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Subaqueous Soils: A Pedological Approach to the Study of Shallow-Water Habitats

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ABSTRACT: Science-based management of shallow-water habitats is limited by information on the spatial distribution of properties of sediments. This limitation in part stems from the lack of an adequate model or system to classify and delineate subaqueous soil types (sediments). Present classification systems are inadequate because the existing paradigm does not actually consider them as "soils" but merely as "sediments." Field observations suggest that these sediments could be better understood as "soils," and the present paradigm could be modified to incorporate a new one—a pedological paradigm. We propose the application of a pedological paradigm for subaqueous soils of subtidal habitats to develop ecological interpretations of subaqueous soil types and apply an inventory of subaqueous soil resources for management of estuarine shallow-water habitats.

Introduction

In the mid-Atlantic region there are significant efforts underway to evaluate and restore the health of estuaries. Because of their significant ecological role, special emphasis has been placed on shallow-water habitats, many of which support submerged aquatic vegetation (SAV). Also of concern are areas of sediments which do not presently support vegetation but still contribute to the environmental conditions of the littoral zone (such as the potential for acid-sulfate weathering of dredge spoil and SAV restocking sites). This emphasis was documented in the 1987 Chesapeake Bay Agreement where priority was given to the determination of essential elements of habitat quality and needs to support living resources. The Chesapeake Bay SAV Policy of 1989 (Chesapeake Executive Council 1989) and the Implementation Plan of the Chesapeake Bay Implementation Policy of 1990 (Chesapeake Executive Council 1990) emphasized the need to develop SAV habitat requirements. The 1992 SAV Distribution Restoration Targets (Chesapeake Bay Program 1992) established formal goals for restoring SAV (Batiuk et al. 1992; Stevenson et al. 1993), some of which are presently being implemented. A critical component of these efforts is the accurate assessment of habitat requirements and defining the various habitat elements. The vast majority of research has focused on water-quality parameters, which are currently thought to have the greatest impact on SAV growth and survival. Although water-quality parameters have received the greatest attention, there has also been significant research on the relationships between SAV and sediment nutrient availability, organic matter content, and other characteristics. These studies have produced critical values for nutrients, suspended sediment, chlorophyll, and light in the water column (Stevenson et al. 1993). However, sediment-SAV relationships remain vague, and a system needs to be developed to characterize, classify,

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inventory, and map sediment types across and within shallow-water habitats. The purposes of this paper are to illustrate the limited nature of the sediment maps available for shallow water habitats, to discuss the importance of sediments to understanding the habitat elements of shallow-water environments, to explain the value of using a pedological approach in assessing the properties and distribution of subaqueous soils, and to illustrate the potential implications of a subaqueous soil inventory to the management of shallow-water habitats.

Sediment Research and Mapping

Attempts at mapping sediments have largely concentrated on individual components or characteristics, as opposed to a more holistic description of sediment profiles. For example, Folger (1972) utilized published and unpublished data to characterize the distribution of surface texture and organic carbon of sediments in four estuaries in the United States. The texture categories were based on those presented in Inman (1952). For the map of the Pamlico Sound in North Carolina, based on data largely from Pickett (1965), four particle size classes for surface textures were recognized. These were coarse sand, medium sand, fine-very fine sand, and silt. The map was developed at a scale of 1:792,000, or 7.9 km cm^{-1}. Although this does provide information concerning the spatial distribution of surface texture, the utility of a map at this scale for detailed ecological work is limited.

In a subsequent investigation of Pamlico Sound, Wells (1989) compiled additional data from cores taken over the past 40 yr. From these data, maps were compiled illustrating the spatial distribution of such individual characteristics as surface texture and percent calcium carbonate. For the map of modal grain size (surface texture), five texture classes were recognized based on the Wentworth scale for particle size separates. These classes were coarse sand, medium sand, fine-very fine sand, silt, and clay. The map scale utilized was 1:1,130,000, or 11.3 km cm^{-1}. The map for calcium carbonate content is at a similar scale. Once again, maps at this scale do not provide enough detail for intensive ecological interpretation. In addition, maps portraying individual characteristics would need to be "overlain" (and in some cases, normalized to some common class) to determine what combination of sediment characteristics exist at any specific site.

In the mid-Atlantic region, Kerhin (1980) compiled a series of maps of several individual characteristics of sediments within the Chesapeake Bay. Water, total carbon, organic carbon, and sulfur "contour" maps were made illustrating concentration isobars. For sediment distribution and sedimentation rates the maps show delineations for each type or rate. The limitation of the maps for ecological analysis of shallow-water habitats is that a majority of the information presented was collected in areas too deep to support SAV.

Geological aspects of an estuary or bay also contribute to the characterization of sediments in shallow-water habitats. Wells et al. (1994) studied the geochemical nature and geophysical framework of Assawoman and Isle of Wight Bay, Maryland. Their results documented the presence of paleo-channels and the shallow stratigraphic sequence within the two bays. In addition, sediment cores were taken and analyzed for particle size and contents of sulfur, carbon, nitrogen, and six metals. Averages and ranges for each component were determined on a baywide basis. However, no attempt was made to either synthesize specific parameters or present a coherent classification scheme to develop delineations of different sediment types.

A review of literature on shallow-water habitats (Staver and Stevenson in press) reveals surprisingly little information regarding the relationships between SAV distribution and sediment type distribution. However, recent studies at the head of the Chesapeake Bay and in other estuaries suggest that sediment characteristics may be highly correlated with specific SAV species (Barko et al. 1991, Wigand and Stevenson 1994). Investigators originally believed that SAV obtained a majority of their nutrients from the water column (see Stevenson 1988 for review) and only depended on the sediment for root support; however, this view has changed over the past two decades. Bole and Allan (1978) examined uptake of phosphorus in two aquatic plants, *Myrophyllum spicatum* and *Hydrilla verticillata* Royle, and found that they took up most, or all of their phosphorus requirements from the sediment. Barko et al. (1991) found that three species of SAV were able to mobilize and obtain phosphorus exclusively from the sediment. It now appears that SAV generally depend on the sediments as a major source for nitrogen, phosphorus, iron, manganese, and micronutrients (Barko et al. 1991). In addition to the nutrient status of the sediment, organic matter content also appears to play a role in the growth of SAV. As organic matter content in the sediment increased, the growth of SAV was inhibited (Barko and Smart 1983). In a study of two species of SAV grown on 40 different sediments collected from 17 different lakes, Barko and Smart (1986) found that nutrient status, sediment density, and organic matter content all had impacts on SAV growth.

The roots of SAV also appear to have other significant biological roles. As in many terrestrial soils

TABLE 1. German classification scheme for subaqueous soils (after Arbeitskreis Bodensystematik 1985).

Subaqueous Soil Type	Type Attributes
Protopedon	Subaqueous soils composed of different sediments without macroscopic humus, containing various organisms.
Gytta	Subaqueous soils composed of organic and/or mineral sediments (typically limnic in nature). Generally high nutrient content and good aeration. Found most often in freshwater areas.
Sapropel	Subaqueous soils composed of odiferous organic sediments often with metallic sulfides, high nutrient contents, and poor aeration.
Dy	Subaqueous soils typically composed of humic acid gels with low nutrient content and poor aeration.

(Malloch et al. 1980), at least one species of SAV in the Chesapeake Bay has been found recently to have mycorrhizae, or a symbiosis between fungi and roots (Wigand and Stevenson 1994), suggesting that fungal associations with submersed macrophytes may be more common than previously thought (Farmer 1985). However, the role of roots may vary considerably depending on the species of SAV in question and the inherent nature of the sediment. Sediments with high concentrations of iron (such as those at the head of the Chesapeake Bay) seem to encourage iron-rich plaque formation around the roots (Mendelson and Postek 1982), which appears to promote colonization by fungi and bacteria. Iron was particularly concentrated adjacent to the root epidermis, suggesting that oxygen pumped via the lacunal system of macrophytes (Sand-Jensen and Prahl 1982; Carpenter et al. 1983; Kemp and Murray 1986; Caffrey and Kemp 1991) is critical in the iron plaque formation process. It is possible that this "iron-curtain" described by Chambers and Odum (1990) may also hinder phosphate mobility. In contrast to vegetation from the head of the Chesapeake Bay, no plaques were observed on eelgrass (*Zostera marina*) in sandy sediments of more saline Virginia waters (Wigand and Stevenson unpublished data). These sediments are comparatively low in organic carbon and iron, as well as being high in sulfides, all of which may inhibit fungal symbionts. Furthermore, eelgrass (*Zostera marina*) rhizomes may not be as effective at oxygenating sediments as other species at the head of the Chesapeake Bay (Iizumi et al. 1980; Smith et al. 1988). However, despite efforts to characterize sediments and toxics in SAV beds at varying salinities (Cornwall and Stevenson 1988), no comprehensive analysis has been conducted to adequately characterize or map the pedological differences among sediments of shallow-water habitats where SAV can occur.

Sediments or Subaqueous Soils

The United States Department of Agriculture-Natural Resource Conservation Service (USDA-NRCS), which has the responsibility for the national program of soil mapping, classification, and interpretation, historically has not examined sediments to any significant extent. In other parts of the world the pedological examination of sediments has also generally been neglected except in a few situations where information was needed for a specific land use. An example of this was the mapping and analysis of the Dutch polder soils for engineering data prior to the building of dikes (R. W. Simonson personal communication 1993). In the early part of this century permanently submerged soils were mapped along the eastern edge of the Florida Everglades in an area slated for drainage and development (Baldwin and Hawker 1915). Since that time, there has been little mapping of sediment types. In the 1960s there was an attempt in Europe to include sediments in the German system of soil classification as "subaqueous soils" (Muckenhausen 1965). Later, this classification scheme for subaqueous soils was divided into four types (Arbeitskreis Bodensystematik 1985), as shown in Table 1. As one of the first (and perhaps only) attempts to classify sediments as "soils," the definitions are somewhat general, relying mainly on the physical composition of the material. There is also some mention of chemical properties such as the presence or lack of sulfides, degree of aeration, and salinity levels.

The official soil classification system of the United States, presented in *Soil Taxonomy* (Soil Survey Staff 1975), has made great strides in addressing soils that were not included in the original taxonomic system. For example, there have been major revisions and additions in the classification of tidal and coastal soils, some of which are partially submerged on a daily basis. These revisions were based on the accumulation of field and laboratory data that indicated the need to further separate, define, and map soils in these environmentally sensitive areas. An additional example of the dynamic nature of soil classification and its ability to assimilate new information, is the inclusion of areas previously considered "mudflats." These areas support vegetation such as pickerel weed (*Pontedaria cordata*), arrow arum (*Peltandra virginica*), and spatterdoc (*Nuphar luteum*) and are only exposed during extreme low tides. These taxonomic revisions generally apply to tidal areas, where water depth fluctuates and the surface of the soil is exposed to the atmosphere. Subaqueous soils are rarely, if ever, exposed to air (whether in fresh or saline water). Currently, a classification scheme for subaqueous soils has not been addressed within *Soil Taxonomy* due to the lack of comprehensive data to establish specific classes and the fact that some of the present classes for tidal marsh and mudflat soils could possibly be utilized with some modification. The acceptance of tidal marsh and mudflat "sediments" as "soils" within the ecological and geomorphological communities (see Stevenson et al. 1986) has assisted in more fully understanding the impact of sea-level rise on low-lying landscapes and their associated flora and fauna.

A basic question that must be addressed before a pedological approach can be applied to sediments is whether these materials actually meet the definition of soil. *Soil Taxonomy* defines soil as "the collection of natural bodies. . .supporting or capable of supporting plants out-of-doors" (Soil Survey Staff 1975). In the *Soil Survey Manual* (Soil Survey Division Staff 1993) a definition is presented, stating "Bodies of water that support floating plants, such as algae, are not soil, but the sediment below shallow water *is* soil if it can support bottom-rooting plants." In his book, *The Fundamentals of Soil Science,* Foth (1978) presents a somewhat more narrow perspective, stating "Soil (is the) unconsolidated material on the immediate surface of the earth that serves as a natural medium for the growth of land plants." Although the definitions vary to some degree, they all make reference to the fact that soils support natural vegetation. In discussions of the above concepts with other resource scientists, we find that some hold to the more restricted definition of soils, desiring to require emergent vegetation and exposure to the atmosphere to be considered "soil." Therefore, if an area were permanently ponded or flooded (and thus unlikely to support emergent vegetation), it would not be considered by some to be soil. Although we understand why some might prefer this narrow concept of soil, we believe the definition in *Soil Taxonomy* is broad enough to include permanently flooded environments in lakes, rivers, and estuaries, where submerged aquatic vegetation can exist. Although SAV are not emergent plants, they *are* rooted plants, therefore establishing their substrate as "soil" as defined in the *Soil Survey Manual* (Soil Survey Division Staff 1993).

Since its inception as a science, pedology has dealt with the origin, genesis, and attributes of upland soils. These concepts have commonly been extended to describe relationships between soil characteristics and plant vitality. The agricultural community, and more recently the ecological and regulatory communities, rely heavily on soils data to determine what types of plants are best suited to various soil types. Soil characteristics can dictate the specific type of plants which will be found under natural conditions and can control the primary level of production expected from a certain agricultural crops. For example, the *Soil Survey of Worcester County, Maryland* (Hall 1973) estimated production levels for various agronomic crops on different soil types based on guidelines contained within the *Soil Survey Manual* (Soil Survey Staff 1951). Soil properties may also impact vegetation depending on the drainage of wet soils containing sulfides, which produce such extreme soil acidity (pH 2–3) that nearly all vegetative growth is inhibited (Pons et al. 1982). The definition of "wetlands" contained in the *Federal Manual for Identifying and Delineating Jurisdictional Wetlands* (Federal Interagency Committee for Wetland Delineation 1989) utilizes *Soil Taxonomy* to determine if a site contains "hydric" soils. Pedologists have consistently demonstrated that soils play a significant role in the production, vitality, and survival of vegetation. We believe that sediments can be considered as subaqueous soils and are a vital component of shallow-water habitats. These soils perform specific functions within the shallow-water habitat, including the distribution and production of SAV.

A Pedological Approach to the Study of Sediments

Pedology is the science that studies the characteristics, evolution, and distribution of soils as natural bodies on the earth's surface. This approach to the study of soils (which originated from the earlier work of Russian and German scientists) was popularized by the work of Jenny (1941) who described the primary factors affecting soil formation by the equation $S = f(C,O,R,P,T)$. His equation illustrated that a soil (S) is a function of five state factors: climate (C), organisms (O) (biological activity), relief (R) (topography), parent material (P), and time (T). This was an attempt to explain the wide range in soil types and soil characteristics found throughout the world. This approach addressed the systematic variation in soil properties which is related to the five soil-forming factors, in addition to random variation which cannot be related to any specific cause (Wilding and Drees 1983). One problem of Jenny's approach is the difficulty in quantifying individual factors in the equation. Nevertheless, pedological studies have been conducted where study sites are selected to minimize variations in four of the factors so that the remaining state factor can be better understood, quantified, and used in mathematical models. A typical example of this approach is the chronosequence, where soil properties are evaluated as a function of time or soil age. The concepts of climosequences and toposequences have been similarly identified and broadly applied to study the effects of climate and topography on soil characteristics and genesis.

The topographic factor has been studied perhaps more than any other single state factor of soil formation. Milne (1936) first suggested the concept of a catena, which is considered to be an interlocking arrangement of soils across a changing landscape. The catena was effectively the concept of the toposequence mentioned above. In pedology, topographic variation can have major impacts on morphological, physical, and chemical soil characteristics. Once the association between soils and topography began to be recognized, further efforts were made to understand the role of topography or landforms in soil genesis. It soon became apparent that geomorphic principles could provide insight into the systematic variation of soil types across the landscape. This led to the further integration of pedology and geomorphology.

Geomorphology is defined by Howell (1957) as the "systematic examination of landforms and their interpretation as records of geologic history." Later, Ruhe (1975) defined geomorphology simply as the science of landforms. In one of the classic papers on soils and geomorphology (Ruhe 1956), specific soils or soil associations were found to occur in a predictable way on five separate geomorphic surfaces in Iowa. Daniels and Gamble (1978) discussed how landscape configuration and its associated hydrologic characteristics affected morphological and physical development of soil profiles on coastal plain areas of the southeastern United States. These concepts were applied to terraces and floodplain soils in New York, where Scully and Arnold (1979) found that the degree of soil development was related to the geomorphic surface on which the soil formed. The understanding of geomorphic concepts and processes has become a valuable tool in aiding the pedologist in predicting the distribution and characteristics of soil types on the landscapes (Daniels et al. 1971; Hall 1983).

In a more recent article, Hudson (1992) discusses the paradigm of soil mapping and the pedological approach. The paradigm of soil mapping is based on soil-landscape relationships, or the ability to use landforms as a tool to predict the variation of soils across the landscape. This can be roughly translated as a synthesis of the five factors of soil formation (Jenny 1941) and the catena concept of Milne (1936). The components of the soil-landscape paradigm (Hudson 1990) are as follows:

1. Within the soil-landscape unit, the five soil-forming factors interact in a distinctive manner. As a result, all areas of the same soil-landscape unit develop the same kind of soil.
2. The greater the difference between the conterminous areas of two soil-landscape units, the more abrupt and striking the discontinuity will be between them. The more similar the two conterminous areas of soil-landscape units, the less striking or abrupt the discontinuity tends to be.
3. The more similar two landforms are, the more similar their associated soils.
4. Adjacent areas of different soil-landscape units have predictable spatial relationships.
5. Once the relationship among soils and landscape units have been determined for an area, the soil type can be inferred by identifying the soil-landscape unit.

This paradigm is the basis for much of the soil resource inventory activities presently underway in the United States. Yet, the pedological approach is infrequently applied to shallow-water estuarine environments. Thus all subaqueous soils are treated simply as geologic sediments. The sampling of these sediments for research purposes, or during limited attempts at conducting resource inventories, has been performed using random or grid

TABLE 2. Profile described in Sinepuxent Bay, Maryland, approximately 400 m due east of Snug Harbor, 25 m south of unnamed spoil island. Field morphological description of pedon S92MD047-058. Vegetation: Widgeon grass (*Ruppia maritima*), rooted algae. Macrofauna present: Clams. Depth of water: 65 cm.

Horizon	Depth (cm)	Description
Ag	0–15	Very dark gray (N 3/) mucky loamy sand; massive; very friable, slightly sticky, nonplastic; common very fine and fine roots; moderately alkaline; moderately saline; clear smooth boundary.
Cg1	15–25	Dark gray (N 4/) loamy sand; massive; very friable, nonsticky, nonplastic; few very fine roots; moderately alkaline; moderately saline; 2% gravel; clear smooth boundary.
2Cg2	25–42	Dark greenish gray (5GY 4/1) loam; massive; friable, slightly sticky, nonplastic; n-value greater than 1.0, materials flows easily between the fingers when squeezed; slightly alkaline; strongly saline; abrupt wavy boundary.
3Cg3	42–89	Dark gray (5Y 4/1) sand; single grain; loose; moderately alkaline; strongly saline; gradual smooth boundary.
4Cg4	89–104	Dark gray (N 4/) loamy fine sand; massive; very friable, nonsticky, nonplastic; strongly alkaline; strongly saline; clear smooth boundary.
4Cg5	104–150	Dark gray (5Y 4/1) loamy fine sand; massive; very friable, nonsticky, nonplastic; strongly alkaline; moderately saline; 30% shell fragments.

TABLE 3. Profile described west side of South Point, Sinepuxent Bay, Maryland, approximately 1 km north of Verrazano Bridge, 30 m from adjacent tidal marsh. Vegetation: 10% eelgrass (*Zostera marina*). Macrofauna present: Tubeworms. Depth of water: 75 cm.

Horizon	Depth (cm)	Description
Ag	0–11	Very dark gray (5Y 3/1) sand; single grain, loose; few very fine roots; moderately alkaline; moderately saline; clear wavy boundary.
2Cg	11–28	Dark gray (5Y 4/1) loam; massive; slightly sticky, slightly plastic; n-value 0.8; 16% clay; moderately alkaline; moderately saline; clear smooth boundary.
0ab	28–150	Dark brown (7.5YR 3/2) muck; sapric soil material; fiber content less than one-sixth of the volume after rubbing; 25% silt loam mineral material; moderately alkaline; moderately saline.

sampling techniques with little attention given to the subaqueous geomorphology. These approaches to sampling are perfectly suitable and valid where systematic variation in soil properties are unknown, and where soil variability would be described as random (Wilding and Drees 1983). But in landscapes where the distribution of soils can be clearly related to a geomorphic surface, a random or grid sampling approach would yield far less information than would be gained utilizing a pedologic approach. In cases where landscapes can be interpreted, a more productive scientific strategy would utilize the alternative approach, which addresses the soil-landscape association, and rely on the pedological approach.

Materials and Methods

Preliminary fieldwork was conducted during the summers of 1993 and 1994 in a section of Sinepuxent Bay, Maryland, to apply a soil classification system to shallow-water sediments. Soil borings were made to a depth of 1.5 m using a standard bucket auger or peat auger. Soil morphological descriptions were made in the field and samples were taken from the profiles for laboratory analyses. Once samples were collected they were placed in plastic bags, sealed, and stored on ice during transport to the laboratory. These precautions were taken to minimize chemical changes due to oxidation. Particle size, organic carbon, sulfides, pH, and salinity analyses were conducted on each of the samples following standard soil characterization procedures (Soil Survey Division Staff 1993). The pH following moist incubation was determined (Soil Survey Staff 1994) to evaluate the potential for acid-sulfate weathering conditions. Benthic organisms present at augered sites were also identified. Based on the results of these limited observations, three basic subaqueous soil types were evident. This is the first step toward representing the spatial patterns of subaqueous soil types cartographically.

Results and Discussion

Within the Sinepuxent Bay study area, three distinct subaqueous soil series have been tentatively identified. Initial observations suggested that the soils existed in spatial patterns large enough to be represented cartographically. A preliminary map of subaqueous soil delineations has been developed and will be published later after additional borings have been made to test its accuracy. Four

TABLE 4. Profile described east side of South Point, Sinepuxent Bay, Maryland, approximately 400 m south of Spence Cove, 50 m west of adjacent tidal marsh. Vegetation: 40% cover, eelgrass (*Zostera marina*). Macrofauna present: Tubeworms, few clams. Depth of water: 70 cm.

Horizon	Depth (cm)	Description
Ag	0–8	Very dark gray (5Y 3/1) sand; single grain; few very fine and fine roots; moderately alkaline; moderately saline; clear wavy boundary.
Cg1	8–15	Dark gray (5Y 4/1) loamy sand; massive; nonsticky; moderately alkaline; moderately saline; abrupt smooth boundary.
2Cg2	15–20	Dark gray (5Y 4/1) coarse sand; single grain, loose; moderately alkaline; moderately saline; abrupt smooth boundary.
3Cg3	20–30	Gray (5Y 5/1) sandy loam; massive; slightly sticky, nonplastic; moderately alkaline; moderately saline; 20% dark olive brown (2.5Y 3/3) organic fragments; 12% clay; clear smooth boundary.
3Cg4	30–51	Gray (5Y 5/1) loam; massive; slightly sticky, nonplastic; moderately alkaline; moderately saline; 12% clay; clear wavy boundary.
3Cg5	51–77	Gray (5Y 5/1) loam; massive; slightly sticky, nonplastic; n-value 0.8; 10% dark olive brown (2.5Y 3/3) organic fragments; 12% clay; moderately alkaline; moderately saline; gradual wavy boundary.
4ACgb	77–94	Dark gray (5Y 4/1) mucky silt loam; massive; slightly sticky, slightly plastic; n-value 0.9; 50% dark brown (10YR 3/3) organic fragments; 14% clay; moderately alkaline; moderately saline; gradual wavy boundary.
0ab	94–150	Dark brown (7.5YR 3/2) muck; sapric soil material; fiber content is less than one-sixth of the volume after rubbing; 10% light olive brown (2.5Y 5/6) organic fragments; 20% silt loam mineral material; moderately alkaline; moderately saline.

TABLE 5. Profile described in Sinepuxent Bay, Maryland, approximately 400 m due east of Snug Harbor, 300 m southeast of unnamed spoil island. Field morphological description of pedon S92MD047-014. Vegetation: eelgrass (*Zostera marina*). Macrofauna present: Clams. Depth of water: 50 cm.

Horizon	Depth (cm)	Description
Ag	0–8	Dark olive gray (5Y 3/2) sand; single grain; loose; few fine and very fine roots; moderately alkaline; moderately saline; 5% shell fragments; clear wavy boundary.
2Cg1	8–45	Very dark gray (5Y 3/1) fine sand; single grain; loose; moderately alkaline; moderately saline; clear smooth boundary.
3Cg2	45–95	Very dark gray (5Y 4/2) silt loam; massive; friable, slightly sticky, nonplastic; n-value between 0.7 and 1.0, material flows between fingers with some difficulty; moderately alkaline; moderately saline; gradual smooth boundary.
4Cg3	95–150	Very dark gray (N 3/) very fine sandy loam; massive; friable, slightly sticky, nonplastic; moderately alkaline; moderately saline.

of the representative morphological descriptions are presented in Tables 2 through 5. These soils differ markedly in many characteristics, including consistence, n-value, particle size class, horizon, structure, root content, carbon content, and shell fragment distribution. Selected soil analytical data for sulfidic materials are represented in Fig. 1 for the subaqueous soil described in Table 2.

The representative soil profiles described in Tables 2 through 5 shows the variation in particle size distribution with depth and between profiles. The USDA textural class of mucky loamy sand for the Ag horizon (0–15 cm) and coarse-loamy particle size family (Soil Survey Division Staff 1993) for the profile in Table 2 are significantly different than the sand texture for the Ag horizons and the sandy particle size families of the other profiles. Results of the moist incubation analysis shown in Fig. 1 indicate that certain horizons in this profile had a greater potential to exhibit acid-sulfate conditions than others. Samples from the Ag (0–15 cm), Cg1 (15–25 cm), 2Cg2 (25–42 cm), and 4Cg4 (89–104 cm) horizons dropped below a pH of 3.5, suggesting that they are "sulfidic materials" as defined in *Soil Taxonomy.* The 3Cg3 (42–89 cm) and 4Cg5 (104–150 cm) horizons remained at or about the same pH.

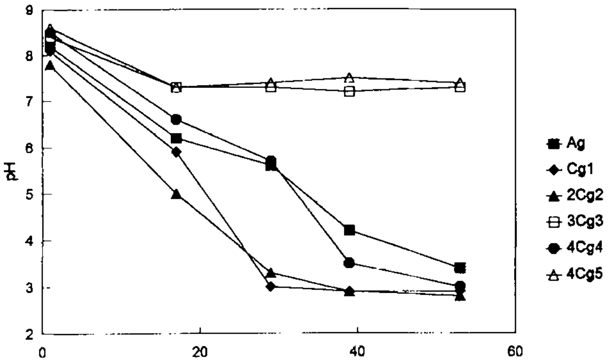

Fig. 1. Graph showing change in pH over time in samples collected from pedon S93MD047-058 (described in Table 2) using the moist incubation technique. The pH measurements were made for samples from the Ag (0–15 cm), Cg1 (15–25 cm), 2Cg2 (25–42 cm), 3Cg3 (42–89 cm), 4Cg4 (89–104 cm), and 4Cg5 (104–150 cm) horizons. The Ag, 2Cg2, and 4Cg4 horizons contain 0.10%, 0.46%, and 0.16% chromium reducible sulfide (CRS), respectively, as determined using the methodology of Cornwell and Morse (1987).

Examination of the subaqueous soil profile descriptions presented in Tables 3 and 4 indicate the presence of previously existing marsh surfaces (Oab horizons). These profile descriptions indicate the probability that many sediments adjacent to tidal marsh areas in the Sinepuxent study area are actually submerged tidal marsh soils and their distribution could be inferred from the adjacent geomorphology of the study area.

Using present guidelines in *Keys to Soil Taxonomy* (Soil Survey Staff 1994) the subaqueous soil in Table 2 could be classified as a sandy, mixed, mesic, non-acid Typic Sulfaquent. The subaqueous soils shown in Tables 3 and 4 would be classified as a coarse-loamy, mixed, mesic nonacid Thapto-histic Sulfaquents. The profile described in Table 5 would be classified as a coarse-loamy, mixed, mesic, nonacid Typic Sulfaquent. These series differ significantly at the family level of taxonomy and therefore can be separated into soil series or types. The classifications also indicate the potential for acid-sulfate weathering problems if the materials were dredged, and the presence of an underlying tidal marsh soil.

The results of this initial study indicate that the application of traditional field pedological techniques, modified slightly, could be applied in a nontraditional soil mapping environment and be used to produce soil information and, ultimately, soil maps similar to those presented in modern upland soil surveys. During the course of the next two years we will work toward the identification of subaqueous landscapes and soil types, and testing the applicability of the pedological approach to a wider range of shallow-water estuarine environments.

Prior to this preliminary investigation, there was no reported application of the pedological approach to the study of sediments in shallow-water habitats. Our results suggest that subaqueous soils in shallow-water habitats meet the definition of soil stated in *Soil Taxonomy* (Soil Survey Staff 1975) and the *Soil Survey Manual* (Soil Survey Division Staff 1993), and thus fall within the purview of pedology. Further detailed study of subaqueous soils from a pedological perspective could provide detailed information on the physical and chemical characteristics of subaqueous soils, and their spatial distribution within estuarine environments. Once the pedological approach is established, a classification scheme based on *Soil Taxonomy* could provide the framework to group sediments into subaqueous soil types (with specific ranges in characteristics) in order to conduct a soils resource inventory of shallow-water habitats.

The resulting maps, produced at a scale of 1: 12,000 (0.12 km cm^{-1}), would provide users with detailed delineations of subaqueous soil types within a given survey area. The subaqueous soil types represented on the maps would have specific characteristics, which could impact a number of management decisions. For example, a subaqueous soil type similar to the one shown in Table 2 would have a high potential for acid-sulfate weathering if dredged and used for island creation or beach replenishment. Exposure of the buried marshes (Oab horizons) (shown in Tables 3 and 4) by dredging or storms may preclude these areas from SAV restocking due to the high organic carbon content. Subaqueous soils found to have high potentials for SAV production could help to better identify and protect unvegetated sites for future SAV revegetation. In addition, subaqueous soil delineations (and their associated physical characteristics) could be utilized to examine the distribution of other benthic organisms such as clams or oysters. Benthic communities have fairly specific requirements in physical properties of estuarine sediments (Rhoads 1974), which could also be described with maps of subaqueous soils. Thus, the establishment of a mapping protocol and taxonomic system for sediments could have a beneficial impact on the manner in which science-based management decisions are made for shallow-water estuarine habitats.

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