Chapter 10

Subaqueous Soil Survey

By Mark Stolt, University of Rhode Island, and James Turenne and Maggie Payne, USDA-NRCS.

Introduction

Subaqueous soils differ from subaerial, or terrestrial, soils by having perennial water on the soil surface. These soils occur in shallow freshwater and marine environments, such as ponds, lakes, and the subtidal areas of estuaries and tidal embayments. The Soil Survey Staff (2014) defines "shallow" as approximately 2.5 m. At depths greater than 2.5 m, sunlight is typically attenuated and submerged aquatic vegetation (SAV) is typically absent. In especially clear waters, however, this depth may be much greater. Thus, for interpretive purposes, mapping is typically done to depths of 5 meters of water. Areas with extreme tidal ranges are also included as subaqueous soils even though they may be exposed for an hour or two during a neap tide or similar event. Subaqueous soils occur on a range of subtidal and limnic landforms, such as flood-tidal deltas, washover fans, and lake beds (Schoeneberger and Wysocki, 2012; USDA-NRCS, 2016). These soils are currently classified in the Histosol and Entisol orders of Soil Taxonomy (Soil Survey Staff, 2014).

Occurrence

Subaqueous soils occur worldwide, except in the driest inland areas where water does not pond permanently to form lakes or ponds. In coastal areas, these may be the most extensive soils on the landscape. For example, Rhode Island has approximately 700,000 acres of subaerial soils. If the area of subaqueous environments having water depths of less than 5 m are included, the total area of soils would almost double.

Importance

The world's population centers are in coastal areas. In the United States, coastal watershed counties make up less than 10 percent of the land area, but more than 50 percent of the population lives in these counties. If the cities and towns within a short distance of the Great Lakes were included, that number would be significantly larger. Coastal and inland waters are used for transportation, recreation, farming, and other livelihoods. From an ecological perspective, shallow and inland waters are the nursery grounds for most of the animals that inhabit these ecosystems. The subaqueous soils in these shallow habitats provide the foundation and structure of the ecosystem. The many anthropogenic activities in the shallow water habitats disrupt, disturb, and may even destroy these habitats. Therefore, understanding the distribution and characteristics of the subaqueous soils is critical to properly managing and using these habitats so that these ecosystems properly function and continue to be healthy and vibrant. The use and management of subaqueous soils in shallow water ecosystems may include dredging, dredge placement, restoration of submerged aquatic vegetation, identification of areas for shellfish aquaculture, restoration of wild stocks of shellfish, and identification of areas for docks and moorings (e.g., Stolt and Rabenhorst, 2011; Erich et al., 2010).

Sampling, Description, Characterization, and Classification

Chapters 2 and 3 provide standards for describing soil profiles and their site characteristics in the subaerial settings common to soil survey. The subaqueous soil environment presents unique challenges for observing soil profiles, collecting samples, and describing soil properties. This section provides information specific to subaqueous soils. The *Field Book for Describing and Sampling Soils* has a section that provides important information specific to mapping, describing, and sampling subaqueous soils (McVey et al., 2012).

Sampling

Subaqueous soils can be sampled by several traditional soil approaches, but marine science approaches are best. For cursory descriptions and sampling, a standard bucket auger can be used. In order to sample from the exact location with depth, some soil mappers use a piece of PVC pipe with an inside diameter a little larger than the teeth on the bucket auger. The auger is placed into the pipe, and the sample is collected in the typical fashion. While the bucket is being removed, the PVC pipe is pushed deeper into the soil. The sample is retrieved and placed in a tray (typically a meter-long piece of vinyl gutter). The auger bucket is pushed down the pipe again, the spoil from pushing the PVC pipe down is removed, and then the next depth is sampled. This procedure is effective for sampling the upper 75 cm of the soil. Below this depth, however, collecting samples with a bucket auger becomes very difficult.

In shallow water where soils are non-fluid, sampling with a bucket auger can be done while wading. A small light raft (typically made from floating dock material of Styrofoam) works well in holding the sample tray. A small anchor (e.g., a brick with holes) is used to keep the raft in place. In deeper water, samples can be collected from the side of a boat. A boat with a deck at the bow can be used, but a pontoon boat with a 60 x 60 cm sampling port cut into the deck between the two pontoons (i.e., a moon-pool) is preferred (fig. 10-1). The boat is anchored at two points, and the bow faces into the wind or the direction of oncoming waves to keep the boat in the place while sampling. Sampling should be avoided if there is significant wind or waves. In freshwater systems in northern climates, sampling can be done through ice. A standard ice auger is used to cut a hole in the ice, and the soil is sampled through the hole.

For organic soil materials or fluid mineral materials, a Macaulay peat sampler is very effective. Most Macaulay samplers have sampling chambers 50 cm long. Machine shops can construct auger chambers to longer lengths (such as 1 m), which work well for subaqueous soil sampling. These samplers can be used easily through the moon-pool, off the side of the boat, or through a hole in ice. Because water depths vary, extensions on the bucket auger or peat sampler should be easy to add on or remove.

For detailed sampling and description of non-fluid materials, a vibracore sampler is ideal. Vibracore samplers consist of a concrete mixer motor, a cable that delivers the vibration from the motor to the sampling tube, and a vibration head that clamps onto the irrigation pipe (core barrel) to deliver the vibration to the core barrel that collects the sample (fig. 10-2). The vibration loosens (or liquefies) the soil material around the core barrel so that the core can be easily pushed into the soil with a minimal amount of pressure from the top of the pipe. This sampling approach is typically done from a pontoon boat with a moon-pool. If the body of water is too small for a pontoon boat, or gas-powered

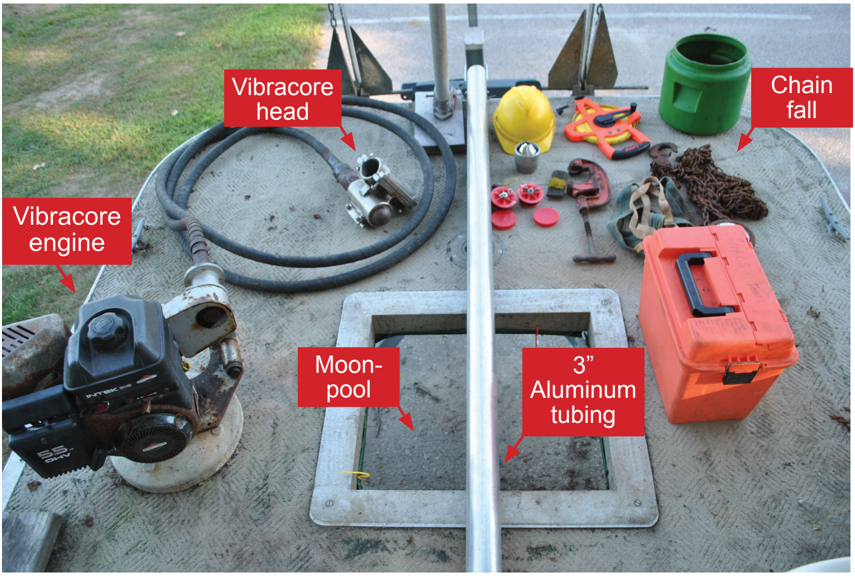
Figure 10-1

A pontoon boat used for subaqueous soil sampling. The sampling is conducted through the moon-pool. A sealed core is strapped to the end of the chain fall. The chain fall is attached to the tripod, which is centered over the moon-pool.

boats cannot be used, a small barge with a moon-pool in the middle can be used. In this case, the concrete mixer motor is in the small boat used to pull the barge and the soil is collected and retrieved through the moon-pool in the barge. There are "backpack" types of vibracores that can be used off barges or through the ice. In some cases, these types of corers are not powerful enough to push the tubes through dense soil materials.

Core barrels used for vibracoring are typically 10 cm in diameter (fig. 10-3) and should be long enough to accommodate both the soil sample and the overlying water. Once the barrel is pushed into the soil to the desired depth, a lead weight (sinker) attached to a string is

Figure 10-2

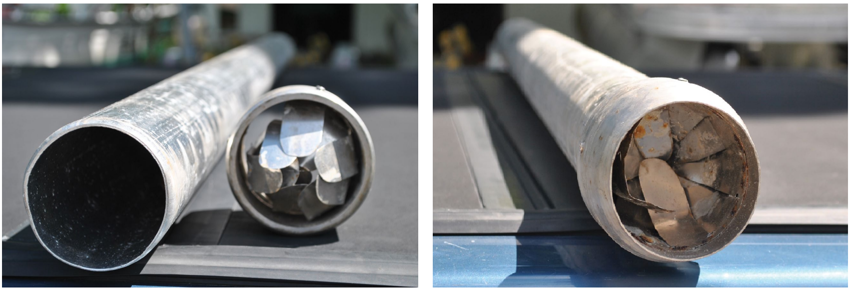


Equipment for vibracore sampling. A vibracore sampler consists of an engine, cable, head, and core barrel. The engines are typically gasoline driven (sold as a device to keep concrete mixed so it does not set). The cable carries the vibrations to the head, which is attached to the core barrel with four bolts.

dropped into the core barrel to measure the distance from the top of the core barrel to the soil surface in the tube. The same thing is done on the outside of the core. These measurements are made to determine the amount of collapse (settlement) that has occurred to the soil during coring (McVey et al., 2012). Significant collapse should be noted when recording horizon depths and reporting soil bulk density.

To retrieve the soil, the core is first slowly filled with water. A cap (test plug) is placed on the top that, when tightened, seals the top of the core. This creates a suction and, for most materials, keeps all of the soil material in the core barrel when it is removed. In some soil materials, particularly those that are coarse textured with many rock fragments, some of the soil material may fall out of the bottom of the core barrel when it is retrieved. In these cases, a core catcher can be added to the base of the core before it is vibracored into the soil (fig. 10-3). Once the core is sealed, it is attached with a heavy strap to a winch or chain fall and pulled out of the soil. Using a chain fall attached to a tripod mounted

Figure 10-3



A core barrel and core catcher. Left image—Core barrels used for vibracoring are typically 10 cm in diameter. The view of the sand catcher is from the perspective of the inside of the barrel. Right image—For sandy or loose materials, a core catcher may be attached to the bottom of the core barrel.

over the moon-pool is the safest way to remove the core (fig. 10-1). For sampling off a barge or through the ice, an aluminum ladder is commonly used instead of the tripod because of its lighter weight.

Once the core is pulled from the soil and sealed at the bottom (to prevent loss of the sample), a small hole is created in the irrigation pipe just above the top of the soil in the core barrel to allow the water on top of the core to drain slowly (see above information on measuring the depth from the top of the core barrel to the top of the soil). After the water is drained, the tube is cut just above the soil surface with a tube cutter and the cap is screwed back in place to preserve the core. The bottom is sealed with a cap first to prevent loss of suction. The core barrel is dried and clearly labeled with a pedon number and the correct orientation. The core can be opened on the boat, or it can be stored in a rack and later described and sampled on land or in a lab. Vibracores in the lab should be maintained at 4 ^{0}C to minimize drying and oxidation of sulfides prior to sampling and analysis.

Core barrels are best opened by laying the core down on a table or lab bench and cutting lengthwise on opposite sides with electric metal shears (fig. 10-4, top image). A circular saw works but creates safety issues and produces aluminum shavings, which need to be collected. A piano wire or steel guitar string is slid between the cuts in the aluminum tube to split the core in two. The two sides are lifted apart. One side is described and sampled, and the other is archived if needed (fig. 10-4, bottom image).

Figure 10-4

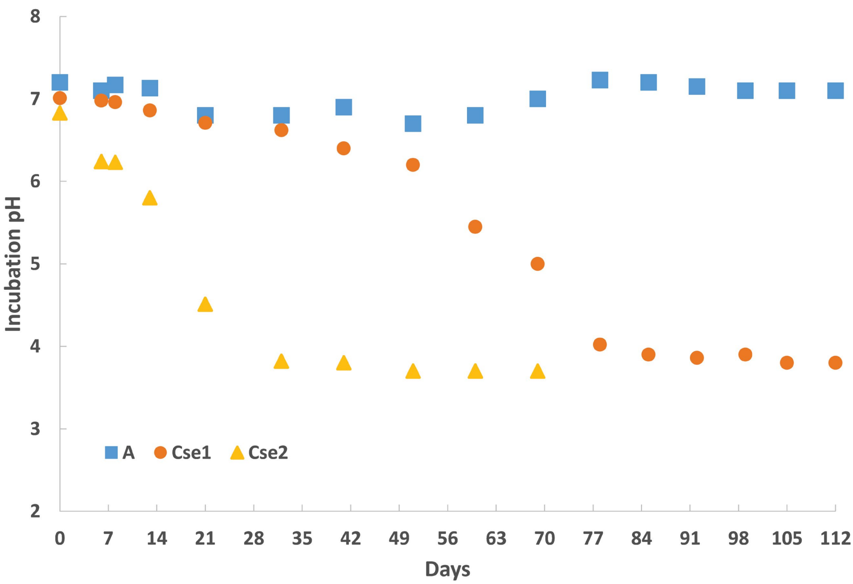
A core from subaqueous sampling. Top image—Cutting open the core with electric shears. Bottom image—A split core exposing the soil. One side is typically sampled, and the other may be stored and archived.

Description

In general, subaqueous soils are described the same way as subaerial soils (Schoeneberger et al., 2012) but using the setting terminology, sampling method, and various chemical and morphological properties of subaqueous soils described by McVey et al. (2012). It is worth reiterating that caution is needed when estuarine soils are sampled and described since these soils typically have significant amounts of sulfides. Once soil materials containing sulfides are removed from their natural state (underwater), the sulfides begin to oxidize (even when stored in a sealed core barrel at 4 ^{0}C). Mono-sulfides are more reactive to oxidation than di-sulfides, such as pyrite. The oxidation of sulfides may cause a change in soil color and a rapid decrease in pH as the sulfides are converted to sulfuric acid (in some cases pH decreases from more than 7 to less than

3; see fig. 10-5) (Fanning et al., 2010; Rabenhorst and Stolt, 2012). If the materials have a very low pH, the aluminum pipe housing the soil core may start to corrode and create Al salts. If soil color, pH, salinity, and particle-size distribution are important to the soil characterization, the soils should be sampled and described as soon as possible or samples should be frozen immediately after sampling to minimize the amount of sulfide oxidation.

Figure 10-5



Incubation pH for three horizons (A, Cse1, and Cse2) from a Fluventic Sulfiwassent, collected from the Thimbles Island estuary in Connecticut. Samples that have a pH of 4 or less after 16 or more weeks of moist incubation and that have a drop in pH of at least 0.5 unit meet the requirements for sulfidic materials. Both the Cse1 and Cse2 horizons meet these requirements. The Cse2 horizon attained the critical pH in less than 4 weeks while the Cse1 horizon took almost 12 weeks to reach a pH of 4.

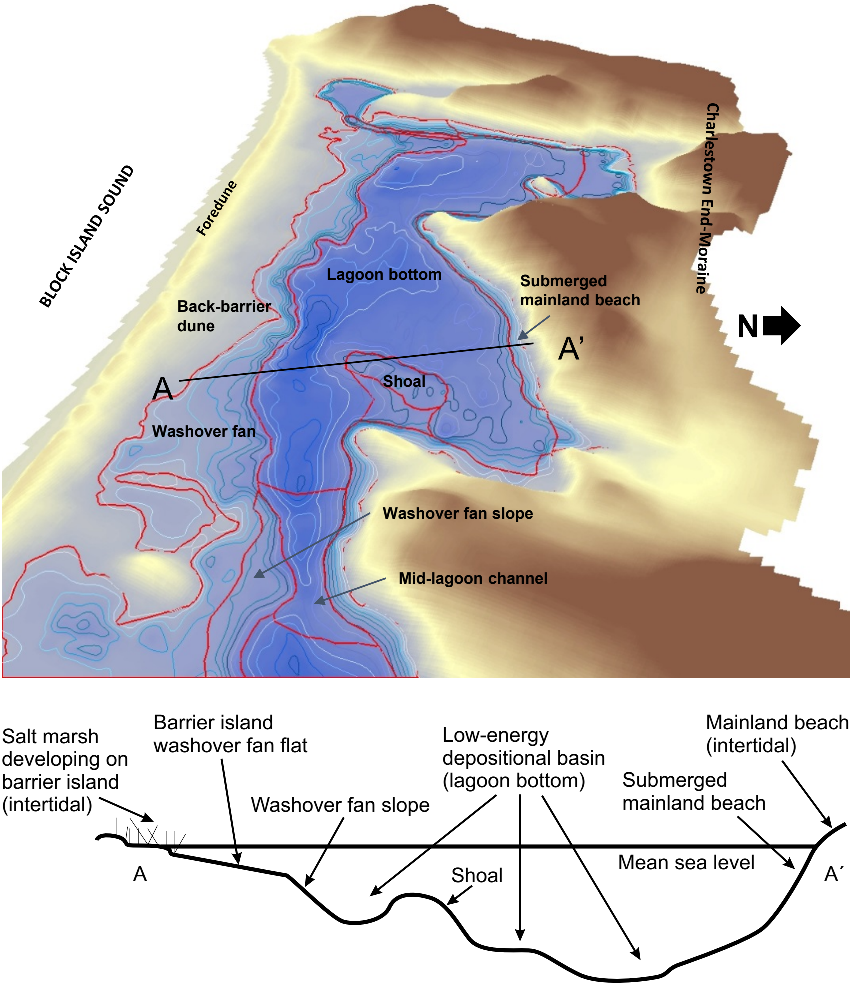
Important Properties for Classification and Interpretation

Soil properties important for classification and interpretations of subaqueous soils include type of organic soil materials, content of soil organic carbon, electrical conductivity (EC), fluidity, incubation pH, content of pore-water sulfides, particle-size distribution, mineralogy, and soil color. The presence of odors (such as sulfur or petroleum), the presence of shell fragments or former vegetation, and the nature of the depositional environment are also important. Subaqueous soils that are dominated by organic soil materials or are fluid cannot support dock pilings and typically require special moorings (Surabian, 2007). Electrical conductivity is used to discern between freshwater and estuarine soils and to identify soils that may have halinity issues when dredged and placed on the soil surface. Incubation pH is a measure of the potential acidity of the soil materials. Subaqueous soils dominated by mono- and di-sulfides may have dramatic drops in pH when dredged and placed on the land surface. In some cases, pH values decrease to less than 4 and acid sulfate soils are created (Clark and McConchie, 2004; Fanning et al., 2010). High sulfide contents, especially in the pore waters, can be toxic to submerged aquatic vegetation and may indicate a highly anoxic environment uninhabitable for many benthic organisms. Subaqueous soils typically have low chroma (< 2) and a neutral (N), yellow (5Y), or blue-green (BG) hue. Brighter chromas (> 2) or redder hues commonly indicate aerobic inputs (from ground water or the water column) or relict subaerial soils that are now submerged (see lower part of core profile in fig. 10-4, bottom image).

Soil-Landscape Relationships

Like subaerial soils, subaqueous soils form as a result of various additions, losses, transfers, and transformations occurring within the soil (Simonson, 1959). The dominant processes that form a particular kind of soil depend on where the soil occurs on the subaqueous landscape. Figures 10-6 and 10-7 provide examples of coastal lagoons, which are very common in estuarine systems along the U.S. Eastern Seaboard. Large areas of the basins (bottoms) of coastal lagoons are dominated by fine textured (silt loam and silty clay loam) soils that are rich in sulfides, are very fluid, and have a high content of soil organic carbon to a depth of 2 m or more. Because the lagoon bottom is in a low-energy position, only fine particles (very fine sand or finer) and organic matter are deposited. Little oxygen is available for microbial respiration, and redox potentials are very low. As a result, the transformation of sulfate to sulfides dominates the soil processes. With continued additions of organic matter and little decomposition at the low redox potential, levels of soil organic carbon remain high. Because the silt- and clay-rich parent materials have such fine particles sizes, which are not readily compacted in the permanently inundated low-energy environment, very fluid soils form.

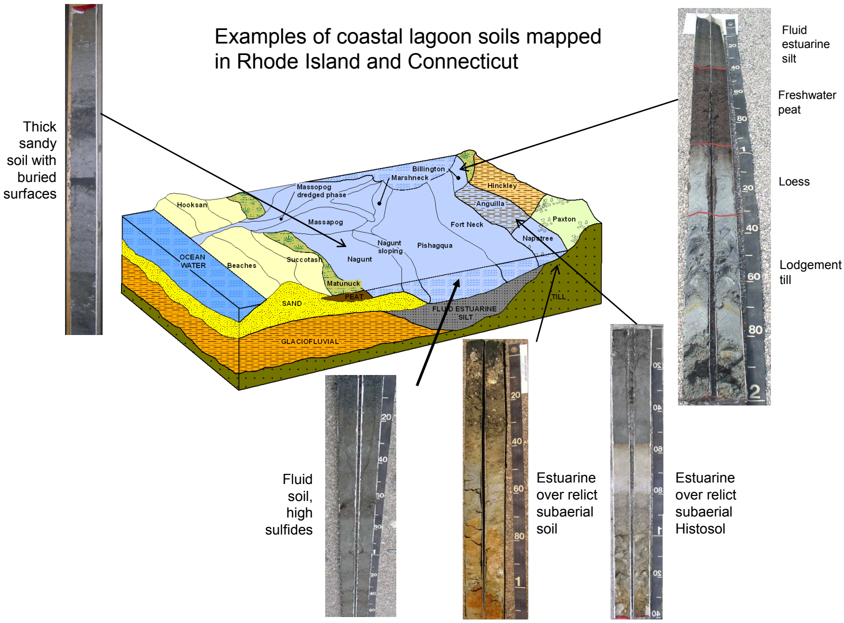
Figure 10-6



Examples of subaqueous landscape units across a coastal lagoon.

Higher on the coastal lagoon subaqueous landscape, typically between the deeper lagoon bottom and the shallower washover fan, water currents have more energy than those in the lagoon bottom where the finest particles and organic matter settle out. During storm events, there is even greater energy due to an increase in waves, fetch, and nearby overwash events and coarser (sand-sized) particles are deposited. Where benthic organisms are continuously mixing the upper part of the soil, textures are

Figure 10-7



Soil-landscape relationships across a coastal lagoon in Rhode Island and Connecticut.

loamy and fluidity is low. In this part of the landscape, subaqueous soils develop A horizons and sulfidic materials are not typically found in the upper horizons because of the mixing and elevation (shallowest water depth).

Adjacent to the barrier island that separates the lagoon from the open ocean, washover fans are the dominant landscape unit. The frequency of overwash events that reach the washover fan increase with decreasing distance to the barrier island, and the soils typically do not have A horizons.

Freshwater systems such as ponds, reservoirs, and lakes are typically low energy. These environments typically do not have the highly depositional and erosional landscape units (such as deltas, washover fans, or current-formed channels) found in estuarine settings. Thus, the landscape patterns in the freshwater systems are much simpler than those in the estuarine systems. For example, Payne (2007) identified a total of 21 different landscape units in her study of three shallow estuarine embayments in Rhode Island. She noted that differences in geology, geomorphology, geography, wind, and tidal patterns accounted for much of the variation in landscape units. In contrast, Bakken (2012) studied six natural and impounded freshwater systems and found only four landscape units (cove, shoal, lakeshore, and lakebed).

There have been two studies of freshwater subaqueous soils (Erich et al., 2010; Bakken, 2012), and both found that soil characteristics in freshwater systems were more influenced by the geologic and anthropogenic history than by the landscape. The subaqueous soils in reservoirs were very similar to those prior to impoundment and flooding. The natural lakes were primarily kettle holes that slowly filled with rising ground water. In most cases, organic soil materials accumulated in the kettle holes when they were wetlands (subaerial soils) with little mineral inputs after permanent inundation and ponding. Thus, these soils typically were Histosols. In areas where there was significant anthropogenic input of nutrients, invasive species such as milfoil (*Myriophyllum* sp.) and fanwort (*Cabomba caroliniana*) proliferated and thick deposits of plant-derived organic materials accumulated, forming present-day subaqueous Histosols.

Survey Methods and Procedures

Special methods and procedures are used to develop base maps for conducting subaqueous soil surveys. Additional remote sensing tools and techniques can also be useful for preparing subaqueous soil survey maps.

Bathymetry

Developing soil-landscape relationship models is critical to the mapping of subaqueous soils (Bradley and Stolt, 2003; Osher and Flanagan, 2007). The first step is obtaining bathymetric data and creating a bathymetric map of the subaqueous landscape (Bradley and Stolt, 2002). The bathymetric map serves the same purpose as the topographic map. Aerial photos, if the water clarity was good on the day the photos were taken, can be helpful in the identification on the map of exact boundaries of landscape units, such as washover fans, shoals, and submerged beaches.

In some areas, accurate bathymetric maps are already available; in other areas, they may need to be created. Bathymetric maps are created by systematically collecting water depth data while recording x and y coordinates. Water depth is typically determined using a fathometer mounted to the hull of a boat. The boat is slowly driven across the water body for a series of transects. Transects are spaced 20 to 30 m apart, and data are collected every 5 to 10 seconds, depending upon the speed of the boat. Each time a water depth is recorded, the x and y coordinates are also recorded with a global positioning system (GPS). A fairly simple fishfinder with GPS capabilities can collect the x and y data and the z (water depth) data at the same time. Caution is needed in areas with dense submerged aquatic vegetation (SAV) since the fathometer may read the top of the SAV as the soil surface. In these cases, manual readings of the water depth should be occasionally collected and checked against the fathometer values. Several transects are also completed parallel to the shoreline to augment the other transect data. In freshwater systems, the water depths can be corrected to the mean water level of the water body. In tidal systems, tidal fluctuations need to be recorded at the same time as the x, y, and z data to correct the water depth data. Any water-level recording device that has time-stamped data can serve this purpose. In areas where tidal fluctuations are complicated, as many as three water-level recording devices may need to be used at one time. In most cases, however, a single-water level measurement device can be used and moved to new locations as the bathymetric data are collected. Because of recent advances in Light Detection and Ranging (LiDAR) for underwater applications, accurate bathymetric maps may eventually be available for most coastal environments.

The bathymetric data are imported into a GIS program to create the contour maps. They are typically kriged, and a stop line is set at the tidal datum chosen as the elevation where the water meets the land. All bathymetric data collected in tidal systems are normalized to NAVD-88 or new vertical datum if available. McVey et al. (2012) discussed the use of various datums for a bathymetric contour map. To normalize the data, the bottom depth (elevation) of each tide gauge must be determined using traditional land survey techniques from an order 1 benchmark. Changes in the shallow subaqueous landscapes are rarely abrupt; thus, contour intervals of the bathymetric maps are commonly on the order of 20 to 30 cm. Using the contour maps and aerial photographs, the various landscape units within the mapping area are delineated. Landscape units in coastal systems include lagoon bottom, bay bottom, flood tidal delta, washover fan, inlet, and shoal (Schoeneberger and Wysocki, 2012; USDA-NRCS, 2016). Landscape units in freshwater lakes and ponds include submerged shoreline, lakebed, cove, and shoal (Bakken, 2012).

The bathymetric contour maps serve as the base maps for the subaqueous soil survey. The landscape unit is the primal factor in the delineation of soil distribution on the landscape. Each landscape unit should be visited in the field and a preliminary assessment done with a bucket auger and peat sampler. To develop initial metrics of soil variability within landscape units, larger units may need to be investigated at three or four random locations. Which units will need additional investigations will depend on the scale of mapping (order 1 or 2). Preliminary assessments can be used to establish initial soil-landscape relationships. Delineations that do not follow these relationships should be reassessed in the field, and additional delineations (soil polygons) added where appropriate. Representative soil types should be identified from the preliminary studies, and their locations established for vibracoring. Transects can be run across the largest units to assess variability within delineations. For stony or bouldery mapping units, a push probe can be used to quickly estimate boulders and stones and better identify boundaries between different phases.

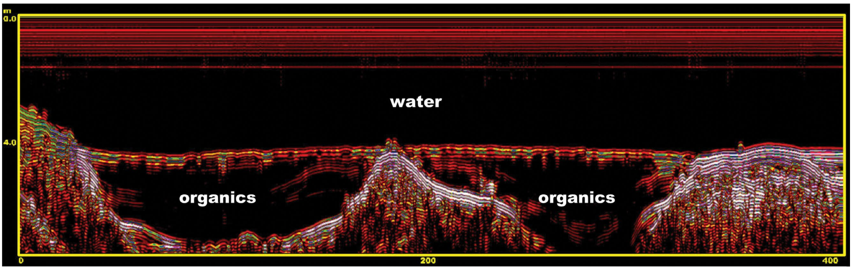
Remote Sensing

Although not necessary, several remote sensing tools can help improve mapping accuracy. In estuarine systems, side scan sonar is effective in identifying surface textures and features, such as stones, boulders, macroalgal cover, SAV, bottom type, and anthropogenic features (Oakley et al., 2012). The side scan is towed behind a boat sending signals in 25- to 50-m swaths. Transects are set apart by the size of the swath to ensure complete coverage. Soundings are recorded and translated in the lab with the appropriate software into a map showing the mosaic of swaths. Surface samples from preliminary soil survey efforts are used as ground truth for the signals that are mapped. Easily identifiable features from the side scan data include extent of stones or boulders and surface textures.

A simple tool that works well in areas with excellent water clarity (low turbidity) is the underwater video camera. The video camera can be towed slowly by the boat and tracked with a GPS. The images are projected onto a laptop. Points of interest (e.g., changes in surface texture or presence, absence, or abundance of coarse fragments or stones and boulders) are noted and the GPS coordinates recorded. Limitations for the video camera are the field-of-view and the possibility of fouling by algae or seagrasses. The field-of-view is often limited to a width of 25 cm because the camera needs to be close to the subaqueous soil surface to clearly observe it. Thus, many transects are necessary to delineate between two mapping units (e.g., soils with a high content of rock fragments and soils with a low content of rock fragments). The closer the camera is to the soil surface the more likely the lens will be fouled by detritus, algae, or seagrasses.

Ground-penetrating radar (GPR) can be invaluable in freshwater systems (it cannot be used in saltwater because the salts attenuate the signal). The GPR antenna can be towed slowly behind a boat in a rubber or plastic raft or across ice. GPR is effective at identifying surface and subsurface stones and boulders, shallow depths to lithic materials, and the depth and distribution of organic soil materials (fig. 10-8). Chapter 6 has additional information about the use of GPR in soil survey.

Figure 10-8



GPR output for a freshwater lake with thick organic materials. Water, mineral soil materials, and organic soil materials are easy to identify from the output.

Significance of Subaqueous Soil Information

Subaqueous soil survey interpretations can have a wide variety of uses. This section provides a few examples.

Water depth characteristics.—For use of a shallow water body, one of the most important spatial data layers is the bathymetry. Although bathymetric maps created for soil survey are not meant for navigation purposes (nautical charts include locations of buoys and other boating information), these maps can be used to understand the effects of storms on coastal systems or identify rapid changes in water depth for recreational purposes (mostly fishing). In most soil surveys of subaqueous soils, water depth is provided as a phase of each soil mapped (similar to slope phases in subaerial soil surveys). Although not perfect for navigation purposes, these data can help in identifying shallow areas boats should avoid or in identifying shallow areas suitable for wading activities, such as clamming.

Mitigation of dredging effects.—Areas of subaqueous soils in estuarine or freshwater settings are dredged to allow boats and ships to move freely in and out of the system or for the development and construction of marinas. Issues related to dredging are primarily disruption of the benthic ecology, re-release of the contaminants and nutrients in the soils, and disposal of the dredge materials. If the dredged materials are placed someplace in the water, another subaqueous area is disturbed. The dredging process alone may re-suspend nutrients or contaminants that are stored in the subaqueous soils. Pruett (2010) showed that soils with high fluidity (Hydrowassents) and soils with sulfidic materials (Sulfiwassents) contained significantly higher concentrations of heavy metals (Pb, Zn, As, Cu, and Cr) than simple soils (Haplowassents) and sandy soils (Psammowassents). Hydrowassents are typically finer textured and contain high levels of soil organic carbon. The soil organic carbon forms a complex with the metals in the water column, and the complex is later deposited on the soil surface. In Sulfiwassents, the metals may also complex with the sulfides. Pruett (2010) found in some cases that the metal concentrations in Sulfiwassents were high enough to negatively affect the benthic ecology. In freshwater systems, Bakken (2012) found that there were significant differences in P concentrations among soil types. Where extractable P concentrations were greater than 200 $\mu g\ g^{-1}$, there was a significantly greater chance of the presence of invasive plants such as milfoil and fanwort.

Commonly, the dredge materials are placed on the land surface. Knowing whether or not those materials contain contaminants or sulfides is critical to managing the dredge materials. When exposed to the air, sulfides will oxidize, release sulfuric acid, and may create acid sulfate conditions or soils. These acid sulfate soils may release metals if reaction approaches extremely acid (pH of 4 or 3). They are also extremely difficult to vegetate. Salisbury (2010) showed that soils in low-energy environments, such as coves, bayfloors, and lagoon bottoms, that contain high concentrations of sulfide may drop in pH from 7.5 to 3.0 in as little as 3 weeks following dredging and placement in an oxidized environment.

Suitability for moorings, docks, and other structures.—Surabian (2007) showed how subaqueous soil properties, primarily fluidity and depth of fluid soil materials, affect the types of moorings that can be used to secure boats. If the soil materials are non-fluid, heavy moorings are required. If they are fluid, mushroom-type moorings are used. Similarly, areas for docks require soil materials that are non-fluid and can support pilings.

Aquaculture.—Salisbury (2010) showed that certain subaqueous soils are more productive for aquaculture than others (in this study, hard shell clams and oysters). For example, an average of 58 percent of the oysters grown on sandy non-fluid soils reached harvestable size in two growing seasons while less than 12 percent of the oysters grown on soils dominated by sulfidic materials reached that size in the same period. Aquaculturists are now using subaqueous soil maps to identify new places to lease for growing oysters in coastal lagoons.

Ecological assessment and restoration.—Seagrasses such as eelgrass (*Zostera marina*) are an important component of the estuarine ecosystem. They provide several ecosystem functions and services, including trapping sediment and pollutants in the water column and serving as habitat for a variety of shellfish, finfish, shrimp, and other benthic fauna. Because eelgrass habitat has been declining worldwide, there have been numerous studies focused on eelgrass distribution and restoration. Restoration of eelgrass has been difficult, with an average success rate of 30 percent (Fonseca et al., 1998). Because a major issue is site selection (Calumpong and Fonseca, 2001), subaqueous soil surveys can provide spatial soil data to use in site selection models for eelgrass restoration.

Carbon accounting.—Another important current issue in soil science is carbon accounting. Subaqueous soils are typically not sampled and analyzed when carbon stocks are assessed. However, studies have shown that, although soil organic carbon concentration in subaqueous soils varies widely, some subaqueous ecosystems may have as much carbon as wetlands and forested ecosystems (Jespersen and Osher, 2007; Payne, 2007; Balduff, 2007; Pruett, 2010; Bakken, 2012). These potential sinks for carbon should be inventoried, characterized, and considered in regional carbon budgets.

References

Bakken, J. 2012. Freshwater subaqueous soils. M.S. thesis, University of Rhode Island, Kingston, RI.

Balduff, D.M. 2007. Pedogenesis, inventory and utilization of subaqueous soils in Chincoteague Bay, Maryland. Ph.D. dissertation, University of Maryland, College Park.

Bradley, M.P., and M.H. Stolt. 2002. Evaluating methods to create a base map for a subaqueous soil inventory. Soil Science 167:222-228.

Bradley, M.P., and M.H. Stolt. 2003. Subaqueous soil-landscape relationships in a Rhode Island estuary. Soil Science Society of America Journal 67:1487–1495.

Calumpong, H.P., and M.S. Fonseca. 2001. Chapter 22: Seagrass transplantation and other restoration methods. *In* F.T. Short and R.G. Coles (eds.) Global seagrass research methods, Elsevier Science B.V., Amsterdam, The Netherlands.

Clark, M.W., and D.M. McConchie. 2004. Development of acid sulfate soil in sub-aerially disposed dredge spoil at Fisherman Islands, Brisbane, Australia. Soil Research 42:553–567.

Erich, E., M. Payne, D. Surabian, M.E. Collins, P.J. Drohan, and L.R. Ellis. 2010. Subaqueous soils: Their genesis and importance in ecosystem management [electronic resource]. Soil Use and Management 26:245–252.

Fanning, D.S., M.C. Rabenhorst, D.M. Balduff, D.P. Wagner, R.S. Orr, and P.K. Zurheide. 2010. An acid sulfate perspective on landscape/seascape soil mineralogy in the US Mid-Atlantic region. Geoderma 154:457-464.

Fonseca, M.S., W.J. Kenworthy, and G.W. Thayer. 1998. Guidelines for the conservation and restoration of seagrasses in the United States and adjacent waters. National Oceanic and Atmospheric Administration (NOAA) Coastal Ocean Office, Silver Spring, MD.

Jesperson, J.L., and L.J. Osher. 2007. Carbon storage in the soils of a mesotidal gulf of Maine estuary. Soil Science Society of America Journal 71:372–379.

McVey, S., P.J. Schoeneberger, J. Turenne, M. Payne, D.A. Wysocki, and M.H. Stolt. 2012. Subaqueous soils (SAS) description. *In* P.J. Schoeneberger, D.A. Wysocki, E.C. Benham, and Soil Survey Staff (eds.) Field book for describing and sampling soils, version 3.0, USDA Natural Resources Conservation Service, National Soil Survey Center, Lincoln, NE, pp. 2-97 to 2-119.

Oakley, B.A., J.D. Alvarez, and J.C. Boothroyd. 2012. Benthic geologic habitats of shallow estuarine environments: Greenwich Bay and Wickford Harbor, Narragansett Bay, Rhode Island, U.S.A. Journal of Coastal Research 28:760 –773.

Osher, L.J., and C.T. Flannagan. 2007. Soil/landscape relationships in a mesotidal Maine estuary. Soil Science Society of America Journal 71:1323–1334.

Payne, M.K. 2007. Landscape-level assessment of subaqueous soil and water quality in shallow embayments in southern New England. M.S. thesis, Department of Natural Resources Science, University of Rhode Island, Kingston, RI.

Pruett, C.M. 2010. Interpretations of estuarine subaqueous soils: Eelgrass restoration, carbon accounting, and heavy metal accumulation. M.S. thesis, University of Rhode Island, Department of Natural Resources Science, Kingston, RI.

Rabenhorst, M.C., and M.H. Stolt. 2012. Subaqueous soils: Pedogenesis, mapping, and applications. *In* H. Lin (ed.) Hydropedology: Synergistic integration of soil science and hydrology. Academic Press, Elsevier, pp. 173–204.

Salisbury, A.R. 2010. Developing subaqueous soil interpretations for Rhode Island estuaries. M.S. thesis, University of Rhode Island, Department of Natural Resources Science, Kingston, RI.

Schoeneberger, P.J., and D.A. Wysocki. 2012. Geomorphic description system, version 4.2. USDA Natural Resources Conservation Service, National Soil Survey Center, Lincoln, NE.

Schoeneberger, P.J., D.A. Wysocki, E.C. Benham, and W.D. Broderson. 2012. Field book for describing and sampling soils, version 3.0. USDA Natural Resources Conservation Service, National Soil Survey Center, Lincoln, NE.

Simonson, R.W. 1959. Outline of a generalized theory of soil genesis. Soil Science Society of America Proceedings 23:152-156.

Soil Survey Staff. 2014. Keys to soil taxonomy, 12th edition. USDA Natural Resources Conservation Service.

Stolt, M.H., and M.C. Rabenhorst. 2011. Subaqueous soils. *In* P.M. Huang, Y. Li, and M.E. Sumner (eds.) Handbook of soil science, 2nd ed., CRC Press, Boca Raton, FL.

Surabian, D.A. 2007. Moorings: An interpretation from the coastal zone soil survey of Little Narragansett Bay, Connecticut and Rhode Island. Soil Survey Horizons 48:90-92.

U.S. Department of Agriculture, Natural Resources Conservation Service. 2016. National soil survey handbook, title 430-VI. Part 629—Glossary of landform and geologic terms. http://www.nrcs.usda.gov/wps/portal/nrcs/detail/soils/ref/?cid=nrcs142p2_054242 [Accessed 8 August 2016]