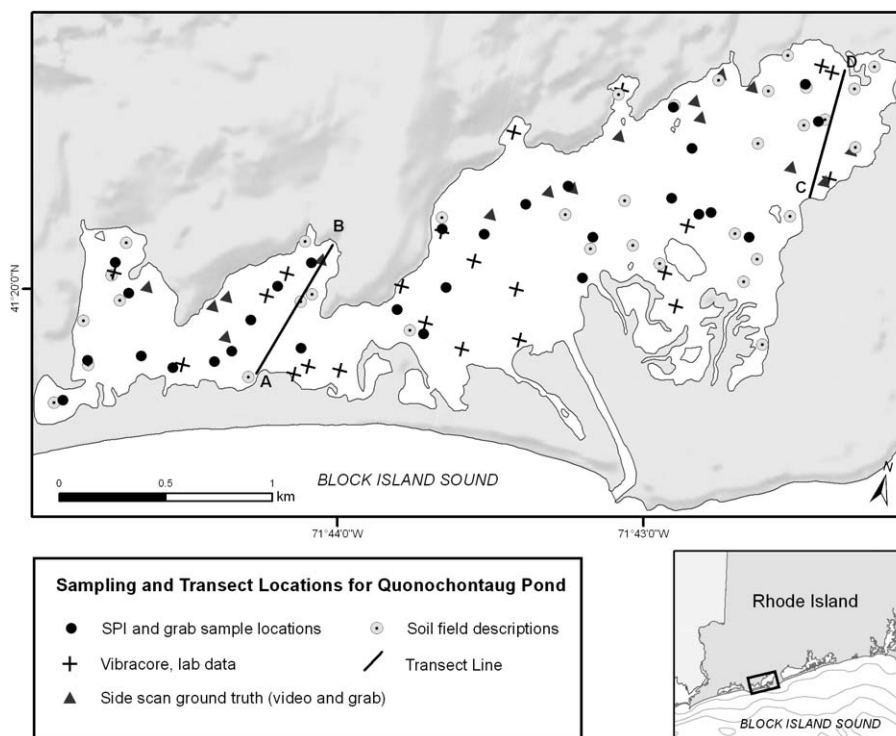


Figure 4. The locations of SPI and grab sample sites in Quonochontaug Pond, Rhode Island. The lines labeled AB and CD refer to two detailed transect surveys.

side-scan sonar mosaics (Ford, 2003) and used grab samples, underwater video, SPI, and aerial photos to ground-truth polygons of eelgrass distributions. The Sideview and Clams utilities (QTC, 2004, 2006) were also used to perform an unsupervised classification of the acoustic backscatter data (McGonigle *et al.*, 2009). This provided an automated categorization of bottom types based on backscatter signatures (grouped into QTC classes), and we evaluated these against our manual interpretation of eelgrass distributions. Benthic community (infauna and epifauna) sampling stations were selected for SPI and grab samples (Figure 4) based on the eelgrass, bathymetric, and landscape unit maps. The locations of stations were chosen to ensure comprehensive sampling across the geomorphic settings.

A digital SPI was used to photograph the sediment-water interface and up to 20 cm below the surface, where most benthic activity takes place. Sediment profile imagery has been frequently used for benthic mapping and assessment by observing organism-sediment relationships and the apparent successional stage of infaunal communities (Rhoads and Germano, 1982; Valente *et al.*, 1992). These cameras allow a rapid evaluation of benthic infaunal community structure through quantification of burrows, feeding voids, animals, tubes, *etc.* The images also allow a quantification of the apparent redox potential discontinuity (aRPD), the depth of lighter colored, more oxidized sediments, an important and informative biogeochemical parameter. Sediment profile image information has been used to develop environmental condition indices such as the organism-sediment index

(Rhoads and Germano, 1986) and the benthic habitat quality index (Nilsson and Rosenberg, 1997).

We conducted SPI surveys monthly at 24 stations (Figure 4) from May to November 2007 and in June, July, and September 2008. The sediment profile imagery was analyzed in Adobe Photoshop 7.0 to record the presence/absence of vegetation, the number of infauna and epifauna, and the presence/absence of burrows, feeding voids/pits, and fecal pellets. Images were not affected by the clarity of the ambient water, but in most cases the resolution was not sufficient to identify benthic fauna to anything more specific than functional groups (*e.g.*, deep burrowing worm, surface tube dweller).

Benthic grab samples were collected at the same 24 sampling stations in Quonochontaug Pond using a Petit Ponar sampler (2.2 L volume, sampling area 0.023 m²). Samples were sieved at 0.5 mm, and organisms were identified to the lowest taxonomic level possible. We collected samples three times (May, August, October 2007) at each of the 24 stations distributed throughout the pond (Figure 4). A multivariate statistical approach, following the techniques outlined in Clarke and Warwick (2001) using PRIMER v6 software (Clarke and Gorley, 2006), was used to analyze infaunal data. For the purposes of this study, data from all of the monthly biotic surveys were aggregated. Significant differences in benthic communities were tested (as defined by SPI and grabs) among acoustic (QTC class), geologic (depositional environment), soil, and eelgrass units.

Samples within polygons containing the speckled side-scan pattern and with visible eelgrass in multiple SPI images were

Table 2. *Depositional environments of Quonochontaug Pond delineated from side-scan sonar records and high-resolution vertical aerial photographs.*

Flood-Tidal Delta	Lagoon				
	Bottom	Channel	Margin	Cove	Other Features
Sand flat	Sand sheet	Lagoon channel (sand)	Erosional terrace (gravel)	Low-energy basin (organic silt)	Bedrock outcrops
Relict flood-tidal delta sand flat	Low-energy basin (organic silt)	Inlet channel (sand and gravel)	Erosional terrace (sand)	Low-energy basin (organic silt with boulders)	Isolated boulders within other environments
Sand flat	Glacial outcrop (boulder and gravel)	Inlet channel (sand)	Depositional platform (sand)		
Flood ramp (sand)		Abandoned inlet channel (sand) Flood channel (sand) Ebb channel (sand) Undifferentiated channel (sand) Dredged channel (sand)	Surge platform (sand) Tidal flat (sand) Tidal flat (mud) Distributary delta (sand) Dredged marina (sand)		

considered “within eelgrass beds.” If a site had a considerable number of eelgrass seeds and more than 25 *Microdeutopus gryllotalpa* (an herbivorous amphipod) but was just outside side-scan sonar eelgrass polygons and eelgrass did not appear in SPI images, then it was considered “adjacent to and influenced by eelgrass.” We classified all other sites as “outside eelgrass beds.”

Once completed, we ground-truthed areas of differing interpretations from the geology and soil delineations and classifications and adjusted them so they shared common boundaries, as appropriate. Finalized data were posted on the MapCoast web site along with FGDC-compliant metadata for each data layer.

RESULTS

Bathymetry

A seamless topobathy model was developed for Quonochontaug Pond from over 19,000 survey grade fathometer soundings and 1575 GPS elevations, as well as elevations derived from photogrammetric sources (>5000 total mass points for TIN model; Figure 2). The pond is one of the deepest along the south shore of Rhode Island, with a mean and median depth of 2.65 m (NAVD88) and maximum depths (5–5.5 m) occurring within the inlet and just north of the flood-tidal delta.

Our accuracy assessment of the topobathy model calculated a mean deviation of 0.12 m, with 91% of the validation points being less than 0.3 m. Validation statistics are reported in the metadata for the topobathy data (www.mapcoast.org).

Geology—Depositional Environments

Depositional environments in Quonochontaug Pond were classified as depositional (low-energy basins, *etc.*) or erosional (terraces, channels, *etc.*) and further grouped into subenvironments (lagoon bottom, channel, margin, cove, *etc.*; Table 2). Four low-energy basins comprise 55% of Quonochontaug Pond, occupying topographic lows in the underlying bedrock and Quaternary surface. Most of the northern, eastern, and

western shorelines of the lagoon are erosional terraces, where wind waves generated by both southeasterly storm waves and southwest sea breezes erode the Pleistocene glacial deposits. This leaves behind a pavement of sand and gravel, while transporting the finer grained (silt and clay) material to other areas within the lagoon, or out of the lagoon *via* the tidal inlet. Areas with a high concentration of boulders are mapped as outcrops of glacially deposited boulder gravel concentrations. Bedrock outcrop is common along the northern shoreline of the pond, as are small bedrock islands and subtidal outcrops throughout the lagoon.

The southern portion of the lagoon margin behind the barrier spit is comprised of primarily sand-sized sediment deposited as overwash during storm events. Where the jettied tidal inlet enters the lagoon, a large flood-tidal delta has accumulated. The flood-tidal delta was further divided into subenvironments, following the terminology presented by Hayes (1975) and Boothroyd, Freidrich, and McGinn (1985), to include intertidal and subtidal sand flats, flood ramps, and differentiated channels.

Subaqueous Soils

In Quonochontaug Pond, 12 subaqueous soil mapping units were identified based on 72 profile descriptions (Table 3). All of the soils were dominated by mineral materials and classified to the Wassent suborder (Soil Survey Staff, 2010). Soils containing sulfidic materials in the upper 50 cm were ubiquitous in the lagoon, with 51% of the soil taxa belonging to the Sulfiwassent great group. Sulfidic materials are mineral or organic soils that, if incubated in a moist state at room temperature, show a pH drop of 0.5 or more to a pH of 4.0 or less within 16 weeks (Soil Survey Staff, 2010). Fluventic Sulfiwassents were very common in the lagoon bottom landscape unit and were found in some of the deepest portions of the lagoon, 2–3 m (NAVD88). These soils have high *n* values (>1), fine particle size distributions (<50% by weight sand), and relatively high levels of organic material (1–15% by weight). Subaqueous soils of the flood-tidal delta and storm-surge platform were typically sandy to depths of 1 m or more (Psammowassents). However, soils

Table 3. Soil map unit names and phases, associated landforms or depositional environments, soil subgroup classification, and soil taxon brief description.

Subaqueous Soil Map Unit	Depositional Environment(s)	Typical Soil Subgroup Classification
Aa, Anguilla bouldery sand	Glacial outcrop (boulder and gravel)	Haplic Sulfiwassent
Bn, Billington silt loam	Lagoon cove	Thapto-histic Sulfiwassent
Fn, Fort Neck silt loam	Lagoon bottom and lagoon cove, low-energy basin	Haplic Sulfiwassent
Kb, Kebek	Lagoon channel (sand)	Typic Haplowassent
Mg, Massapog sand	Flood-tidal delta sand flat, abandoned inlet channel (sand)	Fluentic Psammowassent
MgC, Massapog sand relict channel	Abandoned inlet channel (sand)	Fluentic Psammowassent
Ma, Marshneck sand, sloping	Flood-tidal delta (inactive)	Haplic Sulfiwassent
Pa, Pishagqua silt loam	Lagoon bottom, low-energy basin	Fluentic Sulfiwassent
Rh, Rhodesfolly sand	Storm-surge platform (sand)	Fluentic Psammowassent
Ne, Napatree bouldery loamy sand	Lagoon margin, erosional terrace (sand and gravel)	Aeric Haplowassent
Na, Nagunt fine sandy loam, sloping	Storm-surge platform (sand)	Sulfic Psammowassent
Nx, Napatree extremely bouldery loamy sand	Lagoon margin, Depositional platform (sand)	Aeric Haplowassent

containing horizons with higher silt and darker colors (Munsell color 5YR 2.5/1) were found at depth on the edges of the flood-tidal delta (Fluentic Psammowassent). These soils occur where the sands of the flood-tidal delta are encroaching and over top the finer organic silt loams are found in lagoon bottom soils (Typic Sulfiwassents).

Biological Community Mapping

The most dominant benthic macrofaunal species in Quonochontaug Pond are *Ampelisca abdita*, a tube-dwelling amphipod (42% of individuals collected); *Capitella capitata*, an opportunistic polychaete (12%); *Gemma gemma*, a small bivalve (11%); and *Microdeutopus gryllotalpa*, an herbivorous amphipod (6%). The strongest landscape-level determinant of biological community types was the eelgrass categorization (analysis of similarities, $r = 0.138$, $p = 0.009$). Twelve sampling stations were categorized as “within eelgrass beds” and were dominated by *M. gryllotalpa*. Two stations, located in the lagoon bottom landscape unit just inside of the Washover-Fan Flat in the western area of the lagoon, were “adjacent to and influenced by eelgrass beds” and dominated by *A. abdita*. The remaining 10 grab sample sites fell outside eelgrass polygons, and ground-truthing data confirmed these as “outside eelgrass beds.” These stations were also dominated by *A. abdita*. Average macrofaunal diversity was highest within eelgrass beds and lowest at the edge of beds at sites categorized as “adjacent to and influenced by eelgrass beds.” However, average macrofaunal abundance was highest in these transition zones and lowest within eelgrass beds. The presence of opportunistic species in both eelgrass and noneelgrass habitats (*C. capitata*) reflects early successional stages and suggests that these habitats may be frequently disturbed (Guarinello, 2009). SPI images and underwater video were used to visualize and confirm the composition of the habitats defined by the multivariate analyses, and in some cases, provide additional habitat information (Figure 5). Results from our QTC analysis of side-scan sonar backscatter properties showed fairly good agreement between QTC acoustic class 7 and our eelgrass delineations. However, some areas identified as members of acoustic class 7 fell outside of ground-truthed eelgrass polygons. For this reason, similar acoustic surveys and analyses should be used strictly as a starting point for delineation of SAV habitats.

DISCUSSION

An Integrated, Iterative Mapping Approach

A subtidal habitat is a permanently flooded, spatially recognizable area with physical, chemical, and biological characteristics that are distinctly different from surrounding areas (Valentine, Todd, and Kostylev, 2005). In order to identify boundaries between distinct habitats, a range of tools and

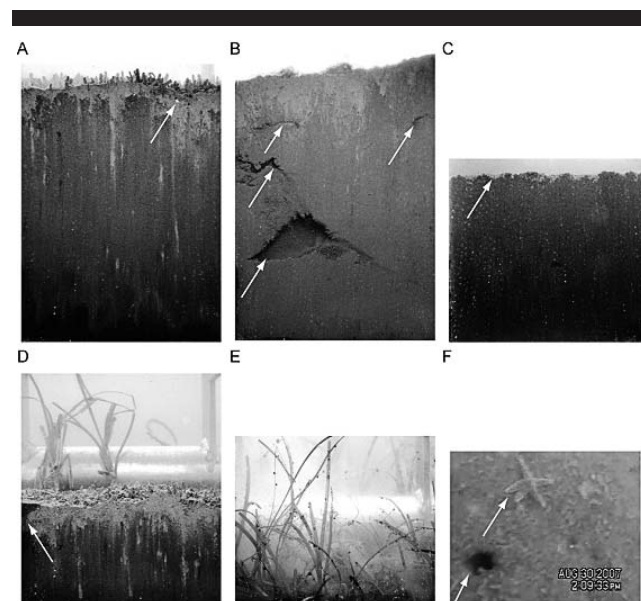


Figure 5. Examples of benthic biological communities visible in (A–E) SPI images and (F) underwater video in Quonochontaug Pond; images are 15 cm wide. (A) Areas where eelgrass is absent are dominated by tube-dwelling *A. abdita*, visible at sediment–water interface, and *G. gemma* bivalves (arrow). (B) Deep-dwelling fauna are evident in areas where eelgrass is absent in this image, showing a network of feeding voids and burrows (arrows). (C) An example of an area with no eelgrass, little macrofaunal activity, and a shallow apparent redox potential discontinuity (arrow). (D) *Ampelisca abdita* and small burrowing fauna (arrow at burrow) were present in areas with eelgrass. (E) Eelgrass is epiphytized by numerous organisms that were not quantified in this study; small gastropods are also visible on individual blades. (F) Underwater video captured more broad-scale biological features that were not always captured by SPI or grabs; a large intact burrow opening and sea star (*Asterias* sp.) are visible in this screen shot (arrows).

approaches is necessary to identify the properties, conditions, biological communities, and environments that, combined, define each habitat. Through use, integration, and reconciliation of multiple data sets, the best possible interpretations of the shallow-subtidal habitat can be made. Our methods are appropriate for mapping shallow-water systems and strive to develop integrated, comprehensive, and seamless representations of subtidal habitats. Our data collection strategies are intended to be iterative, where each dataset builds and supports further data collection efforts. A fundamental goal of this project was to evaluate different methods and datasets required for shallow-subtidal resource inventories. In order to achieve this goal, a variety of tools were used to collect data at multiple scales. To integrate all data sets, we viewed them in a GIS and reconciled areas of conflicting interpretations through ground-truthing. These final maps provide the best approximation of habitat structure for the visualization of potential biological relationships in the coastal lagoons.

Integration and Synthesis: An Example

Use of an iterative process in which collected data guides and sometimes determines further sampling was critical to our success in combining multiple datasets. For example, geologic depositional environment maps and data aided subaqueous soil sampling, and both geophysical data sets aided biological community sampling. By examining these data in a GIS, we were able to explore potential relationships among and between physical and biological parameters. In some cases, a clear match was discovered between habitat measures, whereas in others the relationships were more complex and, therefore, more difficult to distinguish. To illustrate these relationships and to demonstrate the types of geological and soil environments found within short distances in shallow coastal ecosystems, we discuss two transects across Quonochontaug Pond in detail (Figures 4 and 6).

Transect A–B, from south to north, begins at the storm-surge platform (Figure 6). Storms transport sand through overwash channels on the adjacent barrier island and onto the platform. Two soil types are typically associated with this depositional environment. Rhodesfolly soils (Rh mapping unit) are generally found on the gently sloping component (Table 3). On the more sloping component, Nagunt soils (Na mapping unit) are typically found. Both soils show a sequence of buried layers indicative of additions from storm surges. Nagunt soils have a finer grain size than the Rhodesfolly soils as a function of the greater distance from the barrier island and deeper water. In addition, Nagunt soils have an accumulation of sulfides within the upper meter of the soil. Such soils in Quonochontaug Pond tend to support eelgrass, while the Rhodesfolly soils do not. Whether this is a function of the water depth or soil properties is unknown. Shallow areas of the ponds tend to have considerable wave energy, and ice rafting (lodging) of the eelgrass is possible in winter. Correlations between soil properties and eelgrass distribution in these ponds have shown that both water depth and soil type may be important in explaining eelgrass distribution (Bradley and Stolt, 2006; Pruett, 2010).

Within the central portion of the ponds is the lagoon bottom. This depositional environment typically makes up the largest

area of the ponds. For example, in Quonochontaug Pond, 55% of the subtidal area is lagoon bottom. These areas have low energy and are thus dominated by organic silts of varying thicknesses. Soils with organic silts >1 m thick are classified as Pishagqua (Pa mapping unit), and those with organic silts between 50 and 100 cm thick are classified as Fort Neck (Fn mapping unit). Both of these soils tend to support dense beds of eelgrass in the Rhode Island coastal ponds, unless the water depths are greater than 2.5 to 3 m.

Although the lagoon bottom dominates the central portion of the ponds, channel and glacial outcrop depositional environments are also common (Figure 6). The channels carry the majority of the tidal flush to the back of the ponds. These areas have higher energy than adjacent areas and tend to be sandy (sand sheet) with soils classifying at the series level as Kebek. Subtidal glacial outcrops (shoals) are dominated by gravels, stones, or boulders with a thin (<30 cm) layer of estuarine deposits at the soil surface. The estuarine materials meet sulfidic material criteria (Soil Survey Staff, 2010), and the soils classify at the series level as Anguilla. Eelgrass is generally absent from Kebek and Anguilla soils.

Located at the mainland edge or lagoon margin, the subtidal landscape is an erosional terrace (Figure 6). Wave energy erodes what little estuarine sediments that build up, and gravel remnants of the glacial deposits dominate. Eelgrass is typically absent from the Napatree soils that form in these depositional environments because of the rocky nature of the substrate and shallow water depths.

Transect C–D (south to north) starts at the erosional terrace and traverses the organic silts of the lagoon bottom, and, as water depths gradually decrease, ends at the depositional sand platform (Figure 6). Unlike transect A–B, very little eelgrass was observed growing on Pishagqua and Fort Neck soils along the C–D transect. Pishagqua and Fort Neck soils typically have dense beds of eelgrass in Rhode Island coastal ponds. For example, Pruett (2010) found in Ninigret and Potters Ponds that these soils had average eelgrass cover of over 97%. Clearly, this was not the case for Quonochontaug Pond. There could be various explanations for the lack of eelgrass in this area, including excessive water depths, intense herbivory, or excessive sulfides (Holmer and Neilsen, 1997). These observations suggest that relationships among physical and biological parameters are often difficult to discern because of the complex nature of the ecosystem.

Eelgrass was absent from the extremely bouldery Napatree soil type (Nx), although some of the finer textured portions of this unit do support eelgrass (Figure 6). Napatree soils occur on lagoon margins adjacent to shorelines consisting of glacial till. As wind-driven waves erode the shoreline of the finer particles (silt and clay), the sandier particles fall from colloidal suspension and are deposited around the underlying boulders. Unlike the previous transect (A–B), where subaqueous soil types followed and fit within the depositional environment delineations, some differences in the delineations are observed. Because soils are defined and mapped as a three-dimensional body (profiles are typically more than a meter thick) and depositional environments are mapped in two dimensions (units typically represent surficial deposits), there will be inherent differences in some of the delineations. For example,

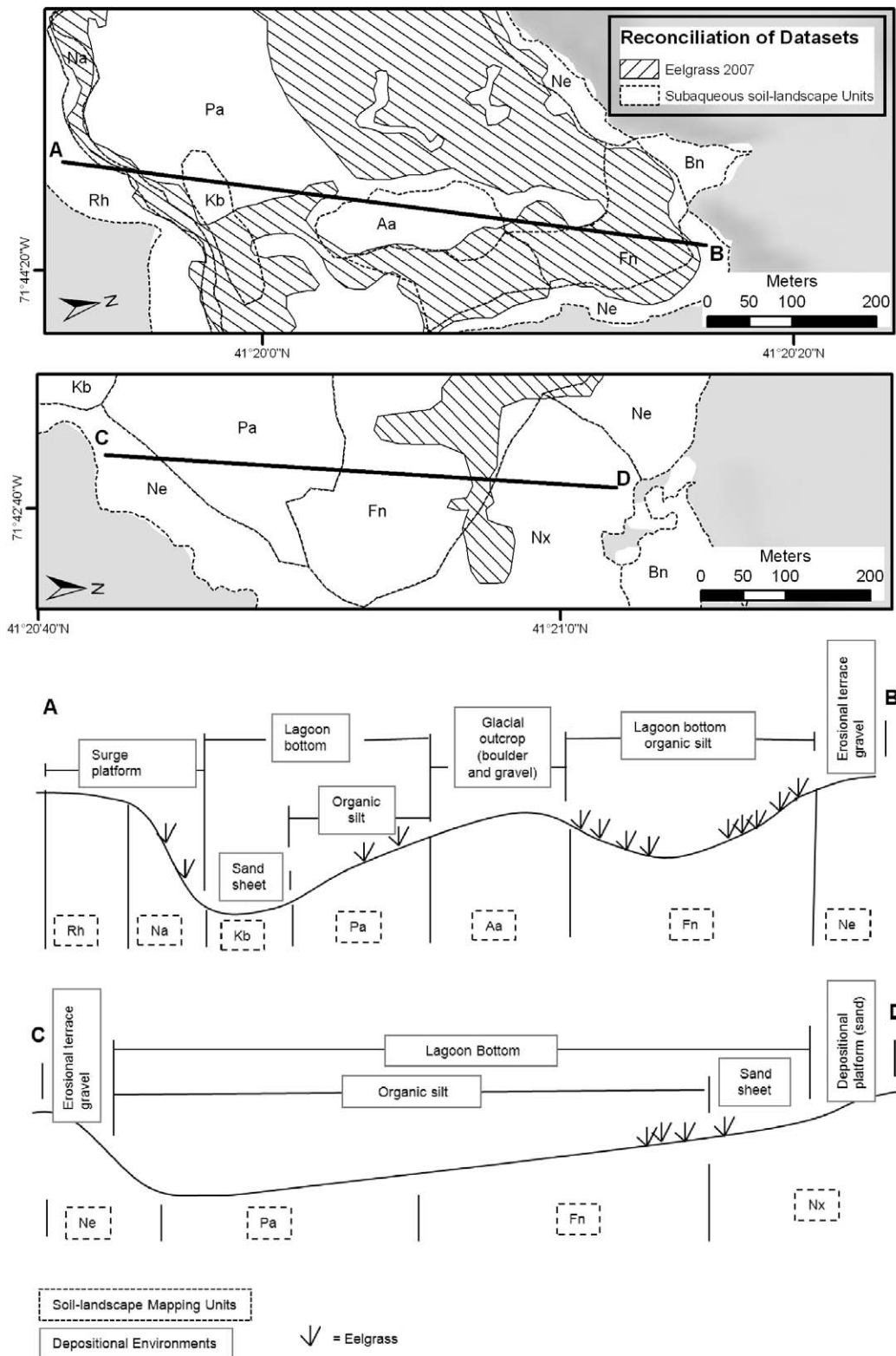


Figure 6. Map and cross-sections showing bathymetry, depositional environments, subaqueous soils, and eelgrass from two transects. See Figure 4 for a smaller scale view of the location of the transect lines.

the extent of the Napatree (Ne) soil type found on the erosional terrace is defined by the subtidal slope of the transgressive shoreline and by horizons of glacial fluvial sand and gravel found throughout the soil profile. At the fringes of the map unit, a thin layer (0–15 cm) of fine organic silts indicative of the low-energy basin may cap the Pleistocene-aged sand and gravel; thus, the area was mapped as a lagoon bottom organic silt depositional environment. However, because sand and gravel dominate the substrate below 15 cm, the subaqueous soil is considered Napatree (Ne). Additionally, because depositional environments are defined and mapped (partly) based on geologic processes such as erosion or deposition, two depositional environments are found within one soil type (Napatree extremely bouldery loamy sand; Figure 6).

Advantages to an Integrative Approach

Our protocols provide interpretations of the structures and processes in shallow-water systems to support improved understanding and management of these coastal areas. Shallow-water bathymetry is fundamental information for coastal resource managers (August and Costa-Pierce, 2007). We used single beam echosounder devices to obtain bathymetry because of their utility in extremely shallow environments, unlike large instruments that are difficult to tow behind watercraft in shallow areas. Interferometric sonar and bathymetric LIDAR surveys represent promising new technologies for collecting shallow-water bathymetry (Guenther, 2007); however, we did not have access to the instrumentation required to collect these data. The data processing and interpolation methods we adopted (TIN) are standard procedures for bathymetric mapping, and the software to perform them are readily available. As dense LIDAR datasets become accessible for coastal landscapes, topobathy surface modeling will need to be able to accommodate very large data volumes. TINs and TIN derivatives (*e.g.*, ESRI Terrain models) are robust and can handle very large mass point datasets in the million–billion source point data range.

We registered our topobathy data to NAVD88 by using a geodetic GPS. An advantage to ship-mounting the geodetic GPS device is that when it is collecting data concurrently with the echosounder, there is no need to deploy tide gauges. However, because NAVD88 is a fixed geodetic vertical datum, it does not reflect local variability in sea level (Rapp, 1994). For example, in Point Judith Pond (Figure 1), which has the highest tidal range and tidal prism of the lagoons we studied (Boothroyd, Friedrich, and McGinn, 1985), the relationship between NAVD88 and tidal datums varied up to 0.1 m between tidal stations. A tidal datum should be considered a local datum, and, as such, should not be extended across areas with differing hydrographic characteristics (NOAA, 2003). Knowledge of local tidal datums is important for delineating supratidal, intertidal, and subtidal environments within a geographic area. Therefore, we used continuous water level observations, collected over a set period (typically one lunar month overlapping with bathymetric surveying), to calculate the tidal datums (*i.e.*, mean lower low water [MLLW], mean sea level [MSL], mean higher high water [MHHW], *etc.*). These datums were determined relative to the stations' NAVD88

elevation using the definitions of Voigt (1998), and we recommend that at least a month-long tidal cycle be measured to establish a tidal datum.

In the past, substrates beneath shallow coastal waters have been typically referred to as sediment and identified or mapped based on the particle size distribution of the upper few centimeters (Wells *et al.*, 1994). Over the last decade, pedologists have examined these substrates from a different perspective and have begun to identify, map, and classify these materials as subaqueous soils (Bradley and Stolt, 2003; Demas and Rabenhorst, 1998; Osher and Flannagan, 2007). There are a number of reasons for this paradigm shift. For one, by definition, soils are a collection of materials at the surface of the earth that contain living matter, are capable of supporting plants, or show evidence of physical, chemical, and biological processes (*i.e.*, pedogenic processes; Soil Survey Staff, 1999). This definition embraces the complexity of shallow-water marine and estuarine substrates by recognizing that their very nature is a function of the interactions of biological, chemical, and physical characteristics and processes.

Using a soil science approach allows for the classification of substrates into a well-established, comprehensive hierarchical taxonomic system with both narrow and broad categories (Soil Survey Staff, 2010). This system has advantages over the traditional classification of substrates into broad classes such as mud, silty sand, and muddy sand (Flemming, 2000). For example, a sediment classification of silty sand (Fegley, 2001) could be better described as a coarse–silty over sandy skeletal, Typic Sulfiwassent (Soil Survey Staff, 2010). This soil classification conveys the grain size distribution of both the upper and lower materials, indicates that there are considerable sulfides in the upper 50 cm, and indicates that the upper materials have a low bearing capacity. Such additional knowledge of the physical and chemical characteristics of the sediment can be used for decisions regarding use, management, and restoration. The current CMECS document embraces the pedological approach to classification of substrates by using Soil Taxonomy for detailed classification of the sub-benthic component.

Our pedological classifications are supported by acoustic data collected with a high-resolution, digital side-scan sonar. The sonar generates an acoustic image of the seafloor with resolution similar to aerial photography. This resolution allows for the identification of geological, biological, and anthropogenic features as small as 30 cm, with data collection rates up to $1 \text{ km}^2 \text{ h}^{-1}$ (Kenny *et al.*, 2003). The resolution of these data allows for mapping of units whose vertical relief is not discernable in the topobathy model. This is extremely important in estuarine and lagoon depositional environments, which have complex depositional and erosional processes acting at a variety of scales. For example, soil–landscape models developed for shallow coastal lagoons suggest that the central portion of the lagoon basin is dominated by thick organic silt deposits (Balduff, 2007; Bradley and Stolt, 2003; Demas and Rabenhorst, 1998). In Quonochontaug Pond, however, certain areas of the central portion of the lagoon basin showed a strong backscatter return on the side-scan mosaic indicative of sandy substrates. These areas were not identifiable in the topobathy model. Additional ground-truth data confirmed that these

areas were sandy, suggesting that some areas of the lagoon basin may have enough current to inhibit the deposition of fine-grained silt. Similarly, side-scan data allowed us to map widely scattered, small patches of eelgrass that would not have been visible in other acoustic or ground-truth data.

Shallow coastal systems, such as Rhode Island's lagoons, are biologically dynamic with biotic features such as infaunal communities and eelgrass distributions varying on yearly and sometimes seasonal scales (Bradley and Stolt, 2006; Guarinello, 2009). Repeated mapping of submerged aquatic vegetation distributions in Quonochontaug Pond reveals that the distribution of eelgrass beds in this lagoon varies temporally and shrinks and expands across subaqueous soil units and geological facies (Figure 6). Biota distribution is not wholly constrained by physical properties but is also driven by disturbance and biological interactions (e.g., predation, herbivory, competition), which can occur over very small spatial and temporal scales. Thus, to have a current representation of biological communities, it may be necessary to sample them on a more frequent time interval than their associated physical habitats.

With the rapid expansion of mapping technology and application, there is a call for a seamless inventory of coastal resources (e.g., NOAA Digital Coast or Google Earth's recent efforts to expand into the ocean) as a response to the need for tools to support coastal zone decision making. The shallow coastal habitat mapping protocols we have developed combine subaerial habitats and subaqueous substrates and offer a promising path toward the creation of a seamless coastal resource inventory.

CONCLUSIONS

Creating a thorough spatial inventory of resources and habitats can be a multilayered, multidisciplinary process. Given the complexities and interactions between physical and biological parameters in shallow coastal ecosystems, numerous complementary databases are needed. The MapCoast project has determined that the minimum suite of data to inform coastal decision making includes bathymetry, depositional environments, subaqueous soils, and submerged habitats (such as eelgrass). The protocols we describe here have been proved effective and efficient in mapping shallow coastal environments.

Mapping protocols evolve as new data and technologies become available. The methods we propose here are robust, use readily available data collection instruments, and can accommodate many different coastal settings. Project-specific requirements will, however, dictate data accuracy levels and minimum mapping unit dimensions. These specifications will in turn inform decisions on mapping scale, sampling density, and acceptable data sources. Thus, it is not possible to provide one suite of sampling specifications that will meet all needs. Furthermore, availability of collateral data to support coastal resource mapping is always changing. For example, after completing the subaqueous soil mapping reported here for coastal ponds in Rhode Island, 15-cm multispectral imagery and 1-m point-spacing LIDAR data were obtained (spring 2011) for the whole study area. These new data will be extremely valuable in future coastal mapping applications but were unavailable for our initial research.

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