SUBAQUEOUS SOILS

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Introduction and Historical Development of Subaqueous Soil Concepts

One of the new frontiers in soil science that has come into focus over the last two decades has been the study of subaqueous soils. Although the concept has appeared in the literature at times (Kubiëna, 1953; Muckenhausen, 1965), only recently have these substrates received recognition in the US and as such are now accommodated under the definition of soils (Soil Survey Staff, 1999). Under the new definition, soils may occur in permanently flooded or ponded environments with water depths up to approximately 2.5 m (Soil Survey Staff, 1999).

Previous opposition to the concept of subaqueous soils was primarily focused upon the idea that subaqueous substrates are not, in fact, soils but sediments. The ruling dogma was that by definition a soil must be able to support the growth of plants (Soil Survey Staff, 1975). Thus, the essential absence of higher plants in many subaqueous environments excluded these substrates from the pedologic realm. A secondary issue was related to the defining boundaries of a soil. The first edition of Soil Taxonomy (1975) stated that the upper limit of soils is ".... air or shallow water. In this sense "shallow water" was meant to exclude soils permanently under water. Thus, these materials were also excluded from being soil by their permanent inundation. Over the 25 years that spanned the development of the 2nd edition of Soil Taxonomy (Soil Survey Staff, 1999), pedological thinking continued to evolve such that pedologists began distancing themselves from their agricultural roots with a loosening of the link between the definition of soils and the growth of plants. Rather, pedologists began to emphasize what had already become deeply entrenched as the foundation to the Taxonomy itself, namely the formation of horizons resulting from those generalized pedogenic processes described by Simonson (1959). For example, Bockheim (1990, 1997) and Campbell and Claridge

(1987) showed that in the harsh-cold climate of Antarctica, where higher plants are not able to grow, soil horizons were still observed as a result of pedogenic processes (i.e. additions, losses, transfers and transformations). Thus, the idea that these areas should be recognized as soils was gaining support among the pedologic community, even though they were not necessarily capable of supporting the growth of higher plants.

Much of the credit for the emergence of subaqueous soils as a field of soil science has to be given to Dr. George P. Demas. The story goes that the concept formed in George’s mind as he was standing on the edge of the marsh in Maryland that he was mapping, and looking down into the shallow tidal water of Sinepuxent Bay, he posed the question “Why should we stop mapping here?” He began to consider that such submersed aquatic vegetation as Eelgrass (*Zostera marina*) and Widgeongrass (*Ruppia maritima*) were rooted in these substrates (Figure 1) and, as he began to closely examine them observed what could be construed as pedogenic horizons. Soon afterwards he published his paper “Submerged soils: a new frontier in soil survey.” in Soil Survey Horizons (Demas, 1993). Over the next six years under the guidance of Dr. Martin Rabenhorst, Demas further developed the ideas and concepts for the characterization, formation, and mapping of subaqueous soils in his PhD dissertation (Demas, 1998).

The works of Demas led to a number of additional studies that form the basis for most of the discussion in this chapter. In particular the most important findings or accomplishments included in the work and dissertation were:

- Subaquesous soils form as a result of the generalized processes of additions, losses, transfers, and transformations (Demas and Rabenhorst, 1999). This led to a change in the definition of soil to include substrates that are permanently under significant water (approximately 2.5 m) and that show evidence of pedogenesis (Soil Survey Staff, 1999).

- Bathymetric maps could be constructed to use as a soil survey basemap and identify subaqueous landforms in a manner analogous to the subaerial landforms that soil scientists had been studying for most of the last century (Demas and Rabenhorst, 1998).
- Similar soils occurred or formed on similar landforms. Therefore, the "soil-landscape" paradigm typically used to map subaerial environments could be applied to the mapping subaqueous soils, and thus specific soil-landscape relationships began to be documented for the coastal lagoons of the Mid-Atlantic USA.
- The establishment of the first official soil series for subaqueous soils: Demas[1], Sinepuxent, Southpoint, Tizzard, Trappe, and Whittington.

Kubiëna (1953) was the first to use of the term subaqueous soils to describe permanently inundated soils. Those soils composed of layers and forming in low-energy subaqueous environs were classified into 4 groups (Kubiëna, 1953). Most of the focus was on soils having considerable soil organic matter: dy, gyttja, and sapropel; terms often applied to substrates in limnological studies (Saarse, 1990). Horizon sequences were typically A, AC, and C regardless of the soil type. Dy soils formed below water columns that were acidic, nutrient poor, and having high concentrations of soluble organic compounds. These soil materials have a gel-like form indicative of amorphous organic matter. Gyttja forms in subaqueous soils rich in nutrients. The majority of the materials are coprogenic in origin, having a loose arrangement (Jongerius and Rutherford, 1979) typical of high *n*-value soil materials (low bearing capacity; Soil Survey Staff, 2006).

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[1] Originally proposed as Wallops, but posthumously named Demas following the untimely death of innovator Dr. George P. Demas in December, 1999.

These subaqueous soil materials have also referred to as sedimentary peat, coprogenous earth, or limnic materials (see Fox 1985; Soil Survey Staff, 2006). Subaqueous layers that contain various amounts of more or less unrecognizable organic debris that are enriched in sulfides were termed sapropels. Most of these sulfides are Fe-monosulfides or pyrite in the solid form, or hydrogen sulfide gas as recognized by the rotten egg smell. Colors are typically black that changes to gray upon drying.

The classification of subaqueous soils by Kubiëna (1953) was cited in the national soil classification system in Germany (Muckenhausen, 1965), but there is no evidence that these soils were the focus of any serious investigation. A decade later, although he did not elaborate nor focus much on what he called “Subaquatic Soils,” Ponnamperuma (1972) did affirm that these soils forming under water reflected “horizon differentiation distinct from sedimentation.” Nevertheless, between the publication of this paper and the time when Demas began to focus on these systems more than two decades later, apparently little attention was paid to subaqueous soils.

Soil Genesis in Subaqueous Environments

In addition to the generalized model of soil genesis (additions, losses, transfers, and transformations) described by Simonson (1959), pedologists have often invoked the state factor equation of Jenny (1941) to describe and conceptually model the formation of soils. While Jenny’s model has limitations, it recognizes the contributions of various soil forming “factors”. In considering the genesis of subaqueous soils, similarities to the processes and factors described by Jenny (1941) were recognized, but significant differences were also noted. The generalized model for estuarine sediments of Folger (1972) was noted where he described their origin as being derived from source geology (G), bathymetry (B), and hydrologic condition (H) (flow regime).

$$Se = f\,(G, H, B)$$

The concepts of both of these previous equations were joined, with some further modifications, into a state factor equation to describe the formation of subaqueous soils (Demas and Rabenhorst, 2001).

$$Ss = f\ (C, O, B, F, P, T, W, E)$$

In this equation, Ss is subaqueous soil, C is the climatic regime, O is organisms, B is bathymetry, F is flow regime, P is parent material, T is time, W is water column attributes, and E is catastrophic events.

Climatic (C), was not included in Folger's equation, and does not include precipitation as in Jenny's model. The climatic component in this model primarily represents temperature. Temperature, for example, will affect the rate of organic matter decomposition (and other biogeochemical reactions).

Organisms (O) was also not included by Folger, and represents the role that biota play in subaqueous pedogenesis. As an example, the burrowing of benthic organisms (essentially irrigating their burrows with oxygenated water) often contribute to the development of light colored, surface horizons, as well at the obvious contributions of plant carbon to the upper soil horizons.

Bathymetry and flow regime (B and F) replace relief (R) in Jenny's equation. The catena concept per se is not applicable in a permanently submersed environment. The role is somewhat different than simply relief or topography as normally considered in soils. Bathymetry contributes to the effects of internal and wind generated waves on the subaqueous soil surface. Flow regime helps to shape underwater topography and accounts for differences in the energies associated with currents and tides. Together, these two factors (B, F) essentially play the same genetic role as relief does in subaerial soil environments.

Parent material (P) was a factor in both the equations of Folger and Jenny and explains the effect of the source material on subaqueous soil profile attributes. For example, subaqueous soils that form in areas where they receive barrier island washover materials are predictably sandy textured.

Time (T) of course represents the amount of time available for the expression of subaqueous soil attributes.

Water column attributes (W) was not included in either Jenny's or Folger's equations, and has been added to include variations in the chemical composition of the water column that could have an impact on subaqueous soil characteristics. Those subaqueous soil profiles developed in freshwater regions or fresh portions of estuaries will likely be significantly different than those formed in more saline or brackish environments where sulfate is available for reduction to sulfide and the potential formation of solid phase sulfide minerals. Similarly, the dissolved oxygen levels in the water column could dramatically impact the formation or the thickness of light-colored, oxidized, surface horizons.

Catastrophic events (E) is included in this equation to account for the possibility that subaqueous soil profiles may be dramatically impacted by major storm events or other uncontrollable or unknown factors. The effects of storms or modest hurricanes, however, do not seem to cause wholesale alterations to large areas of subaqueous soils.

Mapping, research, and agency efforts

Subaqueous soils research and mapping projects have been completed or are in progress along the eastern seaboard of the U.S from Maine to Florida and along the Gulf Coast in Florida and Texas (Table 1). Projects have covered a range of topics including: mapping protocols, soil-landscape relationships, carbon sequestration, soil variability, pedogenesis, use and management interpretations, and relationships between subaqueous soils and submerged aquatic vegetation and water quality. Study and mapping areas have primarily concentrated on estuarine areas such as coastal lagoons and shallow water embayments (Figure 2). In response to mapping efforts, regional and national subcommittees within the National Cooperative Soil Survey have been established to advance national mapping standards and procedures for subaqueous soils. New parent material and landscape-landform terms have been added to the National Soil Survey Handbook (NCSS, 2005) and Soil Taxonomy has been revised to accommodate the classification of subaqueous soils (see section below on Soil Taxonomy). In Rhode Island a partnership was developed (MapCoast, 2009) among Federal agencies such as EPA, NRCS, NOAA, state level agencies, and university researchers and scientists to apply the information provided in subaqueous soil investigations to coastal resource issues and problems. The MapCoast partnership is a consortium dedicated to multidisciplinary mapping of coastal underwater resources, including bathymetry, habitat, geology, soils/sediment, and archeological resources in shallow waters (August and Costa-Pierce, 2007). NOAA is redesigning their classification system for shallow subtidal habitats (similar to the Cowardin et al. system for wetlands) and including a subaqueous soils component (Madden et al., 2008).

Methods for characterizing subaqueous soils and mapping their distribution

One of the big hurdles in investigations of subaqueous soils and mapping their distribution was the lack of methodologies for identifying, sampling, characterizing, and mapping subaqueous soil properties and their distribution. Discussions on topics such as collecting bathymetric data, using a vibracore, collecting soil samples under water, and the handling of subaqueous soil samples for subsequent laboratory analysis were essentially absent from the soil literature.

Creating a Subaqueous Terrain Map

Landscape units provide a first approximation of the distribution of soils on the landscape and offer an objective delineation of soil types. Numerous studies have emphasized the importance of landscape components for predicting and explaining soil distributions (Jenny, 1941; Ruhe, 1960; Huddleston and Riecken, 1973; Stolt et al., 1993; Scull et al., 2005). Subaqueous landscapes are fundamentally the same as subaerial systems and have a discernable topography from which subaqueous landforms and landscape units may be identified. However, because of the overlying water, submerged landscapes and landforms cannot be identified easily using standard methods such as stereo photography or visual assessment of the landscape. Therefore, identification and delineation of subaqueous landscape units is somewhat more complicated than that of terrestrial landscapes, and development of subaqueous topographic maps is a critical first step toward delineating subaqueous landscape units.

Bathymetric data (water depths) are used to produce a contour or bathymetric map from which subaqueous landforms can be identified and delineated to begin the soil survey. Thus, x, y, and z coordinates are necessary to create a contour map. XY locations are obtained with a differential GPS receiver (DGPS) with sub-meter accuracy.

Water depths can be determined in a number of ways. The quickest approach is to use a fathometer or bottom profiler. The transducer portion of the profiler is attached to the boat just below the water line. As the boat moves along the water depths are obtained and stored in the fathometer computer or a device such as laptop. Demas and Rabenhorst (1998) reported that soundings were collected at approximately 4 km^2/hr. Soundings should be collected essentially along fairly evenly spaced transects that are perpendicular to the shoreline. The depths are corrected by adding the depth between the water surface and bottom of the transducer and correcting for changes in the tide while the data is being collected.

Tide corrections are made from data collected from tide gauges operating at the same time that the bathymetric data are being collected. One to three tide gauges are generally required depending upon the size of the area of interest and the complexity of the tidal cycle within the estuary. Tide gauges should be surveyed in from USGS benchmarks. Tide corrections can be made in a number of ways. Most simple tidal fluctuations can be corrected using equations developed from the tidal cycles and applied via a spreadsheet. Complicated corrections may require use of software designed for the purpose.

There has been some discussion and some attempts to use LIDAR (light detection and ranging) to obtain bathymetric data more rapidly. The SHOALS (US Army Corps of Engineers) bathymetry system uses a scanning, pulsed, infrared (1064 nm) and blue-green (532 nm) laser transmitter where the depth of water is determined from the difference in return times of the two beams and knowing the speed of light in water. Optimally, this system can be used to measure water depth from 0 to 40 meters with a vertical accuracy of 20 cm. While this may have promise, there are a number of limitations which can be especially problematic including: 1) water clarity limits the ability of light to penetrate to the bottom; 2) high surface waves and heavy fog decrease the depth penetration of the lasers; 3) heavy vegetation and fluid mud influence the depth penetration of the lasers. Also, in many systems where the maximum water depth is only a few meters, a resolution of 20 cm may not be adequate. Hopefully, advances will continue so that more rapid acquisition of bathymetry becomes possible.

Bathymetric data should be reviewed to remove aberrant depths and aberrant XY locations. A number of software programs are available to construct topographic maps. As an example, an ArcView TIN model was created using the bathymetric soundings and a hard breakline (depth = 0) consisting of the wetline from recent orthophoto. The TIN was converted to a GRID (10 m pixel size). The land/water interface observed from the orthophoto wetline was used as a mask to set all land-based pixels to NODATA. The bathymetric GRID was smoothed by applying a 3 pixel radius averaging filter and contours were created from the smoothed bathymetric GRID. Although the TIN model was used in our example here, other modeling approaches such as kriging have been applied to bathymetric data to create topographic maps.

Using the fathometer from a boat is limited to water depths less than 50 cm. In areas where there is considerable tidal fluctuation (a meter or more tidal fluctuation), shallow water may be profiled at high tides. If tidal fluctuations are less, surveying of the shallow water may be necessary. This can be done with a survey grade GPS that records elevations (RTK), a total station, or an all-purpose elevation rod and level. This approach can also be used to validate contour maps created from bathymetric data.

Landscape and Soil Delineation

(Stolt and Rabenhorst, 2010)

Landscape unit boundaries provide the first approximation of the distribution of soils over the landscape. Landscape attributes such as slope, micro-relief, surface shape, and geographic proximity to other features, and location help define landforms and landscape unit boundaries. Landscape unit boundaries are hidden beneath the water cover in the subaqueous environment and need to be deciphered from contour maps. Landforms and units such as coves, submerged beaches, shoals, washover fan flats and slopes are some common examples found in many estuaries (Figure 3; NCSS, 2005). In some cases, these features can be observed in aerial photographs that penetrate the water, but in general a contour map illustrating slope breaks is necessary to define the boundaries on each unit.

Identifying the soil types within a landscape unit is done through reconnaissance efforts and transects. The same criteria used to separate mapping units in subaerial soils can be used in subaqueous soils. Tools such as a Macaulay peat sampler, bucket auger, and tile probe are effective in providing soil samples and data for identifying soil types. Peat samplers work well in high n-value (soft, low-density) soil materials, low energy environments. In areas where low n-value mineral soils dominate, a bucket auger can be used to sample the upper 75 cm of the soil. Some soil scientists use a sleeve with an inside diameter slightly larger than the diameter of the auger maintain an auger boring location and to minimize slumping of sandy materials into the auger hole. Samples collected in the bucket auger are often transferred to a vinyl tray or gutter on the boat for description and possible sampling. A floating tube with the tray strapped to the tube can work in the case of wading and mapping. Tile probes can be used to find depth to bedrock or similar consolidated or semi-consolidated materials. Percentages of boulders and large stones can also be estimated with the tile probe. Side-scan sonar images, or video footage across proposed mapping units, may aid in proper placement of boundaries and provide spatial data regarding the distribution of stones and boulders extruding from the soil and into the water column.

Just as in subaerial soil mapping, map unit purity and variability need to be addressed. The most common approaches are using random points or transects to assess variability. Studies of soil variability within the landscape units (Demas, 1998; Bradley and Stolt, 2003; Osher and Flanagan, 2007) demonstrate that the concept (common to subaerial landscapes) that soil type follows landscape form (Hudson, 1992) also holds for subaqueous soils (Table 2). For example, Bradley and Stolt (2003) reported that 11 of the 12 map units that were used to map the subaqueous soils in a coastal lagoon had a taxonomic purity (based on the subgroup taxonomic level) above criteria used for delineation of the traditional consociation map units used in most USDA-NRCS soil surveys (Soil Survey Division Staff, 1993).

One of the criticisms of inventorying subaqueous soils is that these environments are considered "ever-changing, unstable, shifting sands". Although some areas such as flood-tidal delta landscapes are quite dynamic, Bradley and Stolt (2002) showed that a detailed 1950's NOAA bathymetric map (NGDC, 1996) of the coastal lagoon (Ninigret Pond) was essentially no different than a bathymetric map created 50 years later. With the lifespan of a soil survey on the order of 25 to 30 years, subaqueous soil surveys should provide descriptions and interpretations for two to three decades of most areas having subaqueous soils.

Sample Collection for Characterization of Typifying Pedons

In high n-value materials, a relatively undisturbed half-core (5 cm diameter) can be collected using a Macaulay peat sampler, which is an excellent tool for providing samples for description and characterization. One limitation is that samples collected with a peat sampler are a bit small, which when coupled with the fact that the materials that can be sampled with the peat sampler have a low density, their dry mass is quite small. Thus, for characterization and descriptive purposes it may be necessary to take multiple adjacent samples if a Macaulay peat sampler is employed. High n-value materials can also be collected in a core barrel. A handle for pushing the core-barrel in and pulling it out is attached to the barrel and weight (usually one or two persons lean on the handle) is added to push the core barrel into the soft materials. Several people are usually needed to pull the sample out.

Vibracore sampling is the most effective approach to obtain minimally disturbed samples for detailed description and sampling of typical pedons (Stolt et al., 2008). A vibracore rig consists of an engine, a cable, and vibracore head (Lanesky et al., 1979). The engine creates a high frequency, low amplitude vibration. The vibration is transferred through a cable to the vibracore head that is bolted to the top of core barrel or tube. This vibration essentially liquefies the soil materials in a thin zone immediately adjacent to the tube, enabling the core barrel to penetrate into the soil materials. Weight is often added to the top of the core barrel to assist in pushing the core barrel into the soils. Vibracores come in a variety of forms from small, lightweight and portable, to large heavy machines.

Core barrels are generally made out of 7.5 to 10 cm inside diameter aluminum pipe (irrigation pipe). Some barrels are made out of polycarbonate (these are clear and light, but also 6 to 7 times more expensive than aluminum). Core barrel lengths should be as long as the soil to be sampled, plus water depth, and an extra 50 or 60 cm.

In many sampling systems, a core catcher is attached to the cutting end of the barrel. The catcher keeps the soil from sliding out of the barrel when the core is removed from the soil. Other systems rely on a rubber plug inside the barrel that rises up as the barrel is pushed into the soil. The plug maintains a short, nearly air-tight space just above the sample to minimize disturbance. This approach also minimizes the suction of the sample out the bottom of the core when the core is removed.

A 2 meter core of subaqueous soil that is collected in several meters of water is generally quite heavy and difficult to pull out of the soil. Thus, in most vibracore systems a tripod is set up with a winch or chainfall on the top to extract the core from the soil. The tripod is set up over an opening in the bottom of the sampling vessel. In most cases, a pontoon boat is used for sampling with a vibracore. Sampling is done through an opening (60 cm x 60 cm) in the deck (“moon pool”). The tripod setup can also be placed over a 2 meter by 2 meter barge that is towed behind the boat. An opening is cut in the middle of the barge. These barges are built from floating dock styrofoam that is encased in marine plywood.

Subaqueous Soil Sampling and Description

Standard descriptive terminology as outlined in the Soil Survey Manual (1993), and by the National Soil Survey Lab (Schoeneberger et al., 2002), and horizon designations outlined in the Keys to Soil Taxonomy (2010) should be used to describe subaqueous soils. Samples collected with a Macauley or bucket auger can be described and sampled immediately.

Cores collected with a vibracore can be sampled and described on the boat or returned to the lab and kept in cold storage prior to sampling. Keeping the samples in cold storage may not be adequate enough to inhibit sulfide oxidation entirely. Cores are extracted from the barrels by cutting the barrels length-wise on both sides and removing the half barrel. Electric shears designed to cut metal are the best option. A circular saw can also be used to the cut through most of the thickness of the barrels and a razor knife used to complete the cut. Prior to using the razor knife the shards of aluminum or plastic should be whisked away.

Sample Analysis

Most sample analysis can be made following standard procedures outlined in the Soil Survey Laboratory Methods Manual (USDA-NRCS, 2004). Certain soil properties will be affected by the subaqueous environment and laboratory procedures should be conducted with this in mind. Many subaqueous soil horizons (especially those collected from brackish or coastal environments) contain sulfides that may oxidize upon exposure to air. If samples are meant to be collected for classification purposes, treatment of the samples to avoid oxidation of the sulfides is critical. The most common approach is to immediately transfer the sample to a labeled bag, press out an air trapped in the bag, and put the sample on ice in a cooler. If the soil materials appear to be very reactive (unstable), or the amount of time between sampling and return to the lab is extended, pressurized nitrogen gas can be used to sparge the bags to remove oxygen prior to sealing. If deemed necessary, liquid nitrogen can be applied to the bag in the field to immediately freeze the sample after which it should be placed on ice.

Sulfides, salts, and shell fragments are the most important to consider when analyzing the soil and are worth noting. The presence of sulfides in the soils has been noted above and should be accommodated. Measurements of sulfides are not well documented in soil survey publications. Thus, if this characteristic is to be measured consideration should be given to the numerous methods to measure chromium reducible and acid volatile sulfides (see Bradley and Stolt, 2006, Payne, 2007). Particle size distribution analysis may need to be altered to accommodate for the weight and flocculation capability of salts. Samples can be washed to remove salts using dialysis tubing. Carbonates in shell fragments can be an issue in measuring organic carbon and should be considered when organic and calcium carbonate carbon is being determined.

Classification of Subaqueous Soils

Soil classification is much different than traditional sediment classification, where the substrate is termed mud, silty sand, muddy sand, (Fegley, 2001) or other somewhat subjective class, and the focus is often on the upper portions of the profile. The soil classification approach offered in *Soil Taxonomy* is more comprehensive and addresses the larger soil profile. For example, a sediment classification of silty sand (for example, see Fegley, 2001) could be better described using *Soil Taxonomy* as a coarse-silty over sandy skeletal, mixed, Typic Sulfaquent soil. This soil classification conveys that: the upper portion of the soil has <18% clay and >70% silt sized particles; the lower soil materials (to a meter depth or more) are sandy with >35% gravels or larger particles; the silt and sand sized particles are not dominated by a particular mineral; and that there are enough sulfides within 50 cm of the soil surface that when the soil materials are allowed to oxidize the pH drops to below 4. Such additional knowledge could be important for decisions regarding the use and management of a portion of the estuary.

The latest version of Keys to Soil Taxonomy (Soil Survey Staff, 2010) includes taxa within Entisols and Histosols (“Wassents” and “Wassists”) to accommodate subaqueous soils. The formative element “wass” is from the German word for water, “wasser” (Ditzler et al., 2008). Criterion for identifying both suborders is a positive water pressure at the soil surface for at least 21 hours each day in all years. The intent of the definition is to identify soils that are inundated every day, every year, with no exceptions for periodic short- or long-term drought cycles. In certain areas with large tidal fluctuations, such as northern Maine in the USA, soils are inundated with one to two meters of water everyday with the exception of a few hours at low tide. The 21 hour minimum is proposed to allow for short daily exposure of these subaqueous soils.

.Six great groups within Wassents are included keying out in the order: Frasiwassents, Psammowassents, Sulfiwassents, Hydrowassents, Fluviwassents, and Haplowassents (see Figure 4 for example profiles). Freshwater subaqueous soils key out as Frasiwassents based on an electrical conductivity of a 5:1 ratio of water to soil of <0.2 dS m^{-1}. Subaqueous soils that have sandy textures throughout the upper meter are Psammowassents. Sulfiwassents have at least 15 cm of sulfidic materials within the upper 50 cm of the soil. Soils with high n-values (low bearing capacity) classify as Hydrowassents. Those soils with an irregular decrease in organic carbon with depth key out as Fluviwassents. Subgroup taxa include: Sulfic, Lithic, Thapto-histic, Aeric, Psammentic, Fluventic, Grossic, Haplic, and Typic. With the exception of Grossic, all of these apply in a similar manner to previous applications in other taxa. Grossic is used to identify subaqueous soils that have very thick layers with high n-values.

Subaqueous Histisols are classified as Wassists. There are three Great Groups: Frasi-, Sulfi-, and Haplo- wassists. The Frasiwassists have low electrical conductivity (<0.2 dSm^{-1}); Sulfiwassists have > 15 cm of sulfidic materials within 50 cm; and Haplowassists are all other Wassists. Three subgroups are proposed: Fibric, Sapric, and Typic, depending on the dominant type of organic materials present. Examples of Wassent-landscape relationships are shown in Table 2. The World Reference Base

(2006) has taxa similar to those proposed for Soil Taxonomy. WRB's Subaquatic Fluvisols correlate to Wassents, and the Subaquatic Histosols correlate to Wassists.

Applications of Subaqueous Soil Information

Shallow-water coastal habitats, including coastal lagoons, shallow bays, and estuarine areas, are highly valued and heavily used resources. Almost two-thirds of the worldwide population currently lives in coastal areas (Trenhaile, 1997) and recent demographic studies suggest that in the next 25 years 75% of the US population will live in close proximity to the coast (Bush, 2004). As subaqueous soil science progresses, a wide range of use and management interpretations are expected to be developed for use with estuarine subaqueous soil maps (Table August and Costa-Pierce, 2007; Surabian, 2007; Payne and Turenne, 2009). These interpretations will aid in coastal, estuarine, and marine restoration, ecosystem management, and conservation efforts. For example, subaqueous soils information can be used to assist in: the restoration of submerged aquatic vegetation and shellfish; identifying shellfish aquaculture sites; design and placement of shoreline protection, docks, and moorings; and identifying subaqueous soils that are of beneficial use from dredging (Demas and Rabenhorst, 1999; Bradley and Stolt, 2003; Bradley and Stolt, 2006; Surabian, 2007). Since subaqueous soils investigations are a relatively new focus in pedology, and most of the subaqueous soils efforts have concentrated on developing field and laboratory methodology, few studies have concentrated on interpretations. Thus, the breadth of information relating soil type with the use and management of these resources is quite limited.

Dredging and Dredge Placement

Dredging of subaqueous soils is a common practice to deepen navigable waterways and to replenish beaches. Subaqueous soils often have layers or horizons where sulfides have accumulated in subaqueous soils as a result of sulfidization (see section on pedogenesis of subaqueous soils). When the sulfide-bearing soils are dredged and placed in the subaerial environment, sulfides oxidize releasing sulfuric acid, lowering the pH, and creating acid-sulfate soils (Fanning and Fanning 1989). Acid sulfate soils may persist for a number of years and are uninhabitable for plants and animals. If deposited near water, these acid sulfate soils can also create runoff that is toxic to aquatic systems (Demas et al., 2004).

To test for sulfides and for taxonomic purposes, subaqueous soils are allowed to oxidize in a moist environment. In general, those soil materials that after at least 16 weeks of moist incubation reach pH values <4 are considered to have sulfidic materials (Soil Survey Staff, 2010) and are potential acid sulfate soils. Whether these soils reach the potential as acid-sulfate soils is dependent upon a number of factors such as the buffering capacity, rate and extent of acid production, weathering, and leaching due to environmental factors are not considered in the laboratory approach. For example, during a moist incubation, a small amount of sulfide would lower the pH in a sandy soil with low organic carbon because of the limited amount of buffering capacity. In such soils, the amount of acid produced would be much less than a soil with a similar incubation pH but a higher buffering capacity because of a finer texture or greater organic matter levels. In a natural setting, a small amount of acid could potentially leave a sandy, minimally buffered soil very quickly as the acidity generated by oxidation would be washed out of the system as a result of precipitation and leaching. In contrast, acid sulfate conditions may remain for decades in a fine-textured, buffered soil. Thus, understanding a number of soil parameters is critical to identifying the subaqueous soils that can be deposited in a subaerial environment as dredged materials and maintain conditions conducive for plant growth and a safe environment.

Water quality

Estuarine ecosystem integrity and sustainability has received tremendous interest in recent years. These interests are being driven by concerns over the negative effects of rapid urbanization and related anthropogenic activities on the coastal environment. As the use of these natural resources has increased, the most urbanized estuaries have been ecologically compromised and common ecosystem functions and values are being lost. Obvious signs of these degraded environmental conditions are accumulations of metals and other contaminants, an increase in emerging diseases and algal blooms (Harvell et al. 1999), and anoxia related fin and shell-fish kills (RIDEM, 1998, 2003). Most of these issues are related to poor water quality.

Water quality has traditionally been used in coastal areas as an indicator of the overall health of an estuary (Glasgow and Burkholder, 2000; Granger et al., 2000; Stevensen et al., 1993). Because water quality can fluctuate with tidal cycles and seasonal and yearly weather changes, water quality trends are difficult to predict or to use as a reliable indicator of extended changes in the health of an estuarine system (D’Avanzo and Kremer, 1994; Cicchetti et al., 2006). Soil properties and characteristics develop in response to the environment, making subaqueous soils a potential long term indicator of the degree that these ecosystems have become degraded (Valente et al., 1992; Germano and Rhoads, 1988). Such an indicator would allow estuary management teams to target particular estuaries for conservation, protection, and restoration of resources based on soil survey information. Understanding the degree and spatial distribution of the degradation is critical to managing coastal estuaries for any number of functions and values, especially aquaculture and restoration of commercially important shellfish populations.

Redox conditions in a soil have important impacts on chemical processes that occur in the soil such as denitrification, changes in forms of iron, manganese, or sulfur, and the solubility of heavy metals (Teasdale et al., 1998; Tomaszek, 1995). The decomposition of organic matter by microbes fuels the redox reactions in soil. Oxygen is the strongest oxidizing agent in aqueous systems and acts as an electron acceptor during microbial decomposition. In subaqueous systems, however, oxygen can quickly be depleted and other electron acceptors are used by the microbes. These other electron acceptors include nitrate, manganese, iron, sulfate, and carbon dioxide. Each species, respectively, is reduced at a lower range of redox potentials depending on the pH (Bohn, 1971). These processes produce a vertical profile of decreasing redox potential with depth as each oxidizing agent is reduced until all organic matter has been decomposed (Teasedale et al., 1998).

The first of these boundaries, where all oxygen has been depleted or reduced, is generally known as the redox boundary, the redoxocline, or the redox-potential-discontinuity (RPD) (Knox, 1986; Teasedale et al, 1998; Hinchey and Schaffner, 2005). The depth of the RPD can be influenced by the grain size, organic matter content, temperature of the soil, as well as the movement and dissolved oxygen content of water above the soil surface (Knox, 1986). A redox potential gradient found in subaqueous soils often includes the oxidized surface layer where oxygen is still present in the interstitial water, a zone of transition where other species are being reduced, and a sulfide zone that is totally anaerobic, H_2S is prevalent, and redox potentials are very low (Knox, 1986). This zonation plays an important role in determining layers in which chemical processes involving organic carbon, nitrogen and sulfur occur, and can serve as an indication of estuary health.

Submerged Aquatic Vegetation

One part of the definition of soil is the ability of soil to support rooted plants in a natural environment (Soil Survey Staff, 1999). Dense beds of submerged aquatic vegetation (SAV, or seagrass) are often found in subtidal estuaries. Unlike macro-algal species, which anchor themselves to a substrate, seagrasses are rooted vascular aquatic plants in which roots serve both structural and nutrient uptake purposes (Barko et al., 1991). One of the most important interpretations from an inventory of subaqueous soils may be seagrass restoration. Submerged aquatic vegetation such as eelgrass provide nursery habitat for economically important fin and shell fish and are important for sediment and nutrient filtering, nutrient cycling, and buffering wave effects. In many estuaries, aerial coverages of seagrass beds have severely declined over recent years. Therefore, seagrass restoration has become a focus of many coastal managers. Seagrass revegetation and restoration projects cost on the order of $100,000 per acre, but few of these projects have been successful. It is highly likely that the projects fail because of site selection. Seagrass revegetation sites are commonly located where past seagrass meadows had been, not at sites where present soil conditions are optimum for success. However, loss of seagrass tends to result in erosion of the subaqueous soils. Thus, soils within areas that previously supported seagrass may be significantly different following the loss of vegetation and subsequent erosion. A detailed knowledge of the relationship between subaqueous soil properties and submerged aquatic vegetation is essential for improving the success of seagrass revegetation efforts. An understanding of the seagrass-subaqueous soil system will help resource managers identify the sites where revegetation efforts can be most successful (Bradley, 2001). Few studies have looked at these relationships. Bradley and Stolt (2006) examined subaqueous soil-eelgrass relationships in a northeastern US coastal lagoon. Similar studies need to be made across regions with a focus on the predominant seagrass species and the breadth of tidal ranges and gradient of temperatures.

Carbon Storage and Sequestration

With the concern with global warming mounting as a result of increasing greenhouse gas emissions there is significant interest in carbon storage and sequestration in soil systems. These interests have led to numerous studies of focused on soil carbon for various land types and covers. Although forested and emergent wetlands have been well studied in regard to carbon sequestration, carbon sequestration and storage studies have largely overlooked estuary soils as important carbon sinks (Chmura et al., 2003; Thom et al., 2003). Considering that the shallow subtidal component may occupy as much as 90% of the estuary, these areas likely represent a significant and unaccounted for sink for carbon. Little is known, however, regarding the contribution of the shallow subtidal portions of the estuaries to the regional carbon stocks

Geologic studies focused on estuarine and oceanic substrates have included organic carbon as a parameter inventory, however, most of these studies focus on surficial soil samples with the goal of understanding the origin and formation of petroleum (Hedges and Oades, 1997). Utilizing a pedologic approach it is possible to quantify the organic carbon content of the subaqueous soil with depth, where it is actually stored, not just within the soil surface. Once soil organic carbon is determined for specific sites within an estuary it will be possible to scale up to a regional or global scale in order to better determine the estuarine soils importance as a global carbon storage unit. Jesperson and Osher (2007) and Payne (2007) investigated the carbon storage capabilities of subaqueous soils in the Taunton Bay estuary in Maine and three embayments in Rhode Island, respectively. In both studies, a soil survey of the estuary was completed as a component of the study to relate organic carbon storage to soil landscape unit. In addition, carbon pools to a depth of a meter in subaqueous soils were compared to their adjacent subaerial upland and wetland soils. The estuarine soil organic carbon pools were found to be equal to, and in some cases greater than, subaerial soil organic carbon pools. Payne (2007) reported higher energy, sandier soil-landscape units, such as shoals and shorefaces, had lower carbon pools than the lower energy soil-landscape units such as bay bottoms. Similar relationships were observed by Jespersen and Osher (2007).

The studies made by Jespersen and Osher (2007) and Payne (2007) were focused on northeastern tidal embayments. Little is known regarding the expansive coastal lagoons of the Atlantic coast or Gulf of Mexico estuarine subaqueous soils. Carbon pools and sequestration rates in freshwater subaqueous soils are also unknown. Future studies should be designed and implemented to investigate these subaqueous soil systems.

Moorings and Docks

With any body of water there are typically structures built or deployed to secure boats. The foundation for these docks or mooring (permanent anchor that boats are secured to in a harbor) are the subaqueous soils. Thus, how well the mooring or dock functions is dependent upon subaqueous soil type. The bearing capacity or n-value of the surface and near surface soils is one of the most important characteristics. Surabian

(2007) examined relationships between subaqueous soils and moorings and found that mushroom anchors work best in high n-value soils. These moorings sink into the low bearing capacity soils and are kept in place by surface area and suction forces. Deadweight anchors are best suited for low n-value soils or soils dominated by coarse fragments (Surabian, 2007).

Shellfish

Subaqueous soils are critical to the structure and function of many of the plants and animals in the estuarine ecosystem and are the foundation for commercial shellfish production and aquaculture. Worldwide the aquaculture industry continues to develop and expand. Although the economics are difficult to quantify worldwide, the value of aquaculture products per acre typically far exceed those of traditional agriculture. For example, in 2007 the average value of Rhode Island aquaculture products (oysters and clams) was 32 thousand dollars per hectare (Alves, 2007). Considering the cash value of these aquaculture products, developing an understanding of the relationships between the submerged landscape, the subaqueous soils, and the growth and productivity of aquaculture species such as clams, oysters, scallops, and mussels is essential. To date very little information is available regarding the relationships between shellfish productivity and subaqueous soil type.

The few works that have studied aquaculture-soil type relationships have focused on clams (Pratt, 1953; Pratt and Campbell, 1956; Wells, 1957; Grizzle and Morin, 1989; Grizzle and Lutz, 1989). These studies investigated clam abundance and shell-size growth rates with environmental factors such as soil type. Soils in these studies were fairly crudely characterized (ie., sand or mud), however, most of the studies found a relationship between growth and particle size existed. In general, increases in fines (muds, silt and clay) were associated with retardation in growth of clams. Grizzle and Lutz (1989) concluded that substrate type is important in some instances but seston flux (the amount of suspended particulate matter including plankton and organic detritus that passes by over a given period in the water column) is more important. Since sandy substrates typically have higher energies, the seston flux is often higher relative to finer textured soils. Thus, current views on the shellfish-soil relationship are that the increased growth associated with sandier substrates in the earlier studies has been reinterpreted to be a secondary result of sandier soil being associated with higher current velocities (Rice and Pechenik, 1992). This suggests that subaqueous soil type may not directly relate to shellfish growth, but may serve as a surrogate for identifying areas of favorable seston fluxes, and could thereby be used to predict areas of the subtidal estuary with the highest potentials for shellfish growth. A better classification of the soil that would come with a subaqueous soil survey (ie. better than sands and muds) may prove a better predictor of shellfish growth and provide delineations for the best locations for aquaculture of clams and oysters.

Future Considerations for Subaqueous Soils

Although subaqueous soils have received occasional mention in the literature for more than 50 years, only in the past decade or so have these soils been investigated with any intensity or focus. The limited number of investigations to date suggests that additional mapping, characterization, and research is needed to better understand these soils. In the United States nearly all of the subaqueous soils projects have been conducted on the eastern seaboard in coastal waters. The same resource, habitat, and ecosystem service issues that have begun to be addressed from a pedological perspective in eastern US estuaries also need to be examined in other shallow-subtidal habitats as well as freshwater systems. As we have shown, the application of subaqueous soils investigations to addressing environmental and ecosystem questions related to restoration, aquaculture, carbon accounting, water quality, etc is dependent upon an inventory of the subaqueous soil resources. The soil survey landscape-level models developed for mapping soils of embayments and lagoons need to be tested further in other Atlantic shallow-subtidal habitats and then in other areas of the country and of the world. Concerted efforts should be made to conduct widespread subaqueous soil survey projects that are founded on established standards and protocols such as those used in the National Cooperative Soil Survey. These subaqueous soil resource inventories should be conducted and published at a scale that will be useful to resource managers attempting to balance both use and conservation of aquatic ecosystems that are heavily taxed and impacted as increasing populations choose to inhabit areas near the water.

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Table 1. Summary of current or completed subaqueous soils projects.

Investigators	Affiliation	Location	Project Focus	Publications
Demas	UMD/NRCS	Sinepuxent Bay, MD	soil survey, methods, pedogenesis	Dissertation, Demas, 1993; Demas et al, 1996; Demas and Rabenhorst, 1998; 1999; 2001
Bradley	URI	Ninigret Pond, RI	soil survey, eelgrass, methods	Thesis, Bradley and Stolt 2002; 2003; 2006
Flannagan	UME	Taunton Bay, ME	soil survey	Thesis; Osher and Flannagan, 2007
Jespersen	UME	Taunton Bay, ME	carbon accounting	Thesis; Jespersen and Osher, 2007
Angell	UMA	Freshmeadow Pond, MA	soil survey	Report
Ellis	UFL	Cedar Key, FL	soil survey	Dissertation
Fischler	UFL	Indian River Inlet, FL	submerged aquatic vegetation	Thesis
Casby-Horton/ Brezina	NRCS	Padre Island, TX	soil survey, ecological site descriptions	----
Payne	URI	Greenwich Bay, RI	water quality, methods	Thesis
Coppick	UMD	Rehoboth Bay, DE	soil survey	Thesis in progress
Balduff	UMD	Chincoteague Bay, MD	soil survey, methods	Dissertation
Keirstead/ Hundly	NRCS	Little Bay, NH	soil survey	---
Surabian/Parizek /McVey	NRCS	Little Narragansett Bay, CT, RI	soil survey, mooring interpretations	Report; Surabian, 2007
MapCoast	MapCoast	Rhode Island estuaries	Soil survey, methods	Web available data
Salisbury	URI	Quonochontaug Pond, RI	shellfish and dredging interpretations	Thesis is progress
Pruett	URI	Point Judith Pond, RI	eelgrass and carbon accounting	Thesis in progress
Wong	NCSU/NRCS	Jamaica Bay, NY	soil survey and eelgrass	Thesis

Table 2. Examples of landscape unit, parent material, and soil type relationships from a Rhode Island coastal lagoon (after Bradley and Stolt, 2003).

Landscape Unit	**Parent Materials**	**Typical Soil Subgroup Classification***
Lagoon Bottom	Silt, fine sand, and organic material	Typic Sulfiwassents
Washover Fan Flat	Holocene sand	Typic Fluviwassents
Flood-tidal Delta Flat	Holocene sand	Typic Psammowassents
Washover Fan Slope	Holocene sand	Sulfic Fluviwassents
Flood-tidal Delta Slope	Holocene sand	Fluventic Psammowassents
Mainland Submerged Beach	Glacial fluvial sand and gravel	Typic Haplowassents
Barrier Cove	Silt, fine sand and organic material over glacial fluvial sand and gravel or Holocene sand	Typic Sulfiwassent
Mainland Shallow Cove	Holocene sand over glacial fluvial sand and gravel	Haplic Sulfiwassents
Mid-lagoon Channel	Glacial fluvial sand and gravel	Typic Haplowassents
Barrier Submerged Beach	Glacial fluvial sand and gravel	Typic Haplowasssents
Shoal	Glacial fluvial sand and gravel	Typic Haplowassents
Mainland Cove	Silts, fine sand and organic material over buried organic material	Thapto-histic Sulfiwassents

*Classification is based on proposed Wassent classification (Ditzler et al., 2008).

Table 3. Summary of selected subaqueous soils interpretations identified by federal and regional resource managers for managing shallow-subtidal coastal areas in the New England (Mapcoast, 2009) and Mid-Atlantic States (King, 2004).

Specific Resource Based Soil Interpretation
Submerged Aquatic Vegetation Restoration
Crab Habitat
Shellfish Stocking
Sustainable Shellfish Production
Mooring and Dock Locations
Identifying Anthropogenic Sites
Nutrient Reduction
Pfesteria Cyst Residence Sites
Benthic Preservation Site Identification
Wildlife Management
Waterfowl, Nurseries, and Spawning Areas
Habitat Protection for Horseshoe Crab
Tidal Marsh Protection and Creation
Bathymetric Maps and Navigation
Dredging Island Creation
Effects of Dredging on Benthic Ecology
Dune and Beach Maintenance/Replenishment

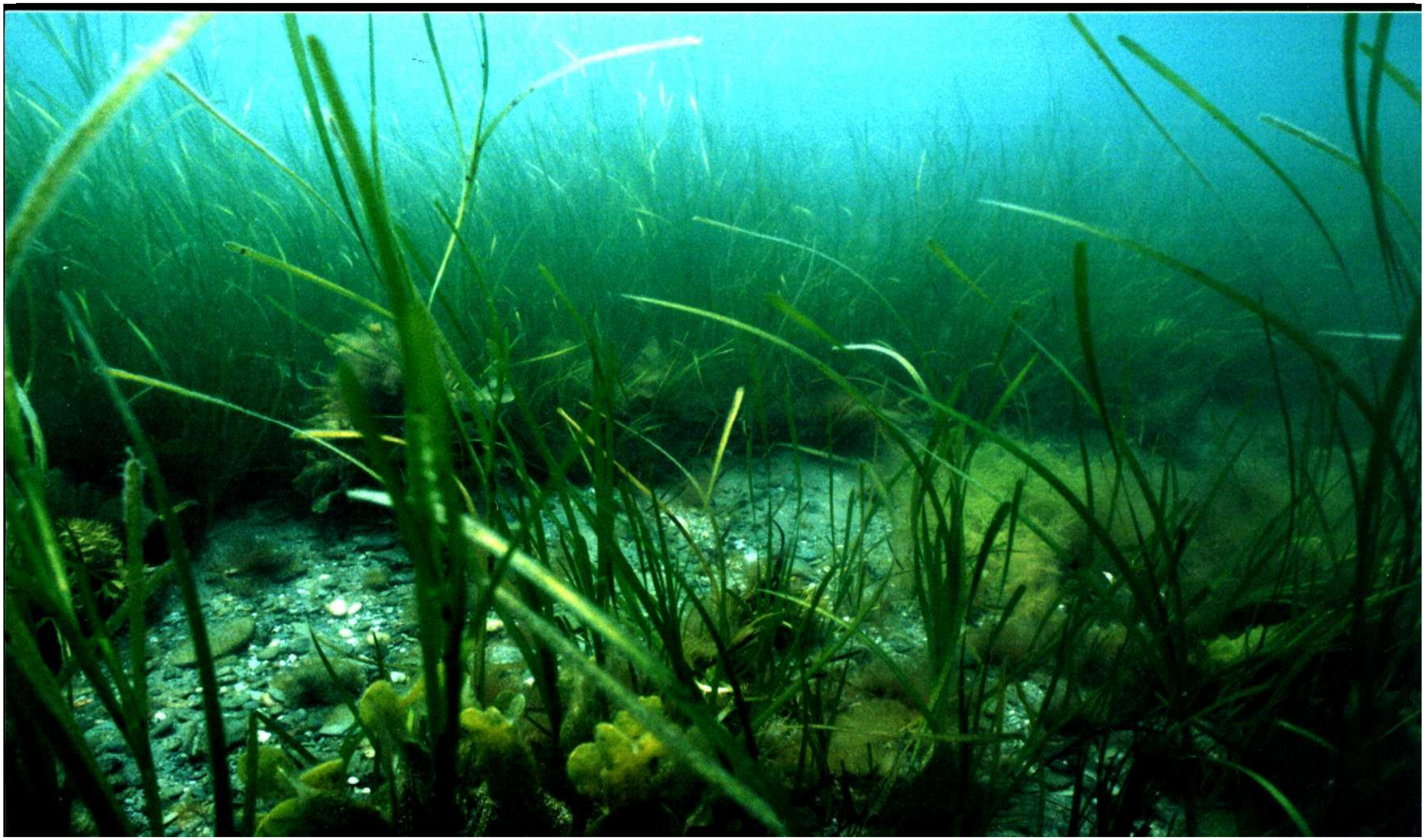

Figure 1. Eelgrass meadow growing on a shoal in 1.5 meters of water. The soil supporting the eelgrass is a sandy skeletal Typic Haplowassent (photo Jim Turenne).

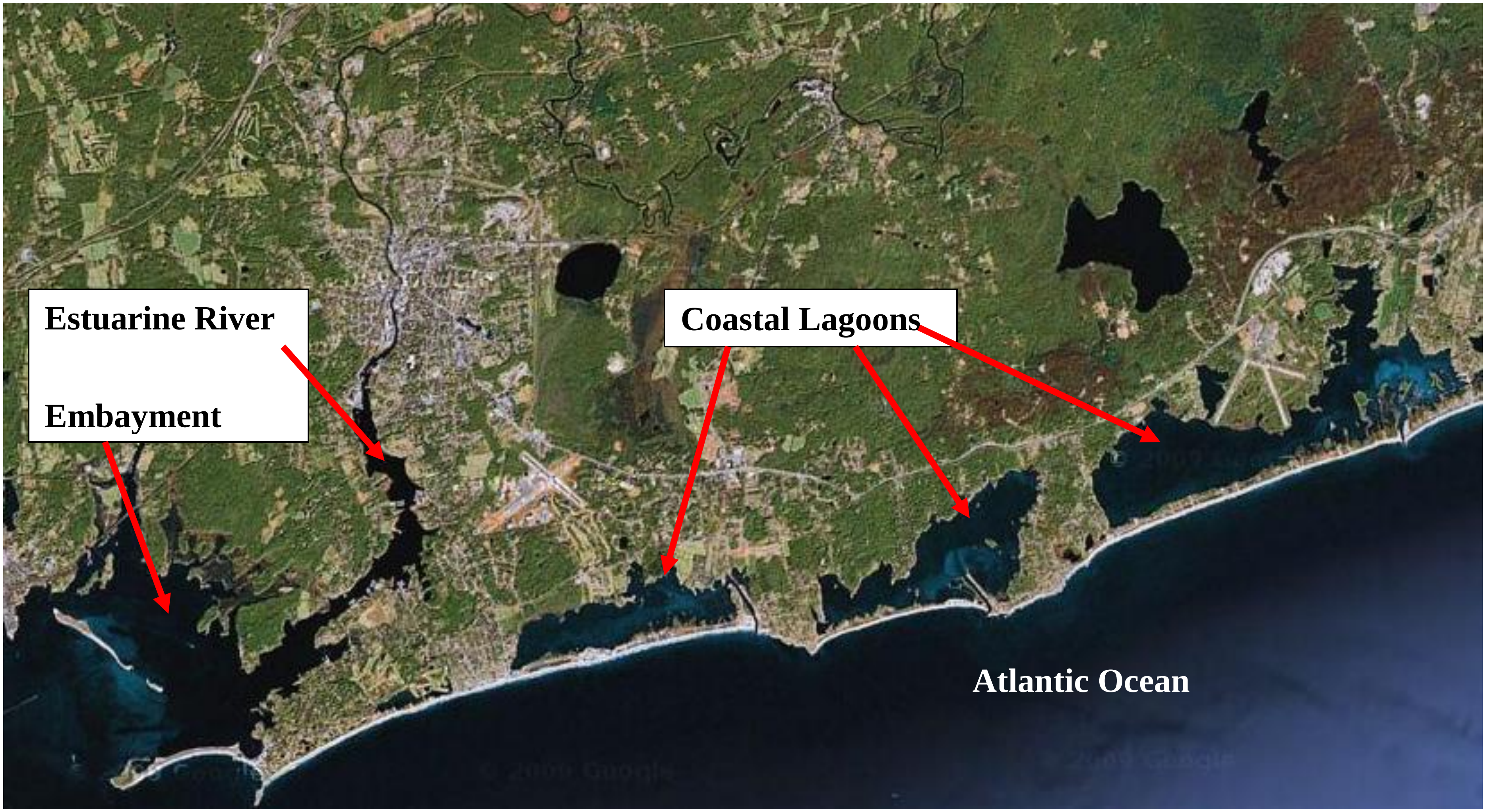

Figure 2. Examples of embayment, coastal lagoon, and estuarine river systems typically examined in subaqueous soil studies. Water depths generally average less than 2 meters at low tide. Image was taken from a 2009 Google map of the southern Rhode Island and Connecticut shoreline.

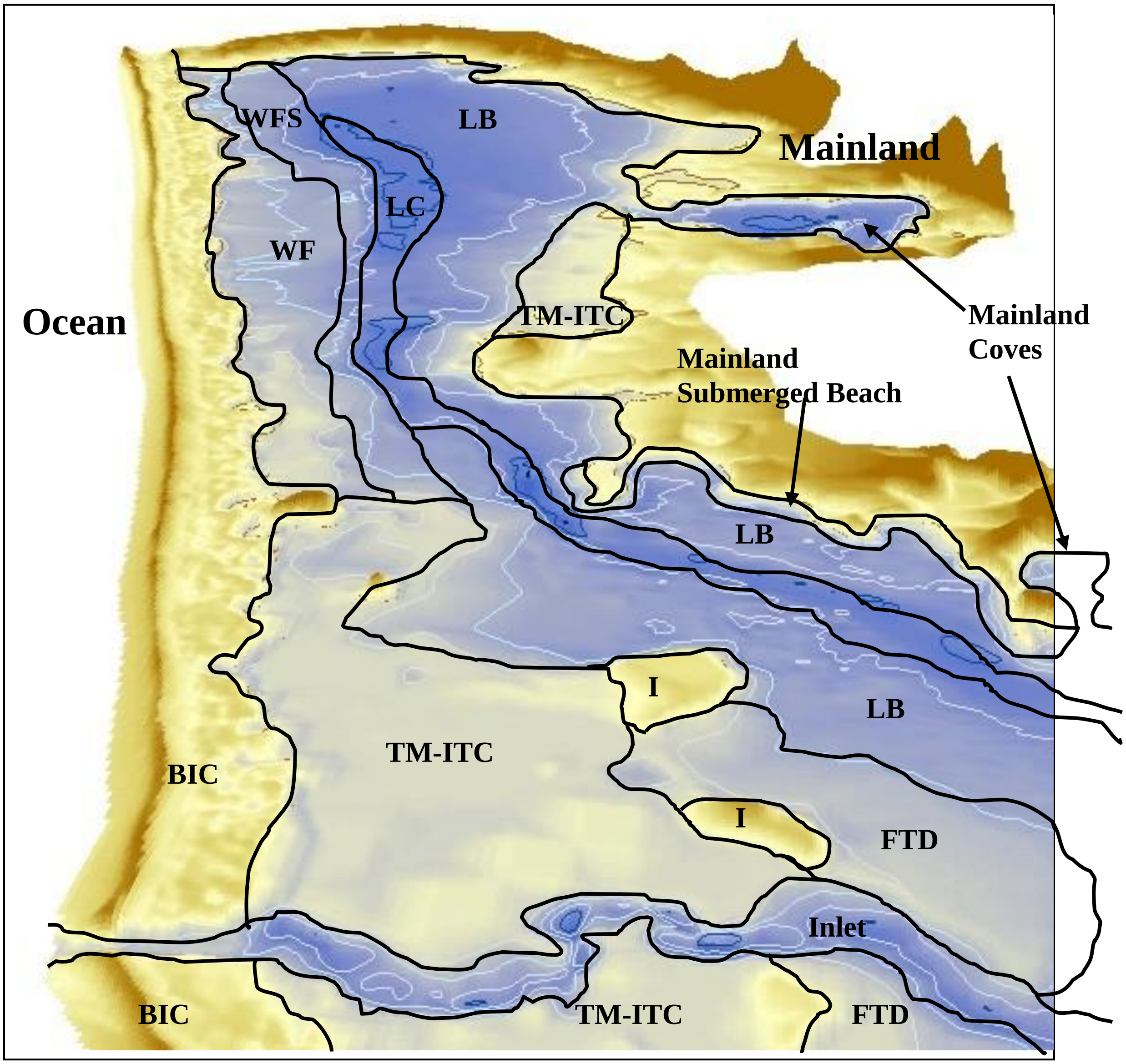

Figure 3. Examples of landscape units within a coastal lagoon. Yellow and brown colors represent subaerial environments. White to dark blue colors represent subaqueous environments; with white the shallowest water and dark blue the deepest. Contour interval is 50 cm. The inlet brings in water from the open ocean on high tides and flushes the lagoon during out-going tide. The barrier island complex (BIC), islands (I), and mainland are subaerial systems. The tidal marsh-intertidal complex is sometimes subaqueous and sometimes subaerial. The flood-tidal delta (FTD), lagoon bottom (LB), washover fan (WF), washover-fan slope (WFS), lagoon channel (LC), mainland cove, and mainland submerged beach landscape units are subaqueous systems.

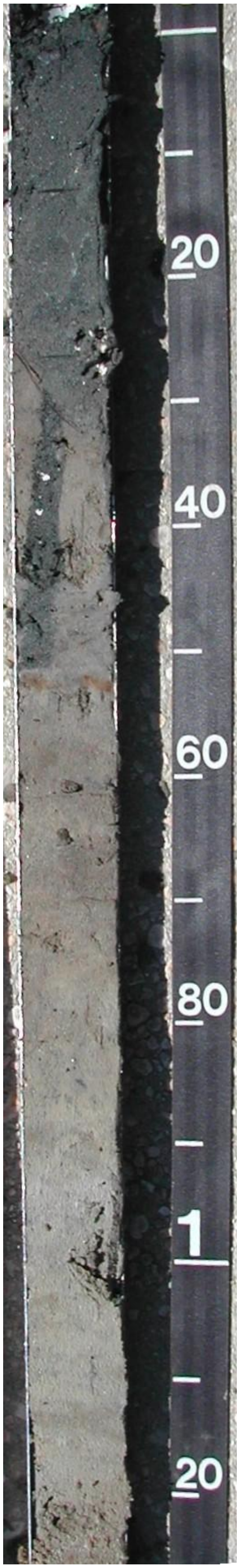

Figure 4a (left). Vibracore profile of a Haplic Sulfiwassent from a shallow mainland cove. The tape shows 10 cm increments. Note the clam krotovina from 30 to 50 cm (C/A horizon). The white pieces in the krotovina are shell fragments. At 120 cm there is a change in parent material from the Holocene aged estuarine sediments to the Pleistocene outwash sand and gravels.

Figure4b (right). Vibracore profile of a Sulfic Fluviwassent. The soil was collected from a washover-fan slope. Note the many buried A horizons that represent storm surges. The buried A horizon starting at a meter represents the upper part of a previous Typic Sulfiwassent prior to encroachment of the washover fan over the lagoon bottom landscape unit.