Subaqueous Soil-Landscape Relationships in a Rhode Island Estuary

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ABSTRACT

Subaqueous soils occur from the lower limit of the intertidal zone to a depth of <2.5 m in protected estuarine coves, bays, inlets, and lagoons. These soils support a diverse floral and faunal assemblage and are a vital component of the estuarine ecosystem. Only recently have pedologists considered these substrates soil, thus, very few subaqueous soils have been characterized and relationships between subaqueous soils and associated subtidal landforms are unknown. In this study, we investigated shallow-subtidal settings and associated subaqueous soils within a 116-ha area of a Rhode Island estuary. Our objectives were to gain an understanding of soil distribution within a coastal lagoon and to elucidate subaqueous soil-landscape relationships within differing geomorphic settings. Twelve submerged landscape units were delineated based on water depth, slope, landscape shape, and the depositional environment. Soils were sampled, described, and representative samples from each landscape unit were analyzed for pH, electrical conductivity, $CaCO_3$, particle-size distribution, and organic matter. The Lagoon Bottom landscape unit was mostly comprised of Typic Hydraquents (70%). These soils had the finest particle-size distribution of all soils sampled (silt contents ranged from 23 to 64%; clay contents ranged from 16 to 30%). All the subaqueous soils found within the Storm-surge Washover Fan Flat were classified as Typic Sulfaquents. Greater than 75% of the Barrier Submerged Beach, Mainland Submerged Beach, Shoal, and the Mid-lagoon Channel landscape units contained Typic Endoaquents. Thapto-histic Hydraquents were found in 60% of the Mainland Cove landscape units. These relationships suggest that landscape units can be used to model subaqueous soil distribution at the subgroup taxonomic level. Understanding of the distribution of these soils and the associated characteristics should prove valuable to coastal specialists managing these critical resources.

Recently, the Natural Resources Conservation Service (NRCS) amended the definition of soil to include sediment under as much as 2.5 m of water (Soil Survey Staff, 1999). This change is the result of work in Maryland in which estuarine substrates in shallow water were shown to undergo pedogenesis (Demas, 1998; Demas and Rabenhorst, 1999). Estuarine subaqueous soils are permanently flooded soils that occur immediately below the intertidal zone to water depths of <2.5 m at extreme low tide in protected coves, bays, inlets, and in back-barrier coastal lagoons. Processes operating in subaqueous soils include additions of biogenic $CaCO_3$ and marine humus from benthic biota (Valiela, 1984), bioturbation from shellfish and worms, and chemical transformation of S and Fe in anoxic environments, all of which differentiate surficial sediment into soil horizons (Demas, 1998).

The correlations between shallow water estuarine sediment and the classic tenets of soil formation (Jenny, 1941) support the inclusion of these substrates within the realm of soil science (Goldschmidt, 1958; Demas, 1998; Demas and Rabenhorst, 1999). One of the principle components of the definition of terrestrial soils is the ability 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, SAV species are rooted vascular aquatic plants in which roots serve both structural and nutrient uptake purposes (Barko et al., 1991). A highly diverse benthic faunal community also depends on subaqueous soils for nutrients, structure, and habitat (Rhoades, 1974; McCall and Tevesz, 1982; Barko et al., 1991). The actions of these marine animals are similar to those inhabiting terrestrial soils. Marine animals mix grain sizes, diffuse O_2 to the subsurface layers (McCall and Tevesz, 1982), decompose organic matter, and concomitantly supply organic C from decaying organisms, fecal pellets, and excretion of mucus (Valiela, 1984). Finally, numerous studies have emphasized the importance of landscape components for predicting and explaining soil distributions (Jenny, 1941; Ruhe, 1960; Huddleston and Riecken, 1973; Wright and Sautter, 1988; Stolt et al., 1993). Subaqueous landscapes are fundamentally the same as terrestrial systems in that they have a discernable topography from which subaqueous landforms and landscape units may be identified (Demas, 1998; Demas and Rabenhorst, 1998).

Considerable research has focused on many components of estuarine and coastal ecosystems including hydrology (Odum et al., 1974; Chinman and Nixon, 1985), vegetation (Odum et al., 1974; Tiner, 1987; Hurley, 1990; Bertness, 1999) and floral and faunal interactions (Rhoades, 1974; Valiela, 1984; Bertness, 1999). However, the substrate, which supports a wide variety of benthic invertebrates and supports dense areas of SAV, has been largely ignored. Geologic studies have focused on this realm of the ecosystem (McGinn, 1982; Boothroyd et al., 1985; Wells et al., 1994; Wells et al., 1996), but the information provided by these studies is not detailed enough to be of ecological significance (Demas et al., 1996; Demas, 1998), and most of these studies focused on a single parameter (e.g., grain size). An advantage of using the pedological approach to study shallow water sediments is that soils are studied as a collection of horizons that are linked with depth across the landscape. These horizons are studied and characterized by examining a combination of properties and characteristics, instead of a single component or parameter. In this study, we use a pedological approach to study shallow water estuarine substrates. The objectives of our research were: (i) to identify different shallow-subtidal geomorphic settings in a representative area of a Rhode

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Abbreviations: GPS, global positioning satellite; NRCS, Natural Resource Conservation Service; SAV, submerged aquatic vegetation.

Island estuary; (ii) to describe and characterize the soils found in these settings; and (iii) to investigate the relationships between geomorphic setting and subaqueous soil type.

MATERIALS AND METHODS

Study Area

After a reconnaissance survey of several coastal lagoons along the southern shore of Rhode Island and a series of sites in Narragansett Bay, Ninigret Pond was chosen for detailed study (Fig. 1). We chose Ninigret Pond because of the diverse suite of geomorphic settings, depositional environments, and the significant eelgrass (*Zostera marina*) cover found within this estuary. Ninigret Pond is a 677-ha coastal lagoon that formed as a result of sea-level rise following the last glacial period and the consequent flooding of low-lying glaciofluvial plains, glaciofluvial channels, and ice-block basins (Conover, 1961; Fisher and Simpson, 1979; Boothroyd et al., 1985). This coastal lagoon is separated from other coastal lagoons to the

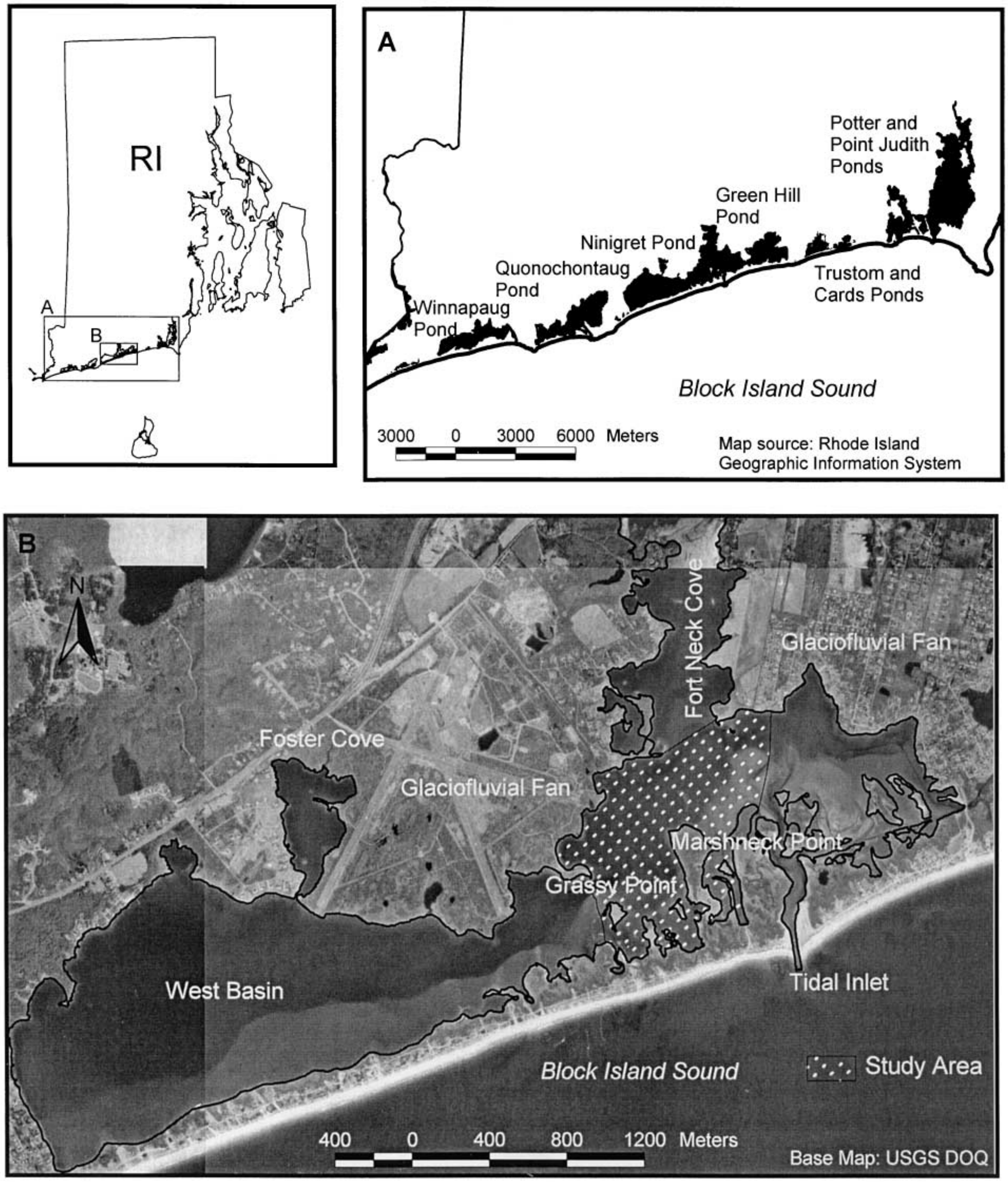

Fig. 1. The distribution of coastal ponds along (A) the south shore of Rhode Island and (B) the location of the 116-ha study area within Ninigret Pond.

east and west by glacial headlands comprised of glacial till and glaciofluvial material, and is separated from the open ocean by a barrier spit comprised of Holocene sand deposited by long shore transport (Fisher and Simpson, 1979; Boothroyd et al., 1985). Tidal fluctuations within Ninigret Pond range from 7 to 16 cm (Boothroyd et al., 1985). The soils around Ninigret Pond have formed from aeolian silt, till, and glaciofluvial material comprised of stratified sand and gravel (Rector, 1981).

We selected a 116-ha area within Ninigret Pond to examine subaqueous soil distributions and landscape relationships (Fig. 1). The tidal inlet channel marks the southeastern edge of the study area. The channel was made permanent by the U.S. Army Corps of Engineers in 1951-1952 and remains stabilized through jetties that protect the mouth of the inlet (Fisher and Simpson, 1979). In the central part of the study area there are islands and points (e.g., Marshneck and Grassy Points) that are comprised of glaciofluvial material. Depositional environments within the study area can be classified as flood-tidal delta, subtidal storm-surge washover fan, and back-lagoon, low-energy basin deposits (McGinn, 1982; Boothroyd et al., 1985). Sediment enters the pond through the tidal inlet, temporary storm surge channels across the barrier spit, and overwash transport of sand (Boothroyd et al., 1985).

Soil Sampling Techniques

A 1:10 000 scale contour map (with 30-cm contour intervals) of the submerged topography was used as a base map to delineate landscape units (Bradley and Stolt, 2002). Slope, land-surface shape, and geographic location were used to differentiate landscape units. Soils were examined at multiple locations within each landscape unit. These locations were chosen to capture both the variability and extent of soil types within each landscape unit. Soils were accessed by wading or by boat. Soil description locations were recorded using a global positioning system (GPS). Eelgrass cover for landscape units was estimated by visual observation during the summer months. Soils were described to a depth of 75 to 125 cm using samples collected with a standard bucket auger. For very soft and fluid material (high *n* value soils) and organic soils, a MacCauley peat sampler was used. Based on these descriptions, representative soils were sampled for laboratory analysis from each landscape unit using a vibracorer (Lanesky et al., 1979), standard bucket auger, or a McCauley peat sampler. Vibracores were driven into the soil as far as possible, or to a depth of 1.5 m. Vibracores were extracted from the soil using a jack secured to a 2.4-m^2 floating platform. Once extracted, core barrels were sealed and refrigerated. Core barrels were cut open length-wise and the soils described following standard procedures (Soil Survey Division Staff, 1993). All soil samples (vibracore, bucket auger, and McCauley sampler) were frozen until needed for lab analysis.

Laboratory Analysis

Soil samples were analyzed for percentage of coarse fragments, percentage of shell fragments (larger than 2 mm), pH, electrical conductivity, particle-size distribution, levels of $CaCO_3$, and organic C. Particle-size analysis followed methods outlined in Gee and Bauder (1986). The clay fraction was determined by pipette; and sand fractions were separated by sieving. Percentage of coarse fragments (rocks and shell fragments >2 mm) was determined by weight. Electrical conductivity and pH measurements followed standard and modified Soil Survey Staff (1996) guidelines. Electrical conductivity was measured on saturated paste extracts using a conductivity meter. Due to small sample sizes, 10 g of soil was used to make a saturated paste and the pore-water separated using a centrifuge. Measurements of pH were done on thawed samples in a 1:1 soil/deionized water mixture. Samples were then incubated at room temperature for approximately 120 d and pH was measured again. Organic matter and $CaCO_3$ combustion were assumed to occur at 550 and 1000°C, respectively (Rabenhorst, 1988). Levels of organic C and $CaCO_3$ were estimated by percentage of weight loss-on-ignition (Nelson and Sommers, 1965) and assuming a soil organic C/organic matter ratio of 0.5.

RESULTS

Landscape Units

Twelve landscape units were delineated based on the submerged topography, land-surface shape, geographic location, water depths, and depositional environment (Table 1, Fig. 2). The Lagoon Bottom, Storm-surge Washover Fan Flat, and the Flood-tidal Delta Flat landscape units comprised 73% of the study area (Table 1). The Lagoon Bottom unit is located in the central portion of the study area and is a low-energy depositional basin characterized by relatively deep water (1.1–2.0 m) and

Table 1. Characteristics of the landscape units identified within the study area adjacent to Marshneck Point and Grassy Point in Ninigret Pond, RI.

Landscape unit	Area (% of study area)	Water depth range	Slope†	Landscape description (Soil Survey Division Staff, 1993)
	ha	m	%	
Lagoon Bottom	45.2 (39.0)	1.1–2.0	0.1	Nearly level to slightly undulating; microrelief
Storm-surge Washover Fan Flat	21.2 (18.3)	0–0.8	0.2	Nearly level and linear-linear
Flood-tidal Delta Flat	19.6 (16.9)	0–1.1	0.3	Nearly level to undulating due to dissecting channels
Storm-surge Washover Fan Slope	5.8 (5)	0–1.4	1.0	Nearly level and linear-linear
Flood-tidal Delta Slope	5.7 (4.9)	0.8–1.1	1.0	Linear-linear and convex-convex
Barrier Cove	4.7 (4.1)	0.5–1.7	0.6	Linear-concave
Mainland Submerged Beach	4.9 (4.2)	0–1.4	6	Variable; gently sloping and linear-linear, linear-concave, linear-convex
Mainland Cove	2.9 (2.5)	0–1.4	0.6–1.6	Variable; nearly level and concave linear and linear-concave
Mainland Shallow Cove	2.4 (2.0)	0–1.1	1.7	Nearly level and linear-linear
Mid-lagoon Channel	2.0 (1.7)	1.4–2.3	4–12	Gently to strongly sloping, linear-linear
Barrier Submerged Beach	1.5 (1.3)	0–1.4	5	Gently sloping, linear-linear, linear-convex, linear-concave
Shoal	0.8 (0.7)	0.8–1.4	2.4	Gently sloping, convex-convex

† Slope calculated from topographic map (Bradley and Stolt, 2002).

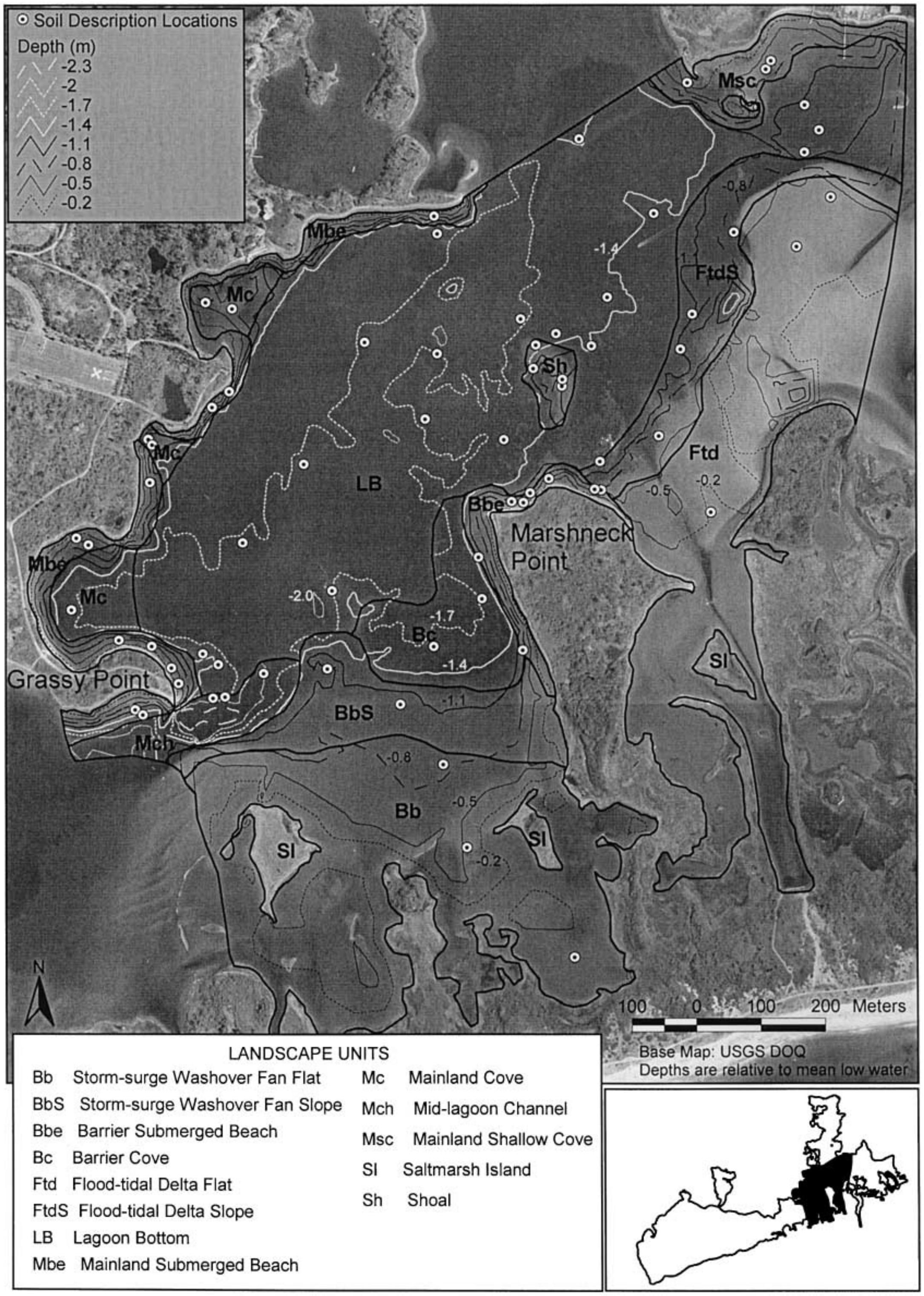

Fig. 2. Pedon sampling and description locations and landscape unit delineations within the 116-ha study area of Ninigret Pond.

a nearly level, slightly undulating topography. Adjacent to the barrier spit is the Storm-surge Washover Fan Flat. This unit was created as the result of overwash from storm surges that transports sediment from the seaward side of the barrier spit to the landward side (Fisher and Simpson, 1979; Boothroyd et al., 1985; Davis, 1994). Sediment is carried through temporary overwash channels that form in the dune complex on the barrier spit (Fisher and Simpson, 1979; Boothroyd et al., 1985; Davis, 1994) and onto the platform. The Storm-surge Washover Fan Flat has nearly level slopes (0.2%), a linear-linear land-surface shape, and is covered by shallow water (0–0.8 m). The Storm-surge Washover Fan Slope unit slopes away from the Storm-surge

Flat, and toward the deeper waters in the Barrier Cove, Lagoon Bottom, and the Mid-lagoon Channel landscape units (Fig. 2).

The steepest slopes and deepest water (1.4–2.3 m) in the study area were found in the Mid-lagoon Channel unit, where channel slopes equaled 12.5% in portions of the unit (Table 1). This landscape unit is likely a relict outwash channel that is maintained by relatively strong currents during tidal cycles (Short, 1975). The Mainland Submerged Beach landscape unit occurs along the shore of the mainland and follows the boundary between the mainland and Ninigret Pond for much of the study area. A series of Mainland Cove landscape units, approximately 100 m apart, also follow along this length of the shore. A similar submerged beach unit is found on the barrier side of Ninigret Pond and adjacent to Marshneck Point. Both of these submerged beach units are extensions of the glaciofluvial landforms that define the adjacent shoreline. The Shoal unit, just to the north of Marshneck Point, also appears to be an island remnant of the glaciofluvial landform.

The Flood-tidal Delta unit is a sink of sand-sized particles created as sediment accumulates from the tidal inlet (Boothroyd et al., 1985; Davis, 1994). Flood tides transport sediment through the tidal inlet and over a flood ramp where currents slow and dissipate (Davis, 1994). Generally, flood-tidal deltas along microtidal coasts are multi-lobate and unaffected by ebbing currents (Davis, 1994). A Flood-tidal Delta Slope unit is comprised of portions of the flood-tidal delta that slope toward deeper water. The Flood-tidal Delta Slope is made up of flood channels, areas of the Flood-tidal Delta that are not actively accumulating sand (inactive lobes), and parts of the terminal lobe of the Flood-tidal Delta (Boothroyd et al., 1985).

Subaqueous Soils

Sixty-nine soil profiles were described within the twelve landscape units. These soils classified into five different great groups and six different subgroups (Tables 2 and 3). All of the soils met the criteria for the Aquent suborder (Soil Survey Staff, 1999). Great group classifications were differentiated based on high *n* values and surface horizons with 8% or more clay (Hydraquents), an irregular decrease in organic C with depth (Fluvaquents), profiles that were sandy throughout (Psammaquents), and soils with sulfidic materials (Sulfaquents). The remaining soils were classified as Endoaquents. Several soils had thick dark surface horizons with high amounts of organic C; these horizons have *n* values >1 (Table 2) which excludes them from having a mollic epipedon (Soil Survey Staff, 1999).

Most of the soils (70%) found within the Lagoon Bottom classified as Typic Hydraquents (Table 3). These subaqueous soils are characterized by greenish black (10Y 2.5/1), black (N 2.5/), and very dark gray (5Y 3/1), silty clay loams, silt loams, and very fine sandy loams with high soil fluidity ($N > 1$). Relatively fine textures are found throughout the profiles; however, thin lenses of sand (5–10 cm) may occur at almost any depth. Organic C contents are more than 33 g kg^{-1} to depths of a meter or more (Table 2). Eelgrass cover is high (>50%) and eelgrass rhizomes and fragments, and periwinkle shells can generally be found throughout the soil profile. The submerged topography is generally flat and slightly undulating with 1 to 2 m of water covering the landform.

The Storm-surge Washover Fan Flat and Flood-tidal Delta Flat landscape units are characterized by shallow water (<1.1 m), flat topography, and virtually no eelgrass cover (Table 1). Subaqueous soils found within these two units had similar morphology, with horizons consisting of very dark gray (5Y 3/1) and dark gray (5Y 4/1) fine sand and sand. Organic C levels are generally <6 g kg^{-1}. Subaqueous soils within the Storm-surge Washover Fan Flat were classified as Typic Sulfaquents, while soils of the Flood-tidal Delta were mostly classified as Typic Psammaquents (Table 3).

The Mainland Submerged Beach, Barrier Submerged Beach, Shoal, and Mid-lagoon Channel landscape units consisted solely of glaciofluvial sand and gravel (Table 3). Subaqueous soils within these units are dominated by black (5Y 2.5/1) and dark olive gray (5Y 3/2) loamy sand and coarse sand with 15–70% gravel and cobbles in virtually all horizons. Typically, A horizons display black (5Y 2.5/1) iron mono-sulfide coatings and low (<6 g kg^{-1}) amounts of organic C. Nearly all the subaqueous soils in these units were classified as Typic Endoaquents (Table 3).

Subaqueous soils of the Mainland Cove were mostly Thapto-histic Hydraquents (60%) (Table 3). These soils were found in protected coves along the mainland shoreline. The subaqueous soils of this unit were black (5Y 2.5/1), very dark gray (5Y 3/1), and dark gray (5Y 4/1), loamy sand, fine sandy loams, and silt loam. Two types of buried organic horizons (300 g kg^{-1} organic C) were found at depths of 50 to 80 cm. One type is reddish black (7.5YR 2.5/1) in color and likely represents remnants of a buried Atlantic white cedar (*Chamaecyparis thoides*) swamp. The Oe and Oa horizons of this Hydraquent lacks the hydrogen sulfide odor generally associated with salt marsh peat and has the lowest electrical conductivity of any of the horizons (Table 2) supporting the freshwater origin. The other buried organic horizon found in the Mainland Cove units is yellowish black (5Y 3/1), smells of hydrogen sulfide, and is probably buried salt marsh peat.

DISCUSSION

The purpose of a soil survey is to delineate areas of landscape into units that have similar properties and characteristics. In the soil survey process, soil mappers use a conceptual model to predict where the various soils will be found on the landscape. In this study, we tested a submerged-landscape attribute conceptual model for determining subaqueous soil boundaries. Of the twenty Lagoon Bottom soils sampled, the majority (70%) classified as Typic Hydraquents (Table 3). These soils have high *n* values, (*n* value > 1) and the finest particle-size distribution (silt contents range from 23 to

Table 2. Classification and characterization data for representative pedons found in the study area (EC = electrical conductivity, ND = not determined). All horizons were structureless.

Horizon	Lower depth	Sand	Silt	Clay	Coarse frags.	Shell frags.	pH (initial)	pH (after 120 d)	EC	$CaCO_3$	Organic C
	cm	%							dS m^{-1}	g kg^{-1}	
Coarse loamy, mixed, nonacid, Typic Fluvaquent Landscape Unit: Flood-tidal Delta Slope Average water depth: 1.1 m											
A1†	13	37	55	8	0	0	7.4	7.3	54	9	16
A2†	26	36	53	11	0	0	7.3	5.7	54	9	20
C1	44	90	9	1	0	0	8.0	7.7	39	4	4
2Ab†	62	45	47	8	trace	trace	7.7	6.0	45	8	13
2C	69	65	33	2	0	0	8.1	7.8	47	ND	ND
3Ab†	86	41	50	9	0	trace	8.1	7.6	50	9	16
3C1	93	84	15	1	0	0	8.5	7.8	48	ND	ND
3C2	100	81	18	1	0	0	8.1	7.6	46	ND	ND
4Ab	108	77	21	2	0	0	8.5	7.5	46	ND	ND
Siliceous, nonacid, Typic Psammaquent Landscape Unit: Flood-tidal Delta Flat Average water depth: 0.2 m											
C1	9	97	2	1	0	0.0	7.9	6.8	46	3	2
C2	33	96	3	1	0	3.9	8.2	7.5	42	3	2
C3	53	95	4	1	0	0.0	8.2	8.0	27	ND	ND
C4	66	95	4	1	0	0.0	8.3	7.9	44	ND	ND
Sandy-skeletal, mixed, nonacid, Typic Endoaquent Landscape Unit: Barrier Submerged Beach Average water depth: 0.8 m											
A1	12	95	4	1	2	0.1	7.8	5.8	43	2	5
C1	34	95	4	1	60	0.1	8.2	6.8	28	2	5
C2	60	97	2	1	51	0.0	7.8	5.7	20	ND	ND
Fine-silty, mixed, nonacid, Typic Hydraquent Landscape Unit: Lagoon Bottom Average water depth: 1.7 m											
A1†	10	18	60	22	0	0.0	7.6	6.8	72	14	42
A2†	38	61	23	16	0	0.0	7.8	6.6	79	10	38
C1†	60	23	55	22	0	0.0	8.1	7.1	73	16	57
C2†	71	14	56	30	0	0.2	7.8	6.9	74	11	33
C3†	100	14	64	22	0	0.3	7.7	ND	63	13	38
Coarse-silty, mixed, nonacid, Typic Sulfaquent Landscape Unit: Barrier Cove Average water depth: 1.7 m											
A1†	11	63	21	16	0	0.0	7.6	5.8	62	14	33
C1†	24	71	16	13	0	0.4	7.7	4.0	60	16	18
C2	30	91	8	1	0	0.0	8.3	7.8	44	3	6
C3†	47	22	62	16	trace	0.0	7.9	7.4	60	2	26
C4†	61	42	42	16	48	4.7	8.3	7.6	61	ND	ND
2C	81	82	17	1	1	0.1	7.6	5.6	30	ND	ND
Sandy, siliceous, nonacid, Typic Sulfaquent Landscape Unit: Storm-surge Washover Fan Flat Average water depth: 0.5 m											
C1	10	98	0	1	0	0	7.6	7.7	59	1	2
C2	28	99	0	1	13	0	7.1	6.2	39	1	2
C3	40	97	2	1	trace	trace	5.1	3.9	28	ND	ND
2Ab	49	94	3	3	trace	6	8.0	7.8	30	5	6
2C1	64	98	1	1	4	0	8.2	7.8	17	ND	ND
2C2	107	98	1	1	0	0	8.4	8.4	45	ND	ND
Fine-silty over sandy, mixed, nonacid, Thapto-Histic Hydraquent Landscape Unit: Mainland Cove Average water depth: 1.3 m											
A1†	18	23	55	22	0	0	7.6	6.3	50	18	65
AC†	38	25	53	22	0	trace	8.0	7.2	45	20	74
C1	63	80	18	2	1	66	8.1	4.5	18	5	16
C2	78	82	16	2	4	0	7.9	4.8	15	ND	ND
C3	83	71	27	2	0	0	7.7	5.8	15	ND	ND
2Oeb	115	ND	ND	ND	0	0	7.7	6.5	6	28	296
2Oab	124	ND	ND	ND	0	1	7.6	6.9	7	11	121

† Horizons had *n* values > 1.0.

64%; clay contents range from 16 to 30%) of all of the soils studied (Table 2). These relatively fine textures are characteristic of a low energy depositional environment. The Lagoon Bottom is one of the deepest areas in Ninigret Pond and is located away from the strong currents of the tidal inlet channel. Therefore, current speeds are quite low and the finer-textured materials (silt, clay, and organic materials) are allowed to settle out of suspension. Organic C levels are generally high throughout the profile in the Lagoon Bottom. Eelgrass covers nearly 100% of this landscape unit and root and plant remains are likely a C-rich source. Another C source may be the organic materials suspended in the water column derived from organisms such as algae. These materials are filtered out of the water column by the dense eelgrass cover and have a chance to settle out with the mineral materials in this relatively low energy environment adding a considerable amount of organic matter

Table 3. Parent materials and soil classifications for the twelve landscape units identified in the study area.

Landscape unit	Parent materials	Soil subgroup classification†
Lagoon Bottom	Silt, fine sand, and organic material	Typic Hydraquent (14) Typic Endoaquent (4) Typic Fluvaquent (2)
Storm-surge Washover Fan Flat	Holocene sand	Typic Sulfaquent (3)
Flood-tidal Delta Flat	Holocene sand	Typic Psammaquent (2) Typic Fluvaquent (1)
Storm-surge Washover Fan Slope	Holocene sand	Typic Fluvaquent (2)
Flood-tidal Delta Slope	Holocene sand	Typic Fluvaquent (2) Typic Psammaquent (2) Typic Endoaquent (1)
Mainland Submerged Beach	Glacial fluvial sand and gravel	Typic Endoaquent (12)
Barrier Cove	Silt, fine sand and organic material over glacial fluvial sand and gravel or Holocene sand	Typic Sulfaquent (2)
Mainland Shallow Cove	Holocene sand over glacial fluvial sand and gravel	Typic Endoaquent (3)
Mid-lagoon Channel	Glacial fluvial sand and gravel	Typic Endoaquent (3)
Barrier Submerged Beach	Glacial fluvial sand and gravel	Typic Endoaquent (6) Typic Fluvaquent (1)
Shoal	Glacial fluvial sand and gravel	Typic Endoaquent (3) Typic Fluvaquent (1)
Mainland Cove	Silts, fine sand and organic material over buried organic material	Thapto-histic Hydraquent (3) Typic Hydraquent (1) Typic Endoaquent (1)

† Number of pedons for each classification is indicated in parenthesis (Soil Survey Staff, 1999).

to these subaqueous soils (Kenworthy et al., 1982; Thayer et al., 1984)

Buried O horizons were found in soils within the Mainland Cove landscape unit (Table 2). These soils classified as Thapto-histic Hydraquents. Demas and Rabenhorst (1998) also found buried organic horizons in the Deep-Mainland Cove landforms that they studied in a Mid-Atlantic estuary. The origin of the buried organic materials in both of these studies are likely former wetlands, either tidal marshes or freshwater swamps, which were covered with water as a result of rapid sea-level rise during the Holocene. Similar processes occur in tidal marshes; however, in tidal marshes sea-level rise is not as rapid, and marsh accretion keeps up with the rate of sea-level rise and the soils remain within an intertidal setting. Such marsh soils are recognized as submerged uplands (Darmody and Foss, 1979; Stolt and Rabenhorst, 1991).

The Storm-surge Washover Fan Slope and the Flood-tidal Delta Slope landscape units contained soils with buried A horizons. These soils classified as Typic Fluvaquents (Tables 2 and 3). In riparian areas, such soils are recognized as the classic floodplain alluvial soils where soils are buried as a result of stream or river flooding following a storm event. Along the Flood-tidal Delta Slope, burial of A horizons may occur as a result of a shift in the position of the tidal inlet following a particularly large storm event (Davis, 1994). On the Storm-surge Washover Fan Slope burial can occur as a result of breaching of the barrier by overwash channels during storm surges that transport sand from the barrier into the lagoon (Boothroyd et al., 1985). Demas and Rabenhorst (1998) found that similar processes were operating in a Mid-Atlantic estuary that resulted in Sulfic Fluvaquents occurring on landforms described as Barrier Island Washover Fans.

Second only to the Lagoon Bottom, the Flood-tidal Delta Flat and the Storm-surge Washover Fan Flat are the largest landscape units in the study area (Table 1 and Fig. 2). The Flood-tidal Delta Flat area of the estuary typically receives deposits of sand-sized particles associated with daily flood-tidal cycles (Boothroyd et al., 1985). Thus, these sandy soils are not stable for a long enough period for most soil forming processes to operate and most of the soils found within this landscape unit are Typic Psammaquents (Tables 2 and 3). Demas and Rabenhorst (1998) found that Typic Psammaquents were commonly found within Shallow Mainland Cove and Barrier Island Overwash Fan landscape units. With the exception of one pedon on the Flood-tidal Delta Slope, Typic Psammaquents were only found on the Flood-tidal Delta Flat landscape unit in Ninigret Pond.

Many of the soils examined showed evidence of sulfide accumulation as indicated by a considerable drop in soil pH following incubation (Table 2). In addition, many of the A horizons in the submerged beach landscape units had the very black (5Y 2.5/1) colors typically associated with the presence of mono-sulfides (Fanning et al., 1993). The accumulation of sulfides, termed sulfidization by Fanning and Fanning (1989), is most often associated with tidal marsh soils. These same processes also operate in estuarine subaqueous soils. Enough sulfides accumulated in the soils forming on the Barrier Cove and the Storm-surge Washover Fan Flat landscape units to meet the Sulfaquent criteria (Table 2). Tidal flushing and influx of dissolved O_2 in these areas may not be as great as those landscape units closer to the tidal inlet, and the strongly reducing conditions necessary for sulfide formation may develop. Demas and Rabenhorst (1998) also found Sulfaquents in Shoal and Deep Mainland Cove landscape units.

The parent materials of the adjacent terrestrial landscapes likely play an important part in determining the soil type in the near-shore subaqueous landscape units. For example, the Flood-tidal Delta Flat and the Storm-surge Washover Fan Flat landscape units are adjacent to the barrier spit (Fig. 2). The processes that formed the barrier (longshore transport of sand and washover events) are similar to the processes that formed these subaqueous landscape units. Therefore, the soil parent materials are also similar (Table 3). Other near-shore areas of Ninigret Pond, such as Mainland Submerged Beach, Mainland Shallow Cove, and Barrier Submerged Beach, are bounded by mostly glaciofluvial material on the upland. Estuarine depositional materials are thin, as is the case with the Shallow Mainland Cove unit (5–20 cm sand horizon), or totally absent and the soils are dominated by the glaciofluvial parent materials. The lack of estuarine materials in the Submerged-Beach landscape units is likely due to the constant exposure to wind and wave energy that keeps the finer-sized particles in suspension. Although not directly adjacent to the shore, the Shoal landscape unit is also composed primarily of glaciofluvial deposits and with little or no estuarine depositional materials. Nearly all of the soils dominated by glaciofluvial deposits classified as Endoaquents (Table 3) and show little effects due to the estuarine environment except for the elevated electrical conductivity levels (Table 2).

The distribution of the subaqueous soils within Ninigret Pond appears to follow the various landscape units suggesting that the landscape unit model can be used to delineate soils with similar properties within Rhode Island estuaries. Ninigret Pond was chosen for this study to specifically identify a variety of different submerged landforms and to examine the associated soils. These landforms (i.e., flood-tidal deltas, washover fans, barrier and mainland shorelines and coves) are common to the hundreds of coastal lagoons found along the Atlantic seaboard. Therefore, the relationships established in this study will likely be similar at other study sites, especially the estuaries found in glaciated areas of the northeast. In some cases, the subaqueous soil-landscape relationships observed in our study were similar to those established in a Mid-Atlantic estuary by Demas and Rabenhorst (1998). However, the lack of Hydraquents and Endoaquents, and the ubiquitous distribution of Psammaquents in the Mid-Atlantic estuary, suggests that subaqueous soil-landscape relationships can differ substantially between Coastal Plain and glaciated physiographic regions.

Testing the accuracy of a soil survey is often done by examining the taxonomic purity of the various mapping units. In our study the mapping unit boundaries were established based on landscape attributes. For the 12 map units that were used to map the subaqueous soils in Ninigret Pond, taxonomic purity (based on the subgroup taxonomic level) ranged from 40 to 100%, with only the Flood-tidal Delta Slope unit having <50% of the soils of the same subgroup (Table 3). Six of the 12 map units had purities of 100%. In terrestrial soil mapping, consociation map units are defined as those map units with >50% of the soils of the so named soil taxa (Soil Survey Division Staff, 1993). Eleven of the 12 map units, defined at the subgroup taxonomic level, meet this consociation criterion. Consociations also require that <25% dissimilar soils occur within the map unit. Determining between similar and dissimilar soils is primarily based on interpretations of the use of those soils (Soil Survey Division Staff, 1993). These interpretations have not been established for subaqueous soils. Establishment of such interpretations will allow for soil mappers to step beyond mapping the soils at the landscape level, and begin to delineate soil-mapping units within landscape units.

There are many subaqueous soil use interpretations that can be utilized in managing estuarine resources. One of the first interpretations that should probably be considered is that these are hydric soils, that have both wetland hydrology and hydrophytic vegetation, and thus, these areas meet the definition of a jurisdictional wetland (subtidal wetland) and should be managed as such (Bradley, 2001). Dredging these wetlands may have an impact on not only the immediate wetland landscape, but in the case of sulfide bearing dredged materials, the uplands where these materials are placed. Sulfide bearing dredge materials may oxidize after being placed on an upland creating acid sulfate soil conditions (Wagner et al., 1982). A large portion of the Ninigret study area was dominated by high *n* value soils. These soils have little or no bearing capacity and pilings for docks and piers will need to by set well below the lower depth of the high n-value materials for support. The function and value of submerged aquatic vegetation such as eelgrass has lead to attempts to reestablish eelgrass meadows in a number of estuaries with mixed success. Understanding the distribution and characteristics of subaqueous soils can only be beneficial to these eelgrass restoration efforts. Understanding subaqueous soils and their distribution may also assist in evaluating the value of subtidal wetlands for shellfish habitat and aquaculture. Estuaries are a much used and valued natural resource. Developing subaqueous soil based use and interpretation records offers an excellent approach to the management and conservation of these resources.

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