ABSTRACT

Application of soil information for making use and management decisions is often termed soil-based interpretations. The primary goal of this research was to develop use and management interpretations for upland disposal of dredged material and shellfish aquaculture. An additional objective was to investigate subaqueous soil temperatures on different soil-landscape units. Placement of estuarine dredged materials on the land surface may lead to acid sulfate conditions, resulting in extremely low pH, creation of salts, and mobilization of heavy metals. Upland placement of marine dredged material was simulated using a mesocosm experiment to test for these effects. Dredged materials were sampled from a range of subaqueous soil-landscape units of two embayments and two coastal lagoons in Rhode Island. These materials were placed into mesocosms outside and exposed to natural precipitation. Mesocosm leachate was analyzed for pH, conductivity, and sulfate content. Dredged materials ranged from sand to silt loam textures with increasing percent carbon and calcium carbonates with increasing fineness of the material. Inorganic sulfide concentrations ranged from 6 – 3411 $\mu g\ g^{-1}$, with an average of 1303 $\mu g\ g^{-1}$. Dredged materials from embayments had higher concentrations of inorganic sulfides than those from coastal lagoons, with low energy landscape units (Bottom and Coves) having greater concentrations of sulfides. The four most common heavy metals observed in the dredged materials were lead, copper, chromium, and zinc. Embayments had heavy metal concentrations above the terrestrial soil background for Rhode Island, while only lead was detected above terrestrial soil background levels in dredged material from coastal lagoons. Leachate from finer textured dredged materials (low energy soil-landscape units) showed a large drop in pH (pH $\leq$ 4.0) associated with sulfide oxidation and creation of acid sulfate conditions. These conditions persisted for the duration of the experiment, while leachate from coarser textured materials of high energy landscape units increased in pH (> 8.0). Salts washed out of the dredged material fairly quickly such that leachate reached conductivities of < 5 dS m^{-1} in 10 months. Leachate sulfate content was initially high following dewatering of the mesocosms but decreased afterwards. Results indicate that fine textured soil-landscape units have greater potential to develop acid sulfate conditions, suggesting that when these materials are dredged and placed on the land, they should be managed according to subaqueous soil type. Relationships between subaqueous soil and shellfish growth were investigated on five different subaqueous soil-landscape units in two coastal lagoons in Rhode Island. Oysters (*Crassostrea virginica*) were grown in trays resting on the bottom while quahogs (hard clam, *Mercenaria mercenaria*) were grown in the soil. Oyster and quahog survival and growth were measured over two growing seasons. Water quality was monitored and soils were characterized to investigate shellfish growth with these parameters. Overall oyster growth averaged 31 mm $year^{-1}$ (height), while overall quahog growth averaged 7.9 mm $year^{-1}$ (hinge width). I found that oyster growth rates correlated to increases in sand content, while depressed growth occurred on fine textured soils. Quahog growth rates showed similar trends among soils, in that faster growth and decreased mortality occurred on coarse textured subaqueous soils. Shellfish growth was not correlated to any water quality parameter. These data provide information that should be incorporated as an interpretation within a subaqueous soil survey, and utilized by estuarine resource managers to site future aquaculture farms on the most productive and best areas of these shallow estuaries. Soil temperature was investigated in two shallow coastal lagoons in Rhode Island. Temperature loggers were placed in the soil at two depths (25 and 50 cm) on three different subaqueous soil-landscape units. Subaqueous soil temperature varied slightly among landscape units, and appears to be primarily influenced by water temperature and water depth. Mean annual soil temperatures taken at 50 cm ranged from 12.3 – 12.6 ºC on Washover Fan and Lagoon Bottom soils respectively, while mean annual water column temperatures ranged from 11.5 – 12.0 º C at those sites. Soil temperatures at 50 cm showed less variability than temperature recorded at 25 cm from the soil-water column interface, and from the water column. Subaqueous soil temperatures met criteria of the mesic soil temperature regime, which is similar to that of subaerial soils of Rhode Island.

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PREFACE

This thesis was written in standard format following the guidelines presented by the University of Rhode Island Graduate School. There is an introduction to the research and three chapters: Subaqueous landscape-level assessment of the upland placement of estuarine dredged material (Chapter 1), Subaqueous soil and shellfish growth (Chapter 2), Subaqueous soil temperature (Chapter 3).

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INTRODUCTION

Estuarine subaqueous soils form in substrates of shallow permanently flooded environments such as coastal estuaries and lagoons to a water depth of 2.5 meters (NCSS, 2005; Soil Survey Staff, 2010). Until recently, these areas were not mapped as soils but designated as miscellaneous area (water). With the recognition of these areas as soil, a new frontier of soil science has opened up with opportunities to map, classify, characterize, and develop use and management interpretations for these soil systems.

A number of studies have focused on methods to sample, identify, characterize, classify, and map these soil systems (Demas and Rabenhorst, 1999; Bradley, 2001; Bradley and Stolt, 2003; Osher and Flannagan, 2007; Payne, 2007). Early studies by Demas (1998) and Demas and Rabenhorst (1999) showed that subaqueous soils undergo processes similar to those described by Simonson (1959): additions, losses, transfers, and transformations. For example, additions to subaqueous soil include mineral and organic material as is typical in terrestrial alluvial soils; losses such as erosion by wave energy; transfers through bioturbation of benthic dwelling organisms and human alterations (clamming); and transformations such as sulfidization (Fanning and Fanning, 1989).

Demas et al. (1996) also described a pedological approach to the mapping of substrates in shallow water lagoons, estuaries, and embayments and applied this approach to the study of subaqueous soils in the Sinepuxent Bay area of Maryland (Demas, 1998; Demas and Rabenhorst, 1999). Using terrain analysis, Demas (1998) identified twelve landscape units based on slope, bathymetry, landscape, and geomorphic setting. Available bathymetry maps were found to be inadequate, so detailed bathymetric data were collected to identify changes in elevation among landscapes. Subaqueous soil units were identified following the soil-landscape paradigm articulated by Hudson (1992) where soil types follow in a regular and repeating pattern as identifiable features across landscapes (Demas, 1998; Demas and Rabenhorst, 1999; Bradley and Stolt, 2003; Osher and Flannagan, 2007; Payne, 2007). Six subaqueous soil series were proposed for representative landscape units in Sinepuxent Bay, Maryland (Demas, 1998).

While Dr. Demas was finishing his research in Sinepuxent Bay, Maryland, Mike Bradley started to investigate subaqueous soils in New England (Bradley and Stolt, 2000; Bradley, 2001; Bradley and Stolt, 2003). These works were followed by studies focused in Taunton Bay, Maine (Flannagan, 2005; Osher and Flannagan, 2007), sub-tropical areas in Florida (Ellis, 2006), mapping of embayments in Rhode Island (Payne, 2007) and mapping of subaqueous soils in Chincoteague Bay, Maryland (Balduff, 2007).

Shallow subtidal environments such as estuaries are multiple use areas with interests in both commercial and recreational activities ranging from clamming, boating, swimming, fishing, shellfish and fish aquaculture. Alterations are made to these environments through shoreline stabilization structures, creation of shipping ports, and dredging to maintain channels and inlets. The purpose of mapping soils and creating a soil survey is to provide use and management information regarding the soil resource for such uses. As with terrestrial soil, varying soil types will naturally have different uses. Application of soil information for making use and management decisions is often termed soil-based interpretations. Current mapping and classification of terrestrial soil depends highly on soil interpretations (Soil Survey Division Staff, 1993). Examples of terrestrial soil interpretations include; the suitability for building roads or houses with basements, siting for septic tank adsorption fields, crop yields and agriculture, and suitability of soils for recreational uses (Soil Survey Staff, 2007). As subaqueous soil science progresses, it is expected that a wide range of use and management interpretations will be developed (Demas and Rabenhorst, 1999; Bradley and Stolt, 2003).

King (2003) outlined more than fifteen subaqueous soil interpretations that coastal resource managers are requesting, and when applied to a subaqueous soil survey would provide those managers a use and management tool (Table A.1). These interpretations include: creation of acid sulfate conditions from the upland disposal of dredged materials, submerged aquatic vegetation (SAV) restoration efforts, SAV distribution (Bradley and Stolt, 2003; Balduff, 2007), clam restocking efforts, aquaculture, identifying water quality trends (Payne, 2007), suitability for recreational and commercial uses, carbon storage (Jesperson and Osher, 2006), and suburban docks and moorings (Mapcoast, 2007; Surabian, 2007).

According to the U.S. Commission on Ocean Policy (2004), coastal watershed counties (representing 25 % of the nation's land) support 52 % of the U.S. population. This suggests that the interaction and possible detrimental effects to these ecosystems also increases (and will continue to increase), as does the need for better management. Since subaqueous soil-landscapes in many coastal lagoons and embayments in Rhode Island have already been mapped (Bradley, 2001; Payne, 2007), these subaqueous soil surveys offer an opportunity to investigate existing data and test a number of subaqueous soil interpretations. The development of subaqueous soil interpretations will aid conservation efforts and future management decisions regarding these coastal resources.

The objective of this research is to begin to develop interpretations for subaqueous soils in Rhode Island's embayments and coastal lagoons regarding the upland placement of marine dredged material and subaqueous soil-shellfish growth relationships.

This thesis is comprised of three chapters. The first chapter examines the upland placement of estuarine dredged material from two coastal lagoons and two embayments within Rhode Island. Chapter two investigates shellfish growth on five different subaqueous soil landscapes in two coastal lagoons using the quahog (Hard clam, *Mercenaria mercenaria*) and the eastern oyster (*Crassostrea virginica*), grown using aquaculture techniques. The last chapter describes temporal and seasonal variations in subaqueous soil temperature using data collected on different subaqueous soil types and landscape units.

CHAPTER 1:

SIMULATED UPLAND PLACMENT OF ESTUARINE DREDGED MATERIALS

ABSTRACT

Placement of estuarine dredged materials on the land surface can result in severe environmental issues if acid sulfate conditions develop. These conditions may lead to decreased pH, creation of salts, and mobilization of heavy metals. Upland placement of marine dredged material was simulated using a mesocosm experiment. Dredged materials were sampled from subaqueous soil-landscape units of two embayments and two coastal lagoons in Rhode Island. These materials were placed into mesocosms outside and exposed to natural precipitation. Dredged materials were characterized for various physical and chemical properties. Mesocosm leachate was analyzed for pH, conductivity and sulfate content. Dredged materials ranged from sand to silt loam textures with increasing percent carbon and calcium carbonates with increasing fineness of the material. Inorganic sulfide concentrations ranged from 6 – 3411 µg g^{-1}, with an average of 1303 µg g^{-1}. Embayments had higher concentrations of inorganic sulfides than coastal lagoons. Lower energy environments (Bottom and Cove landscape units) dredged materials classified as sulfidic materials. The four most common heavy metals observed in the dredged materials were lead, copper, chromium, and zinc. Embayments had heavy metal concentrations above the terrestrial soil background for Rhode Island, while only lead was detected above terrestrial background levels in coastal lagoons. Mesocosm leachate showed two

trends. Leachate from finer textured dredged materials from low energy landscape units showed a large drop in pH ($pH \leq 4.0$) associated with sulfide oxidation and creation of acid sulfate conditions. These conditions persisted for the duration of the experiment, while leachate from coarser textured materials of high energy landscape units increased in pH to > 8.0. Salts washed out of the dredged material fairly quickly such that leachate reached conductivities of < 5 dS m^{-1} in 10 months. Leachate sulfate content was initially high following dewatering of the mesocosms but decreased afterwards. Leachate sulfate content from finer textured materials was higher due to high levels of sulfides found in these soils. Sulfate content also spiked during summer months, due to increased temperatures, oxidation, and microbial activity. These two trends suggest that when dredged materials are placed on the land, they should be managed according to subaqueous soil type.

INTRODUCTION

Dredging is a common occurrence in many coastal environments to deepen channels for navigation and to maintain those channels and inlets (Fanning and Fanning, 1989). The United States Environmental Protection Agency (USEPA) and the United States Army Corps of Engineers (ACOE) both share the responsibility for the regulation of dredged materials and issues permits for dredging under the Clean Water Act (CWA) and the Marine Protection, Research and Sanctuaries Act (MPRSA) of 1972. With more than 300 million cubic meters of material dredged by the ACOE each year, most (90 percent) is considered uncontaminated (Winfield and Lee, 1999; Lee, 2000). Various upland placement alternatives have been proposed for the beneficial use of dredged material (Winfield and Lee, 1999). The ACOE identifies ten broad categories of beneficial use including habitat development, beach replenishment, and agriculture. Certain physical and chemical criteria must be met however, before the dredged material can be used (Cheng, 1986; USACE, 1986; Winfield and Lee, 1999; Yozzo et al., 2004; Brandon and Price, 2007). Winfield and Lee (1999) proposed test criteria that include; grain size analysis, water content, permeability, pH, salinity, and contaminant content in order to identify the potential for adverse environmental impacts. Although the recommended criteria provide much needed information regarding physical characteristics (as well as most chemical characteristics) of the dredged material, little attention is placed on the potential for oxidation of sulfide-rich materials and the subsequent implications related to extremely low pH values (< 4.0), metal toxicity, and creation of salts.

Sulfides form in subaqueous soils, tidal marsh soils, and other reducing systems where an adequate supply of sulfate from seawater is present (Goldhaber and Kaplan, 1982; Pons et al., 1982; Brady and Weil, 2004; Fanning et al., 2009). Sulfate is one of the major anions in seawater with concentrations ranging from 1152 - 1344 ppm (Bianchi, 2007). At the soil-water interface sulfate is trapped in the pore space of the soil where it is reduced by anaerobic, organotrophic organisms (Fanning and Fanning, 1989; Paul and Clark, 1996). Under these anaerobic conditions Fe is also reduced and precipitates with sulfides as mono and di-ferrous sulfides (Jorgenson, 1977; Pons et al., 1984; Fanning and Fanning, 1989; Bianchi, 2007). Pyrite, the dominant sulfur mineral in these materials, forms in the presence of organic matter. The overall reaction is:

$$Fe_2O_3 + 4SO_4^{2-} + 8CH_2O + 1/2O_2 \rightarrow 2FeS_2 + 8HCO_3^- + 4H_2O$$

Upon excavation or removal of overburden from sulfide bearing materials through construction and mining activities, or through the upland placement of estuarine dredged materials, pyrite oxidizes to sulfuric acid and insoluble ferric hydroxide (Nordstrom, 1984) illustrated in the following reaction:

$$FeS_2 + (15/4)O_2 + (7/2)H_2O \rightarrow Fe(OH)_3 + 2H_2SO_4$$

The oxidation of sulfide bearing materials creates severe problems from the subsequent release of sulfuric acid (Fanning and Fanning, 1989; Angeloni et al., 2004; Fanning et al., 2004; Orndorff and Daniels, 2004; Orndorff et al., 2008), creating acid sulfate soils.

Throughout the world, several types of materials with the potential to form acid sulfate soils have been documented. Most common are the estuarine dredged materials, sulfide bearing coastal plain deposits, and mine tailings (Pons et al., 1982; Van Breeman, 1982; Wagner et al., 1982; Fanning and Fanning 1989; Dent and Pons, 1994; Angeloni et al., 2004). Sulfide bearing materials typically form in a marine environment where sulfides accumulate in the sediment and become buried over time (Goldhaber and Kaplan, 1982; Pons et al., 1982; Van Breeman, 1982; Fanning and Fanning, 1989; Rabenhorst et al., 2006). When these materials are exposed to the air through excavation, mining, or construction activities, sulfides oxidize producing sulfuric acid which limits plant growth, creates soluble salts, and has the potential to release harmful metals into the environment, creating an environmental nightmare (McMullen, 1984; Cheng, 1986; Fanning and Fanning, 1989; Fanning et al, 2004; Orndorff and Daniels, 2004; Orndorff et al., 2007). The classic example is in the mining of coal, where sulfide rich mine tailings are placed on the land surface and quickly oxidize creating acid conditions, and with rainfall, the sulfuric acid is washed into streams. This process is sometimes referred to as acid mine drainage, leading to polluted rivers and streams with low pH runoff that precipitates heavy metals and iron, staining rivers red and killing stream life (Calvert and Ford, 1973; Wagner et al., 1982; Herlihy et al., 1990; Brady and Weil, 2002; Barrie Johnson and Hallberg, 2005; Gagliano and Bigham, 2006).

Some of the most extensive sulfide deposits in the U.S. are found in the coastal plain region of New Jersey, Maryland, and Virginia (Wagner et al., 1982; Fanning et al, 2009). These coastal plain deposits are Late Cretaceous and Tertiary in age, and are often associated with potassium rich glaconite (Wagner et al., 1982; Fanning et al., 2009). Numerous reports of the formation of acid sulfate conditions resulting from exposure of these sulfide deposits through construction and road building activities have been documented between Richmond, VA and Washington, DC (Wagner et al., 1982; Fanning et al., 2004; Orndorff and Daniels, 2004; Orndorff et al., 2008; Fanning et al., 2009).

Marine dredged materials are often sulfidic, resulting from the reduction of sulfate within the soil (Fanning and Fanning, 1989). Dredging disposal sites have been documented throughout the Chesapeake Bay region, where they may prose a risk for seepage of low pH runoff (Demas et al., 2004). McMullen (1984) and Cheng (1986) examined acid sulfate conditions following upland placement of Baltimore Harbor dredged materials. McMullen (1984) notes that low soil pH in newly deposited dredged material appears to be a long term problem for plant growth and should thus be raised to a pH of 5.5. Only certain plant species are able to colonize recent dredged material (McMullen, 1984). Most sulfide bearing dredged material soils initially classify as Sulfaquents (Cheng, 1982). Over time (<10 years), surface horizons develop and the soils become Sulfaquepts (Cheng, 1982).

Sulfides existing in a reducing environment are effective in immobilizing trace metals such as zinc, cadmium, lead and aluminum, and when oxidized become soluble metal sulfates (Calvert and Ford, 1973; McMullen, 1984; Griffin et al., 1989; Tack et al., 1995). At a low soil pH (<4.0) heavy metal solubility increases making those metals available for plant uptake and thus enter the food chain (Brady and Weil, 2004; Tack et al., 2005). The low pH results in an abundance of Al, Fe, and Mn in solution, creating toxic conditions to plants and leading to the leaching of iron, which can clog pipes and stain rivers red from iron precipitation (Calvert and Ford, 1973; McMullen, 1984; Brady and Weil, 2004). Fanning et al. (2004) reported that in Baltimore harbor dredged materials, metal concentration varied throughout the profile, but depletion of heavy metals in the upper horizons was observed, with increasing heavy metals lower in the profile (Fanning, 2004). Metals associated with sulfides are converted to metal sulfates during sulfuricization (Carson et al., 1982; Fanning et al., 2004). These metal sulfates are quite soluble and may be transported either deeper or moved laterally in the profile, or be wicked to the soil surface (Fanning et al., 2004). Subaqueous soil and dredged materials often contain large amounts of these sulfides and heavy metals (McMullen, 1984; Cheng, 1986; Fanning et al., 2004; Payne, 2007), thus, sulfide bearing materials (subaqueous soils) are of concern due to sulfuricization and subsequent heavy metal release.

Among the hazards of upland placement of dredged material and subaqueous soil, are the large amounts of soluble salts that are created and leached from marine dredged materials. Sources of salts include numerous chlorides that are naturally present in seawater, and production of sulfate salts during the sulfuricization process (Fanning et al., 2004). In order for these materials to be used for a beneficial use such as topsoil, the salts will need to be leached (Daniels et al., 2007). Sodium (Na) and other chlorides are entrapped in the pore space of the material while in a marine environment. When dredged, these salts are transported in the material to their perspective disposal sites where the salts raise the electrical conductivity (EC) of the dredged material (McMullen, 1984; Cheng, 1986). While salts may present an initial problem for the beneficial use of this material, McMullen (1984) suggested that it is a temporary problem and are generally leached or wicked to the surface after a few seasons, while lowered pH from sulfuricization persists much longer. Dense stands of *Phragmites australis* have been shown to lower soluble salt levels and help with the leaching of salts within the soil (McMullen, 1984).

Dredged materials are a potential valuable resource if the right materials are identified and dredged separately. When these materials are placed on land and enough time goes by, the hazards of acid sulfate weathering, metal release, and leaching of salts can be abated. Questions still remain however, regarding which soils to dredge and the length of time it will take before these problems are abated. In this study I examined the relationships between subaqueous soils and the potential for creating acid sulfate conditions when these soils are dredged and placed on the land surface. In addition, I evaluated the length of time that these effects may remain preventing the beneficial use of this material.

MATERIALS AND METHODS

The upland placement of dredged materials was simulated using a mesocosm experiment. The simulated dredged material was collected to a depth of 25 cm using a bucket auger or MacCauley peat sampler from four subaqueous landscape units within two shallow embayments and two coastal lagoons in Rhode Island (Figure 1.1). Greenwich Bay (1200 ha) (Figure 1.2) and Wickford Cove (160 ha) (Figure 1.3) are smaller embayments that reside within the larger Narragansett Bay estuary (McMaster, 1960). The coastal lagoons, Ninigret Pond (667) (Figure 1.4) ha and Quonochontaug Pond (312 ha) (Figure 1.5) lie along the south shore of Rhode Island and are landward of narrow barrier spits underlain by Pleistocene-age glaciofluvial gravel and till (Boothroyd et al., 1985). Landscape units in the embayments were mapped by Payne (2007). Subaqueous soil and landscape units within the coastal lagoons were identified and mapped by Bradley (2001) and Mapcoast (2007).

Landscape units sampled in the embayments include Mainland Shoreface, Shoal, Spit, Bayfloor and Inland Cove. In the coastal lagoons, Flood Tidal Delta, Washover Fan Flat, Lagoon Bottom and Mainland Cove units were sampled. Collectively these soil-landscape units represent an average of 59% of the total subaqueous area in each embayment, and 76% in each coastal lagoon.

Upon collection, the simulated dredged materials were placed into 5 gallon buckets and mixed by hand. Each mixed sample was placed into four replicate 10 cm diameter, 25 cm length polyvinyl chloride (PVC) columns. A funnel was glued onto the bottom of the PVC column along with a nylon filter attached to the end of the funnel in order to filter rainfall leachate from the mesocosm. Rainfall leachate was collected in a 250 ml Nalgene collection bottle. The mesocosms were placed upright on wood platforms in a secure place outside to accept natural rainfall (Figure 1.6). Four replicates were used per landscape unit for a total of 16 mesocosms per study location, 64 mesocosms total.

In the second year, eight additional mesocosms were constructed from different mixtures of Lagoon Bottom and Washover Fan material collected to a depth of 25 cm from Ninigret Pond. The simulated dredged materials were mixed at mixtures of 5%, 10%, 20% and 40% by volume of Lagoon Bottom to Washover Fan material. There were two replicate mesocosms for each mixture.

Rainfall leachate was collected immediately after a rain event or when at least 50 ml of leachate accumulated in the collection bottle following a rain event. Leachate was transferred into labeled 50 ml Nalgene bottles and frozen until analysis. I did not collect leachate over the winter months due to the material being frozen in the mesocosms.

Mesocosms containing fine textured material were mixed with a small trowel to break up compacted material in April of both years. This was performed because finer textured material tended to compact during dewatering and drying creating a space between the mesocosm sidewall and the material, allowing rainwater to bypass the sample.

Leachate was analyzed for pH, sulfate content (SO_4^{2-}) and conductivity (dS m^{-1}). Conductivity was measured using a hand held Oakton® WD-35607 conductivity meter and pH with an Accument® pH ATC combination electrode with silver/potassium chloride reference. Sulfate (SO_4^{2-}) was measured using a modified LaMotte procedure (LaMotte, 2001). Depending on initial sulfate content (very high or low) a 10x or 100x dilution was performed before making the solution up to 10 ml in a graduated cylinder and adding the reagent. The diluted samples were transferred from the graduated cylinder to clean 50 ml Nalgene® bottles where 0.2 g of sulfate reagent was added. Samples were shaken by hand and let stand for five minutes. An aliquot of the sample was transferred to a cuvette and measured using a Spectronic® 20 Genesys™ spectrophotometer (Spectronic Instruments, Inc. Rochester, NY) at 420 nm. Sulfate content was determined using a standard calibration curved based on known concentrations of sodium sulfate. Results were recorded as absorbance and converted to ppm using the calibration curve.

Characterization of the dredged material included: particle size distribution (PSD) (Soil Survey Laboratory Staff, 2004) and loss on ignition (LOI) soil organic matter (SOM) and calcium carbonate. LOI values for carbon were calculated by weight after combustion at 550º C and weight after combustion at 1000º C for calcium carbonates (Rabenhorst, 1988; Nelson and Sommers, 1996; Heiri et al., 2001; Payne, 2007).

Acid volatile sulfides (AVS) and chromium reducible sulfur (CRS) were determined by a diffusion method where sulfides are volatilized and trapped in a sulfide antioxidant buffer (SAOB) (Fossing and Jorgensen, 1989; Lassora and Casas, 1995; Ulrich et al., 1997; Payne, 2007). One gram of frozen soil was added to a 150 ml serum bottle that contained a 10 x 75 mm vial containing 3 ml of SAOB. The headspace of the bottles were immediately filled with N_2 gas and stoppered. A second set of samples were weighed and dried overnight at 105 ºC to determine the oven dry weight. Samples were reacted with 12 ml of O_2-free 2N HCL added with a syringe through the rubber stopper and rotated at 150 rpm on a rotary shaker for one hour, after which the vial was removed for AVS analysis. A second SAOB trap was inserted into the same serum bottle and the headspace purged of O_2 by N_2 gas. Samples were reacted with 4 ml of O_2-free 12N HCL and 8 ml of Cr^{2+} added with a syringe. Bottles were rotated at 150 rpm for 20 hours after which the SAOB traps were removed for CRS analysis. Concentrations of sulfide in the AVS and CRS traps were determined using a silver/sulfide ion specific electrode standardized to known concentrations of sulfide in $Na_2S•9H_2O$ and SAOB solutions (Thermo Electron, 2003).

Incubation pH was measured on all dredged materials collected to identify the presence of sulfidic material (Soil Survey Staff, 2006). Soil pH was measured using an Accumet® pH probe each day for the first two weeks, and then once per week for two months. Approximately 10 g of frozen sample was placed into 25 ml beakers and mixed with DI water to make a 1:1 by volume soil to water mixture. Samples were stirred periodically in order to prevent the accumulation of salts on the beaker glass. DI water was added when needed to keep the samples moist during incubation.

Salinity measurements were performed using an Oakton® WD-35607 hand-held conductivity meter using the saturated paste method (Soil Survey Laboratory Staff, 2004). Immediately after removal from the freezer, samples were thawed and water was added to make a saturated paste. After overnight refrigeration, water was extracted from samples by vacuuming through a glass-fiber filter and the salinity of the extracted water was measured. Salinity after treatment with hydrogen peroxide was also measured. Water was added to the previously washed sample to make a saturated paste. After overnight refrigeration, water was again extracted from the samples by vacuuming through a glass-fiber filter where the salinity was again measured. Salts present after treatment with hydrogen peroxide were generated by the oxidation process.

Concentrations of heavy metals in the simulated dredged samples were analyzed using X-Ray fluorescence (XRF) with a NITON XL3t XRF analyzer. Heavy metals and total sulfur in the simulated dredged materials were analyzed prior to mesocosm leaching (original sample) and post leaching in the mesocosms for each soil landscape unit sampled. Sulfur concentration was corrected using standards of sodium sulfate mixed with five grams of loamy sand. Three replicates were measured to obtain the average metal and total sulfur concentration.

Rainfall measured at the Kingston weather station 0.5 km from the experimental site, totaled 291 cm from mesocosm setup to the end of the experiment. When compared to the 30 year average precipitation (133 cm), 2007 (119 cm) represented a below average year while 2008 (147 cm) and 2009 (151 cm) were above average (Figure 1.7).

Statistical differences between leachate values were carried out using analysis of variance (ANOVA), Bonferroni tests of differences, and t-tests using Analyze it® software (Analyze-it Software, Ltd. Leeds UK), and SAS (SAS 9.1, SAS Institute Inc., Cary, NC, USA). Regression analysis was performed to find relationships regarding sulfide content and texture. Means of the monthly leachate values for each parameter (pH, sulfate, and conductivity) were calculated and plotted over time. Leachate was also classed into two groups consisting of fine textured and coarse textured samples for statistical analysis and comparisons using t-tests.

RESULTS AND DISCUSSION

Simulated Dredged Material Characterization

Subaqueous landscape units were chosen at each study site according to what I expected as low energy and high energy environments. Two high energy landscape units and two low energy landscape units were used within each study site. The high energy landscape units in the embayments were the Mainland Shoreface and Spit. In the coastal lagoons, Flood Tidal Delta and Washover Fan were used. In the embayments, Bayfloor and Inland cove were sampled for low energy landscape units, while Lagoon Bottom and Mainland Cove were sampled in the coastal lagoons. Psammowassents are the most common great group of the coarser textured, high energy units while Sulfiwassents are commonly found in the low energy units (Payne, 2007; Mapcoast, 2009). These two great groups make up the majority of soils classified in these systems (Demas and Rabenhorst, 1999; Bradley and Stolt, 2003; Payne, 2007).

Many studies have recognized the relationships between the formation of landscape units and the physical character of the bottom in these systems (Boothroyd et al. 1985; Bradley and Stolt, 2003; Payne, 2007). Three depositional environments were defined in Ninigret Pond by Boothroyd et al. (1985) as flood-tidal delta, subtidal storm-surge platform, and back-lagoon (low energy basin, lagoon bottom). These landscapes have a relationship with particle size based on the energy of the depositional environment. Higher energy landscape units are the result of tidal currents along channels and inlets (spits or flood tidal deltas) or storm events washing over the barrier island (Washover Fan) depositing coarser textured material (sand) (Boothroyd et al. 1985). Low energy environments (Lagoon Bottom, Bayfloor and Cove) have little wave action, slower currents, and are relatively deeper than other landscapes (Boothroyd et al., 1985). In these low energy environments, silt and clay (upwards of 20%) have a chance to settle out and be deposited.

Differences in the physical and chemical characteristics of the dredged material characterization are very clear between the high energy and low energy units. All of the high energy landscape units had > 80% total sand and ≤ 2% total clay. Low energy landscape units had < 55% total sand and > 8% total clay; the exception was Mainland Cove in Ninigret Pond which had 91% total sand and only 1% clay (Table 1.1). Although the physical properties of this site (Ninigret Pond Mainland Cove) make it more closely related to a 'high energy' unit, its chemical properties are similar to low energy landscape units, and thus it is classed as low energy (Table 1.2).

All initial soil pH values are near neutral or slightly alkaline suggesting that initial soil pH is independent of landscape setting or energy level (Table 1.2). Soil organic matter (SOM) ranges from 0.6 – 2.3% in the high energy units, in contrast to low energy landscape units where SOM is typically 3 – 12 % (Table 1.2). Lagoon Bottom soils typically have eelgrass growing on them which may contribute to SOM (Bradley and Stolt, 2006). Other sources of organic matter are from benthic dwelling organisms, and algae. Calcium carbonates followed similar trends to SOM, lower amounts of carbonates were found in the high energy landscape units (< 0.15 %) and higher levels were found in the low energy landscape units (Bottom, Bayfloor, and Cove; 0.25 – 0.93%; Table 1.2). Initial conductivity (due to seawater) of the simulated dredged material varied considerably across the landscape units (15 - 23 dS m^{-1}) with no apparent trend (Table 1.2).

Acid volatile sulfides (AVS) and chromium reducible sulfur (CRS) were measured on the simulated dredged materials. Total inorganic sulfides (CRS + AVS) ranged from 56 - 3411 µg g^{-1} with an average of 1303 µg g^{-1} across landscape units (Table 1.3). CRS ranged from 56 – 3263 µg g^{-1} while AVS ranged from 0 – 238 µg g^{-1}. On average, materials sampled from the embayments (Greenwich Bay and Wickford Harbor) showed higher total inorganic sulfide concentrations ($\bar{x}$= 1714 µg g^{-1}) than in the coastal lagoons ($\bar{x}$ = 1303 µg g^{-1}). CRS represented the majority of the inorganic sulfides found in these systems which is consistent with what Payne (2007) and Bradley and Stolt (2003) found for these sites. Greater amounts of inorganic sulfides were found in finer textured materials of the low energy environments from Cove, Bottom, and Bayfloor landscape units, corroborating the findings of Payne (2007) and Bradley and Stolt (2003) that sulfide distribution is in part a function of landscape unit and soil texture (Table 1.3). With these dredged materials, there is a significant relationship (R^2 = 0.66) between grain size (percent < 50 mm, silt and clay) and total inorganic sulfide concentration and corroborates with the findings of Payne (2007) (Figure 1.8).

Total sulfur measured by XRF on the simulated dredged materials ranged from undetectable to 8400 µg g^{-1} (Table 1.3). These sulfur concentrations were 2.6 times higher than total inorganic sulfides, suggesting that dredged materials contain sulfur in multiple forms (Table 1.3). Total inorganic sulfides are the sum of AVS and CRS. The methods used in the measurement of AVS and CRS in this study are effective in determining the amount of inorganic sulfides, but not able to detect organic sulfur or sulfate (Canfield et al. 1986; Hsieh and Shieh, 1997; Ulrich et al. 1997). Recent studies have also suggested that the method of AVS analysis used in this study may underestimate the true amount of AVS, due to ferric iron becoming soluble with the acid added to volatilize sulfides for AVS analysis (Hsieh et al. 2002; Hsieh and Shieh, 1997). Sulfate is also present in seawater at concentrations ranging from 1152 - 1344 ppm (Bianchi, 2007). When sulfate is trapped in the pore water of the dredged material, it will be measured in the fraction represented by XRF (total sulfur).

The four most common heavy metals in the simulated dredged material were lead (Pb), zinc (Zn), chromium (Cr) and copper (Cu). Lead concentration in the embayments and coastal lagoons were higher than the background levels for terrestrial soils (background = 13.91 µg g^{-1}). Levels of Zn, Cr, and Cu were also higher in the embayments than terrestrial soil background levels (background = 25.27, 6.53, 6.41µg g^{-1} respectively), but lower than average for subaqueous soils in the coastal lagoons (RIDEM, 1993) (Table 1.4, 1.5, 1.6, 1.7). Overall, the embayments contained higher concentrations as well as a greater variation in metals (copper was not found in the lagoons) (Tables 1.4, 1.5, 1.6, 1.7). This could be due to the location of the study sites. The coastal lagoons are open through inlets to the ocean (Block Island Sound) while the embayments are open to the larger Narragansett Bay estuary. The embayments are more densely populated (especially Greenwich Bay) with considerable industry along the northern shore of Narragansett Bay providing more urban runoff into the embayments, possibly carrying heavy metals and incorporating them within the subaqueous soils. While the embayments are heavily developed (Greenwich Bay and Wickford Harbor; Figures 1.2, 1.3), the coastal lagoons are mostly surrounded by residential properties with little sediment influx from rivers and streams, limiting terrestrial sediment input (and subsequent heavy metals) (Figure 1.4, 1.5). In the coastal lagoons, greater concentrations of heavy metals were found in dredged material sampled from Lagoon Bottom, while greater concentrations were found in the Inland Cove and Bayfloor dredged materials sampled from the embayments (Tables 1.4, 1.6). Materials collected from the Inland Cove of Greenwich Bay have noticeably higher heavy metal contamination than any other reported landscape (Table 1.4). This soil landscape unit is in a protected cove at the mouth of one of the major streams (Hardig Brook) entering Greenwich Bay (Figure 1.2). This stream and the associated heavily developed watershed are the likely source of the metals.

Simulated Dredged Material Oxidation

Sulfidic materials are defined in Soil Taxonomy (Soil Survey Staff, 2010) as: Materials that have a pH value (1:1 in water) of more than 3.5 and when incubated at room temperature as a layer 1 cm think under moist anaerobic conditions, the pH decreased by 0.5 or more units to a value of 4.0 or less within 16 weeks. The changes in dredge materials resulting from the oxidation of sulfides can be seen rather quickly in laboratory incubation pH measures (Table 1.2). In most cases, all of the pH values decreased in the low energy landscape units, dropping to a pH of 4 or less within 8 weeks (Table 1.2). In two of the samples, the incubation pH was greater than the original pH, rising above pH 8.2. This suggests salts and carbonates are controlling the pH (Table 1.2). The materials that changed little or rose in pH were 99% sand and had the lowest SOM and carbonate content.

Upon oxidation of sulfidic materials, sulfate salts are produced. As a measure of those salts, samples are washed to remove initial salts then treated with hydrogen peroxide. After the sample is treated (oxidized), the pore water is filtered from the sample, and conductivity of the leachate is measured (H_2O_2 oxidized conductivity, Table 1.2). In all cases, additional salts are generated suggesting the formation of sulfate salts as a result of the oxidation of sulfides. In most cases, conductivity from the low energy landscape units increased much more than high energy landscape unit dredged material. Higher salt concentrations in finer textured landscape units support the incubation pH and sulfide data, that there are more sulfides in the low energy environments. Exceptions were the Inland Cove and Spit landscape units sampled from Wickford Harbor. These two samples exhibited lower and higher conductivities respectively, than what were expected (Table 1.2).

Over the extent of the mesocosm experiment, total sulfur content in the simulated dredged materials decreased as a result of oxidation and leaching (Tables 1.4, 1.5, 1.6, 1.7). Sandier landscapes such as Mainland Shoreface and Shoal, tended to lose nearly 100% of sulfur after oxidation in the mesocosms than finer textured materials. For example, materials collected from the sandy Greenwich Bay Mainland

Shoreface and Shoal started with an average sulfur content of 1315 µg g^{-1}, by the end of the experiment essentially 100% of the sulfur had been lost (Table 1.4). In contrast, the finer textured Inland Cove and Bayfloor samples from Greenwich Bay had an average sulfur content of 7189 µg g^{-1} and ended with an average concentration of 3141 µg g^{-1} S, representing a 44% loss in total sulfur (Table 1.4). These changes in total sulfur content are the result of the oxidation of sulfides producing sulfate, subsequent leaching of the sulfate, and leaching of sulfate initially present from seawater.

With the oxidation of sulfides and drastic pH changes that are illustrated by the laboratory incubation pH (Table 1.2), I expected heavy metals to be mobilized and leached from the mesocosms. The XRF data, however, provides no clear trends in metal leaching from the initial concentrations of the unoxidized material to the oxidized (2 year old) simulated dredged material (Tables 1.4, 1.5, 1.6, 1.7). I only collected a small bulk sample from the interior and exterior of the mesocosms. Perhaps if I had measured metals in the extremely low pH leachate collected from fine textured landscape units, heavy metals would have been detected.

<u>Mesocosm Rainfall Leachate</u>

Initial soil pH of the simulated dredged material ranged from 7.47 – 8.11 (Table 1.2). This narrow range can be attributed to the presence of seawater in the pore spaces of the subaqueous soils buffering the pH. In general, leachate pH remained above neutral during the first two months of the experiment across all landscape units sampled (Figures 1.9, 1.10, 1.11, 1.12). There were a couple of exceptions however. Leachate from mesocosms containing dredged materials from Cove units in Wickford Harbor and Ninigret Pond decreased in pH to < 4.0 within two months (Figure 1.10, 1.11). Simulated dredged materials collected from the Bayfloor in Greenwich Bay also experienced a rapid decrease in pH (Figure 1.9). These results are corroborated by the laboratory incubation pH values, which after 8 weeks of incubation, dropped to as low as 2.8 (Table 1.2). Materials collected from Cove landscapes in Wickford Harbor, Ninigret Pond, and Quonochontaug Pond, showed the fastest pH drop over time. In Greenwich Bay, Ninigret and Quonochontaug Ponds, dredged material collected from Bottom and Bayfloor landscapes took 10, 10, and 14 months respectively to reach a pH $\leq$ 4.0, while leachate of the dredged material collected from the Bayfloor landscape in Wickford Harbor reached a pH of 4.0 in two months.

Mainland Shoreface, Spit, Washover Fan, and Flood Tidal Deltas often remained near the initial pH of the leachate during the first year of leaching as can be seen in leachate from these units in Greenwich Bay and Ninigret Pond (Figures 1.9, 1.11). After the first year of leaching however, the leachate pH from dredged materials collected at the aforementioned landscapes tended to increase above the initial leachate pH, possibly due to salt creation and low buffering capacity of these sandy materials. Dredged materials collected from sandy subaqueous landscape units often ended with a high pH (9.0), as can be seen with leachate from dredged material collected from Greenwich Bay and Quonochontaug Pond (Figures 1.9, 1.12). All of the materials collected from high energy subaqueous landscapes (coarser textured) showed a high degree of variation throughout the experiment, but mean leachate pH values from these dredged materials never dropped below 5.0, while materials collected from low energy environments had mean pH values (for the duration of the experiment) close to 4.0 (Figure 1.13).

After 25 months of being exposed to oxidizing conditions, leachate from fine textured landscape units were still at a pH $\leq$ 4.0, with exception to Mainland Cove in Ninigret Pond (Figure 1.11). This anomaly may be due to the fine sand texture (coarser than other comparable landscapes) of this particular sampled cove (Table 1.1). Low pH values over the last several months in the fine textured dredged material (Figures 1.9, 1.10, 1.11, 1.12) is due to the presence of sulfides in these materials that continue to be oxidized and produce sulfuric acid (XRF data; Tables 1.4, 1.5, 1.6, 1.7).

Mean leachate pH values showed two general trends. Finer textured materials of the Cove, Bottom, and Bayfloor landscapes had lower mean pH values than those of the coarser high energy landscapes, indicating extensive development of acid sulfate conditions (Figure 1.13). Following this trend, I grouped the dredged materials into fine and coarse materials to elucidate the differences in pH between these materials (Figure 1.14). Across all sites, differences between fine and coarse textured materials were significant each year ($p < 0.05$), suggesting that simple grouping of soils by depositional every level is an effective approach to identify potential acid sulfate conditions following upland placement of dredged materials.

Initial sulfate concentration in mesocosm leachate ranged from 1000 to 2000 ppm reflecting concentrations in seawater (1152 - 1344 ppm) (Figures 1.15, 1.16). Mesocosm leachate sulfate content varied over time, but showed peaks during the summer months of both years (Figures 1.15, 1.16). Sulfate content from the leachate increased during initial dewatering of the mesocosms during the first 2 months of simulated upland placement in materials collected from Wickford Harbor, Greenwich Bay, and Ninigret Pond as seen in materials from Wickford Harbor (Figure 1.15). This initial spike of sulfate was not seen in simulated dredged materials from Quonochontaug Pond (Figure 1.16). After the winter of the first year and during the spring of 2008, sulfate concentrations in the leachate of coarse textured dredged materials dropped by an order of magnitude, but spiked to 1000 ppm in the summer months of 2008 suggesting the importance of temperature on increasing microbial activity and subsequent sulfide oxidation (Figures 1.15, 1.16). Leachate sulfate content of the dredged material collected from Cove, Bayfloor, and Lagoon Bottom landscape units shows these materials produced large quantities of sulfate. As the oxidation process continued during the summer months of 2008, sulfate concentrations above the initial dewatering values were observed (> 2000 ppm SO_4^{2-}) (Figures 1.15, 1.16). No significant differences were observed between mesocosm leachate sulfate content from high or low energy landscape units during the first year of oxidation (Figure 1.17). In the second year (2008), mean leachate sulfate content from the low energy (fine textured) dredged materials was higher than in the high energy (coarse textured) materials (1510 and 519 ppm SO_4^{2-}respectively). Mesocosm leachate sulfate content during 2009 was < 500 ppm in both the high and low energy units, although leachate from the low energy materials contained significantly more sulfate (Figure 1.17).

Over time, mesocosm leachate conductivity showed similar trends across all samples and landscape units, although differences were observed (Figures 1.18, 1.19). Dewatering of the mesocosms produce leachate with high conductivity, but initial salts washed out quickly. Within 10 months, conductivity dropped from 40 dS m^{-1} to less than 5 dS m^{-1}. Leachate conductivity from mesocosms containing coarse textured materials (high energy units) was higher than low energy units during the first year of leaching (Figure, 1.20). In 2008 and 2009, mesocosm leachate from low energy environments (fine texture) was higher than leachate from high energy (sandy) landscape units (Figures 12.18, 1.19, 1.20). Increases in conductivity were observed during the summer months of 2008 in mesocosms containing fine textured dredged material (Cove, Bayfloor and lagoon Bottom), while leachate from sandy dredged material remained low (Figures 1.18, 1.19). This increase conductivity in the low energy material (fine texture) could be due to increased sulfide oxidation during the summer from sulfides still present in the material as indicated by XRF data (Table 1.4, 1.5, 1.6, 1.7). This sulfide oxidation produces sulfate salts, thus raising the conductivity of the fine textured materials. Mesocosms containing high energy dredged materials (Mainland Shoreface, Spit, Flood Tidal Delta and Washover Fan) produced much more leachate after one rain event than mesocosms containing fine textured dredged materials (Bayfloor, Cove, Lagoon Bottom). This could have possibly diluted the leachate from coarser textured dredged materials, producing lower conductivity readings.

Dredged Material Mixture Experiment

The leachate data from this experiment clearly show that there is a well defined difference between the high and low energy landscape units (fine and coarse textured). These differences were observed in the leachate pH, conductivity, and sulfate content from the mesocosms. Low energy environments consisting of Cove, Bottom and

Bayfloor landscape units pose a greater risk to the development of acid sulfate conditions than materials sampled from high energy environments (Mainland Shoreface, Spit, Washover Fan, and Flood Tidal Delta). A natural question however, is if dredging occurred across these units (mixed), and the materials oxidize when placed on land, what are the effects?

Four different mixtures were created consisting of 5% Washover Fan (WF) material, 95% Lagoon Bottom (LB), 10% WF (90% LB), 20% WF (80% LB), and 40% WF (60% LB). Each sample characterized as fine sand, with decreasing sand content and increasing silt-clay content associated with decreasing WF material and increasing LB material (Table 1.8). Ranges of particle size classes across each mixture included: 92 - 96% sand; 1-4% silt; and 3-5% clay (Table 1.8). Each mixture increased in percent carbon and calcium carbonates with increases of Lagoon Bottom material (Table 1.9). None of the mixtures classified as sulfidic materials upon 8 week laboratory incubation pH (Table 1.9). Total sulfides in the ‘mixed’ mesocosms averaged 542 $\mu g\ g^{-1}$. CRS in the mixed mesocosms ranged from 377 – 623 $\mu g\ g^{-1}$ while AVS ranged from 12 – 40 $\mu g\ g^{-1}$ (Table 1.10). These sulfide amounts are 42% lower than the total sulfides found in Lagoon Bottom material from Ninigret Pond and 46% higher than the total sulfides found in Washover Fan materials due to the mixing of materials (Table 1.3).

Leachate pH from the ‘mixed’ mesocosms collected in August 2008 showed similar trends to dredged materials previously collected. After 1 month, the mixtures with higher percentages of Lagoon Bottom material (20% and 40%) dropped in pH to < 4.0 while pH of the mixtures containing 5 and 10% LB dropped much more slowly.

However, within a year, these mixed materials dropped below pH 4.0 with no noticeable difference between the four mixtures. These data show that even a small percentage of lagoon bottom material (5%) may affect the chemical properties of marine dredged material, and lower the pH due to the development of acid sulfate conditions. Sulfate content of the mixed materials was initially higher than those previously recorded from other dredged materials (3500 ppm upon first rainfall) but decreased to less than 1000 ppm after 9 months (Figure 1.22). Sulfate content was still fluctuating by the end of the experiment suggesting continued generation of sulfate. Mixed mesocosm leachate conductivity show similar trends to the previous experiment, conductivity was initially high, and decreased during dewatering, with no noticeable difference between the four mixtures (Figure 1.23). After 4 months, leachate conductivity fell below 5 dS m^{-1} (Figure 1.23).

SUMMARY AND CONCLUSIONS

Dredging activities are a common procedure to deepen channels, inlets and other areas to improve navigation in shallow subtidal estuaries such as embayments and coastal lagoons. In this study, I simulated the dredging and upland placement of subaqueous soils to determine if subaqueous soil type controlled their impact when placed in the subaerial environment. I found that dredging and placement of fine textured soils from subaqueous landscape units such as Coves, Bottoms, and Bayfloors quickly (within 2 months) resulted in acidic leachate (pH <4.0) and the formation of acid sulfate soils. These soils represent 42, 47, 49 and 51% the total subaqueous bottom area of Greenwich Bay, Wickford Harbor, Ninigret Pond and

Quonochontaug Pond respectively, and are likely to produce the most problems if dredged and placed on land. With the case of upland placement of marine dredged materials, sulfide distribution and soil texture are the controlling factors for the creation of acid sulfate conditions. My study shows that fine textured materials from low energy environments leach salts and produce sulfate for a longer period of time then materials collected from high depositional energy environments. These fine textured materials also contain more sulfur and retain it for a longer period of time when compared to coarser textured dredged materials.

Dredged materials from all sites were found to contain heavy metals including lead, zinc, chromium and copper. Higher than average heavy metal concentrations were found in the embayments when compared to the terrestrial soil background, but were lower than average for material collected from the coastal lagoons with the exception for lead. Higher metal content was found in finer textured materials, suggesting the need to separate these materials from the ‘low impact’ coarser textured, sandy materials of Mainland Shoreface, Spit, Washover Fan, and Flood Tidal Delta. These metals may become a problem in dredged materials due to the mobilization of metals with decreasing pH (associated with sulfide oxidation). My data, however, did not suggest this was the case.

Results from the mixed mesocosm experiment suggest that as little as 5% of fine textured material (Lagoon Bottom) may influence the extent and duration of the development of acidic conditions. Subaqueous landscapes should be managed accordingly (and wisely). Accurate subaqueous soil surveys would allow managers to dredge certain areas accordingly. A subaqueous soil survey would provide resource managers with a tool to determine beneficial uses for the dredged spoil. While these materials may provide a resource that is varying in texture and chemical properties (such as carbon), they must be managed accordingly and separately from one another due to the development of acid sulfate conditions, potential to leach heavy metals, and high salt content.

Table 1.1. Particle size distribution of simulated dredged materials among subaqueous landscape units. Materials were collected to a depth of 25 cm. Mainland Shoreface, Spit, Flood Tidal Delta and Washover Fan represented the higher energy landscape units. Bayfloor, Inland Cove, Lagoon Bottom and Mainland Cove represent the low energy landscape units. Textures ranged from silt loam to sand, with low energy environments comprising of silt loams to fine sands. Very coarse sand (vcos), coarse sand (cos), medium sand (ms), fine sand (fs), very fine sand (vfs), and coarse fragments (CF). Textures: silt loam (sil), fine sandy loam (fsl), loamy fine sand (lfs), and sand (s).

Site	**Landscape**	**vcos (%)**	**cos (%)**	**ms (%)**	**fs (%)**	**vfs (%)**	**Total: sand (%)**	**silt (%)**	**clay (%)**	**CF (%)**	**Texture**
Greenwich Bay	Mainland Shoreface	2	7	40	48	2	98	2	0	0	s
"	Spit	1	2	12	40	26	81	17	2	0	lfs
"	Bayfloor	2	1	3	18	29	53	38	9	0	fsl
"	Inland Cove	0	1	2	3	10	16	64	20	0	sil
Wickford Harbor	Mainland Shoreface	0	1	24	66	7	98	2	1	0	fs
"	Spit	7	14	32	42	3	98	0	2	0	s
"	Bayfloor	2	3	7	9	7	28	52	20	0	sil
"	Inland Cove	1	1	1	1	3	7	69	24	0	sil
Ninigret Pond	Flood Tidal Delta	0	0	27	66	5	98	2	0	0	fs
"	Washover Fan	3	23	52	19	1	99	1	0	0	s
"	Lagoon Bottom	1	0	0	2	20	24	67	8	0	sil
"	Mainland Cove	7	7	11	52	14	91	8	1	0	fs
Quonochontaug	Flood Tidal Delta	10	22	39	22	4	97	3	0	0	s
"	Washover Fan	34	31	29	5	0	99	1	0	0	s
"	Lagoon Bottom	2	0	1	3	12	18	59	23	0	sil
"	Mainland Cove	1	0	0	1	13	15	64	20	0	sil

Table 1.2. Selected chemical properties of simulated dredged materials among subaqueous landscape units. Organic matter (O.M.) and calcium carbonate ($CaCO_3$) was calculated from loss on ignition. Conductivity was measured from saturated pastes of initial sample and after oxidation with hydrogen peroxide. Incubation pH was measured over a two month period. Coarse textured landscapes (high energy units) such as Shoreface, Spit, Shoal, Washover Fan and Flood Tidal Delta expressed a smaller pH change upon incubation than the low energy landscape units of Bayfloor, Bottom, and Cove.

Site	**Landscape Unit**	**O.M. (%)**	**$CaCO_3$ (%)**	**conductivity ($dS\ m^{-1}$)**	**H_2O_2 Oxidized conductivity ($dS\ m^{-1}$)**	**Initial Soil pH**	**Incubation pH (8 week)**	**Incubation pH change**
Greenwich Bay	Mainland Shoreface	1.09	0.11	22.7	5.7	7.9	5.0	-2.9
"	Spit	1.29	0.13	25.1	3.3	8.1	6.2	-1.9
"	Bayfloor	7.40	0.81	15.2	16.5	7.7	3.3	-3.6
"	Inland Cove	12.58	0.93	18.7	22.4	7.7	3.0	-3.7
Wickford Harbor	Mainland Shoreface	2.29	0.13	22.2	4.2	8.0	7.3	-0.7
"	Spit	1.28	0.12	26.5	19.0	8.2	7.6	-0.6
"	Bayfloor	8.76	0.84	25.9	16.0	7.7	4.1	-3.6
"	Inland Cove	8.93	0.89	26.9	8.9	7.6	4.0	-3.5
Ninigret Pond	Flood Tidal Delta	0.78	0.15	21.4	4.6	8.1	7.6	-0.5
"	Washover Fan	0.64	0.04	17.0	6.0	8.0	7.5	-0.5
"	Lagoon Bottom	6.15	0.43	21.8	15.1	8.1	3.4	-4.6
"	Mainland Cove	3.36	0.25	17.8	13.9	7.7	2.8	-4.9
Quonochontaug	Flood Tidal Delta	0.68	0.09	27.6	6.9	7.8	8.2	0.4
Pond	Washover Fan	0.61	0.05	N/A	6.3	8.0	8.5	0.6
"	Lagoon Bottom	5.39	0.32	17.4	33.3	7.7	3.1	-4.6
"	Mainland Cove	12.00	0.60	17.1	21.9	7.5	3.8	-3.7

Table 1.3. Total sulfur (XRF, TS) and sulfide distribution of the simulated dredged materials sampled from landscape units. AVS = acid volatile sulfides; CRS = chromium reducible sulfur. TIS = total inorganic sulfides; TS = total sulfur.

Location	**Landscape Unit**	**AVS μg/g^{-1}**	**CRS μg/g^{-1}**	**TIS μg/g^{-1} (AVS+CRS)**	**XRF TS μg/g^{-1}**
Greenwich Bay	Mainland Shoreface	22	1087	1109	1455
"	Spit	0	359	359	1175
"	Bayfloor	33	2368	2401	7121
"	Inland Cove	147	3263	3411	7258
Wickford Harbor	Mainland Shoreface	0	131	131	3267
"	Spit	0	180	180	Not Detectable
"	Bayfloor	130	2810	2940	6166
"	Inland Cove	1	3178	3179	6035
Ninigret Pond	Flood Tidal Delta	1	130	131	Not Detectable
"	Washover Fan	0	247	247	1153
"	Lagoon Bottom	1	927	928	3416
"	Mainland Cove	227	1695	1922	3280
Quonochontaug Pond	Flood Tidal Delta	0	85	85	Not Detectable
"	Washover Fan	0	59	56	Not Detectable
"	Lagoon Bottom	238	1307	1545	4509
"	Mainland Cove	132	2093	2225	8400

Table 1.4. Average (n = 3) sulfur and heavy metal content of simulated dredged material from Greenwich Bay. Mean (standard deviations). Initial = before placement in mesocosms; Surface = sample taken at surface of mesocosm post leaching; Interior = sample taken 10 cm within mesocosm post leaching. N/D = not detectable.

	Initial	**Surface**	**Interior**
	$\mu g/g^{-1}$	$\mu g/g^{-1}$	$\mu g/g^{-1}$
		Mainland Shoreface	
S	1366 (648)	N/D	N/D
Pb	6 (11)	0 (0)	5 (9)
Zn	16 (27)	20 (17)	25 (3)
Cr	11 (19)	0 (0)	0 (0)
Cu	0 (0)	0 (0)	0 (0)
		Spit	
S	1103 (219)	N/D	N/D
Pb	7 (12)	0 (0)	5 (10)
Zn	31 (3)	21 (18)	19 (18)
Cr	0 (0)	0 (0)	27 (24)
Cu	0 (0)	0 (0)	0 (0)
		Inland Cove	
S	6812 (721)	2465 (426)	2950 (262)
Pb	196 (5)	204 (6)	187 (4)
Zn	426 (37)	105 (3)	91 (8)
Cr	421 (20)	572 (7)	576 (18)
Cu	206 (28)	168 (10)	139 (29)
		Bayfloor	
S	6683 (679)	2169 (456)	2946 (121)
Pb	147 (6)	135 (14)	151 (3)
Zn	153 (10)	60 (1)	65 (5)
Cr	100 (16)	106 (4)	108 (16)
Cu	95 (18)	76 (13)	92 (21)

Table 1.5. Average (n = 3) sulfur and heavy metal content of simulated dredged material from Wickford Harbor. Mean (standard deviations). Initial = before placement in mesocosms; Surface = sample taken at surface of mesocosm post leaching; Interior = sample taken 10 cm within mesocosm post leaching. N/D = not detectable.

	Initial	**Surface**	**Interior**
	$\mu g/g^{-1}$	$\mu g/g^{-1}$	$\mu g/g^{-1}$
		Mainland Shoreface	
S	3066 (566)	N/D	N/D
Pb	0 (0)	7 (13)	12 (11)
Zn	28 (4)	23 (20)	28 (2)
Cr	0 (0)	0 (0)	0 (0)
Cu	0 (0)	0 (0)	0 (0)
		Spit	
S	N/D	N/D	N/D
Pb	9 (16)	5 (9)	13 (12)
Zn	39 (5)	18 (16)	30 (4)
Cr	0 (0)	0 (0)	0 (0)
Cu	0 (0)	0 (0)	0 (0)
		Inland Cove	
S	5664 (1399)	2798 (339)	2096 (332)
Pb	38 (8)	39 (12)	32 (6)
Zn	106 (6)	53 (5)	55 (3)
Cr	90 (16)	83 (40)	75 (20)
Cu	0 (0)	0 (0)	0 (0)
		Bayfloor	
S	5787 (146)	2226 (100)	2427 (285)
Pb	45 (5)	51 (9)	46 (4)
Zn	104 (14)	53 (3)	71 (2)
Cr	79 (13)	93 (22)	93 (37)
Cu	0 (0)	0 (0)	0 (0)

Table 1.6. Average (n = 3) sulfur and heavy metal content of simulated dredged material from Ninigret Pond. Mean (standard deviations). Initial = before placement in mesocosms; Surface = sample taken at surface of mesocosm post leaching; Interior = sample taken 10 cm within mesocosm post leaching. N/D = not detectable.

	Initial	**Surface**	**Interior**
	$\mu g/g^{-1}$	$\mu g/g^{-1}$	$\mu g/g^{-1}$
		Washover Fan	
S	N/D	N/D	N/D
Pb	10 (9)	15 (1)	0 (0)
Zn	0 (0)	0 (0)	0 (0)
Cr	0 (0)	0 (0)	0 (0)
Cu	0 (0)	0 (0)	0 (0)
		Flood Tidal Delta	
S	1082 (274)	N/D	N/D
Pb	5 (8)	9 (8)	5 (8)
Zn	7 (12)	0 (0)	0 (0)
Cr	0 (0)	0 (0)	0 (0)
Cu	0 (0)	0 (0)	0 (0)
		Mainland Cove	
S	3078 (216)	1186 (207)	827 (828)
Pb	26 (4)	24 (3)	28 (7)
Zn	15 (13)	0 (0)	15 (13)
Cr	11 (19)	0 (0)	0 (0)
Cu	0 (0)	0 (0)	0 (0)
		Lagoon Bottom	
S	3206 (116)	800 (740)	379 (699)
Pb	35 (5)	34 (7)	24 (2)
Zn	44 (14)	24 (22)	28 (5)
Cr	0 (0)	0 (0)	0 (0)
Cu	0 (0)	0 (0)	0 (0)

Table 1.7. Average (n = 3) sulfur and heavy metal content of simulated dredged material from Quonochontaug Pond. Mean (standard deviations). Initial = before placement in mesocosms; Surface = sample taken at surface of mesocosm post leaching; Interior = sample taken 10 cm within mesocosm post leaching. N/D = not detectable.

	Initial $\mu g/g^{-1}$	**Surface** $\mu g/g^{-1}$	**Interior** $\mu g/g^{-1}$
		Washover Fan	
S	N/D	N/D	N/D
Pb	5 (8)	0 (0)	5 (9)
Zn	8 (13)	10 (18)	0 (0)
Cr	0 (0.	0 (0)	0 (0)
Cu	0 (0)	0 (0)	0 (0)
		Flood Tidal Delta	
S	N/D	N/D	N/D
Pb	0 (0)	12 (11)	10 (8)
Zn	0 (0)	0 (0)	6 (11)
Cr	0 (0)	0 (0)	0 (0)
Cu	0 (0)	0 (0)	0 (0)
		Mainland Cove	
S	7883 (985)	3157 (415)	3004 (218)
Pb	37 (8)	40 (3)	40 (2)
Zn	56 (6)	24 (22)	37 (12)
Cr	14 (24)	31 (27)	34 (29)
Cu	0 (0)	0 (0)	0 (0)
		Lagoon Bottom	
S	4232 (419)	313 (571)	683 (631)
Pb	35 (4)	33 (8)	35 (1)
Zn	64 (6)	53 (7)	49 (6)
Cr	46 (7)	55 (17)	40 (37)
Cu	0 (0)	0 (0)	0 (0)

Table 1.8. Particle size distribution of simulated dredged materials of different mixtures of lagoon bottom to washover fan material by volume, collected to a depth of 25 cm in Ninigret Pond.

Mixture by volume LB % : WF %	vcos (%)	cos (%)	ms (%)	fs (%)	vfs (%)	Total: sand (%)	silt (%)	clay (%)	CF (%)	Texture
5 : 95	1	3	18	65	9	96	1	3	0	fs
10 : 90	1	3	17	64	10	94	2	4	0	fs
20 : 80	1	3	17	61	10	92	4	4	0	fs
40 : 60	0	3	17	64	8	92	3	5	0	fs

Table 1.9. Selected chemical properties of simulated dredged materials of different mixtures of lagoon bottom to washover fan material by volume, collected to a depth of 25 cm in Ninigret Pond. Organic matter (O.M.) and Calcium Carbonate ($CaCO_3$) was calculated from loss on ignition (LOI).

Mixture by volume LB % : WF%	O.M. (%)	$CaCO_3$ (%)	5:1 Salinity (dS m^{-1})	Incubation pH (8 week)	pH change
5 : 95	1.09	0.12	2.7	7.39	-0.05
10 : 90	1.87	0.28	3.3	4.24	-1.03
20 : 80	2.30	0.24	3.5	7.19	-0.04
40 : 60	2.82	0.26	2.9	6.47	-0.37

Table 1.10. Sulfide distribution of simulated dredged materials of different mixtures of lagoon bottom and washover fan material by volume. Samples were collected to a depth of 25 cm in Ninigret Pond. AVS = acid volatile sulfides; CRS = chromium reducible sulfur; TIS = total inorganic sulfides.

Mixture by volume LB % : WF%	**AVS μg/g^{-1}**	**CRS μg/g^{-1}**	**TIS μg/g^{-1} (AVS+CRS)**
5 : 95	23	467	489
10 : 90	12	377	389
20 : 80	43	585	628
40 : 60	40	623	663

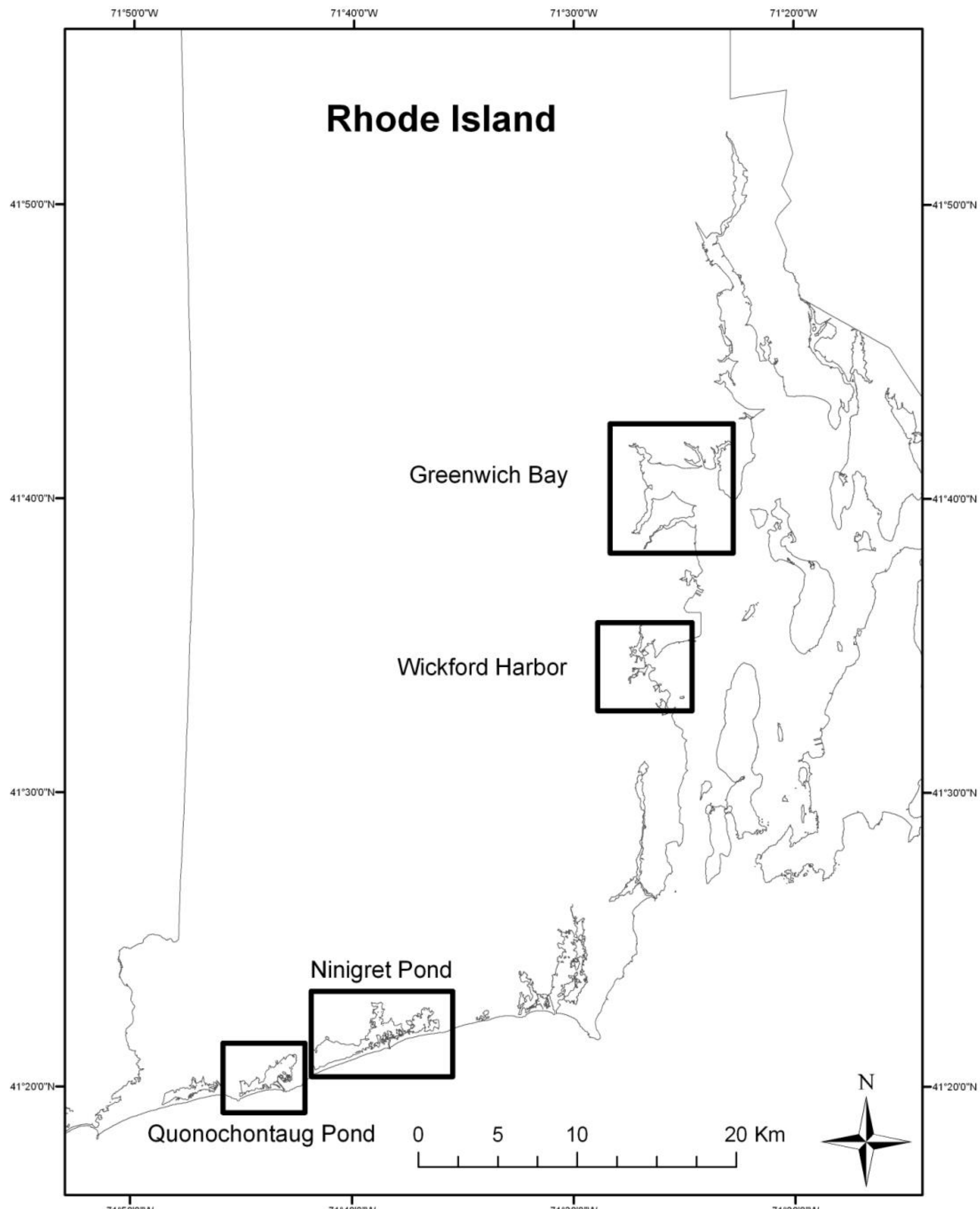


Figure 1.1. Locus map showing simulated dredged material sampling sites. Greenwich Bay and Wickford Harbor are embayments within the larger Narragansett Bay estuary, while Ninigret and Quonochontaug Ponds are coastal lagoons lying on the south shore of Rhode Island.

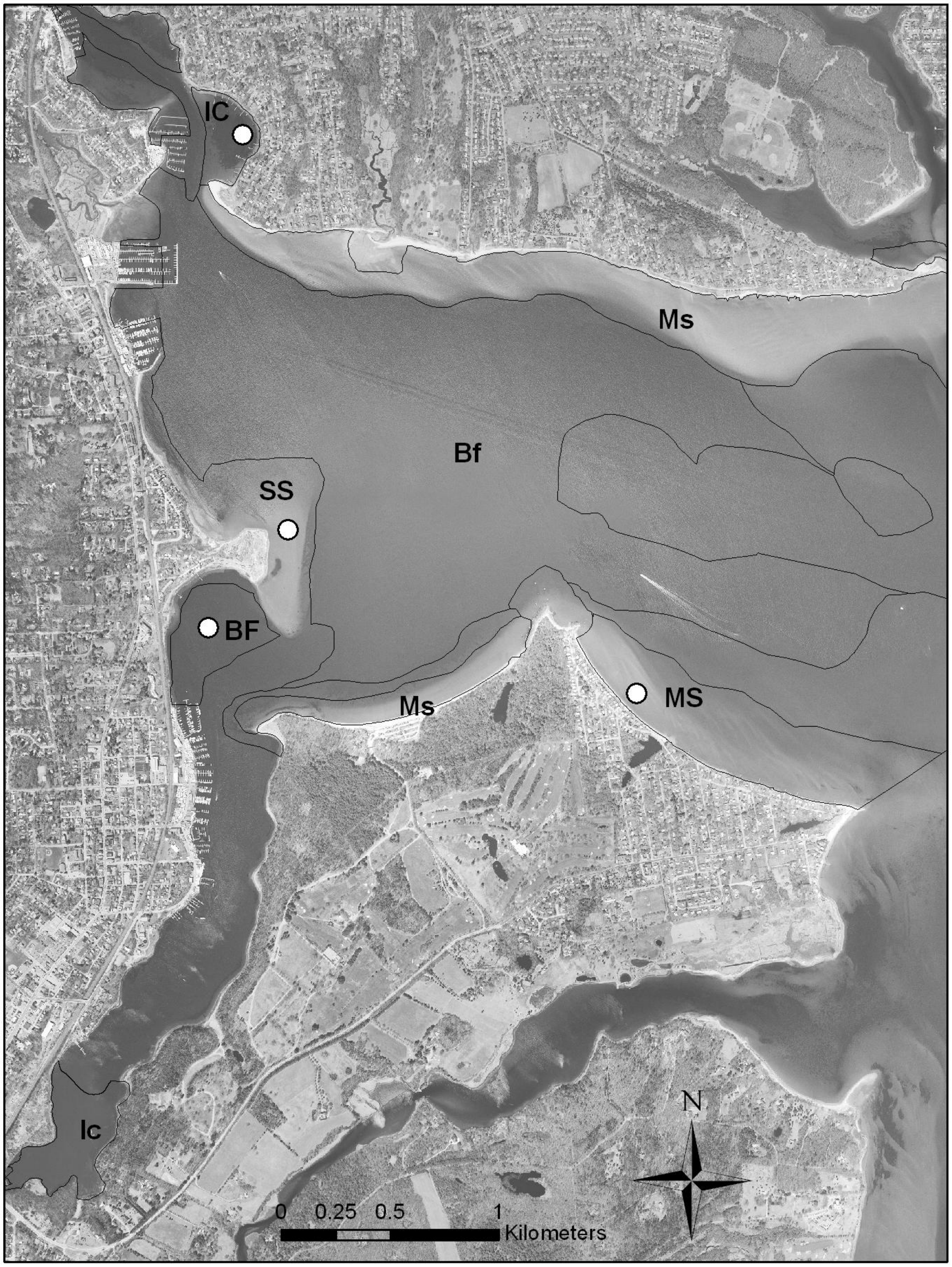


Figure 1.2. Sample locations of simulated dredged material and subaqueous landscape units in Greenwich Bay. Subaqueous landscape units sampled include: Mainland shoreface (MS), Spit (SS), Bayfloor (BF), and Inland Cove (IC).

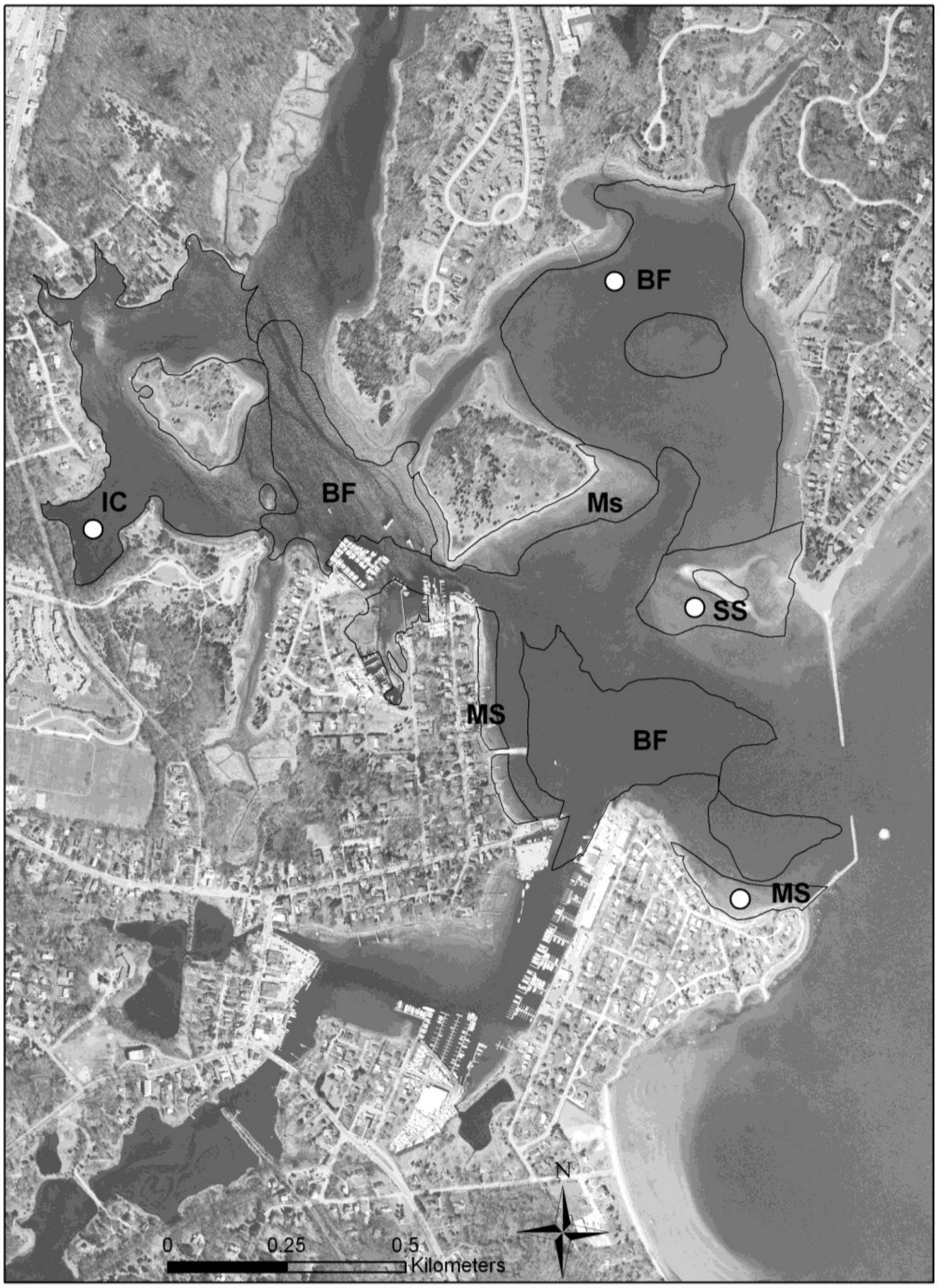


Figure 1.3. Sample locations of simulated dredged material and subaqueous landscape units in Wickford Harbor. Subaqueous landscape units sampled include: Mainland shoreface (MS), Spit (SS), Bayfloor (BF), and Inland Cove (IC).

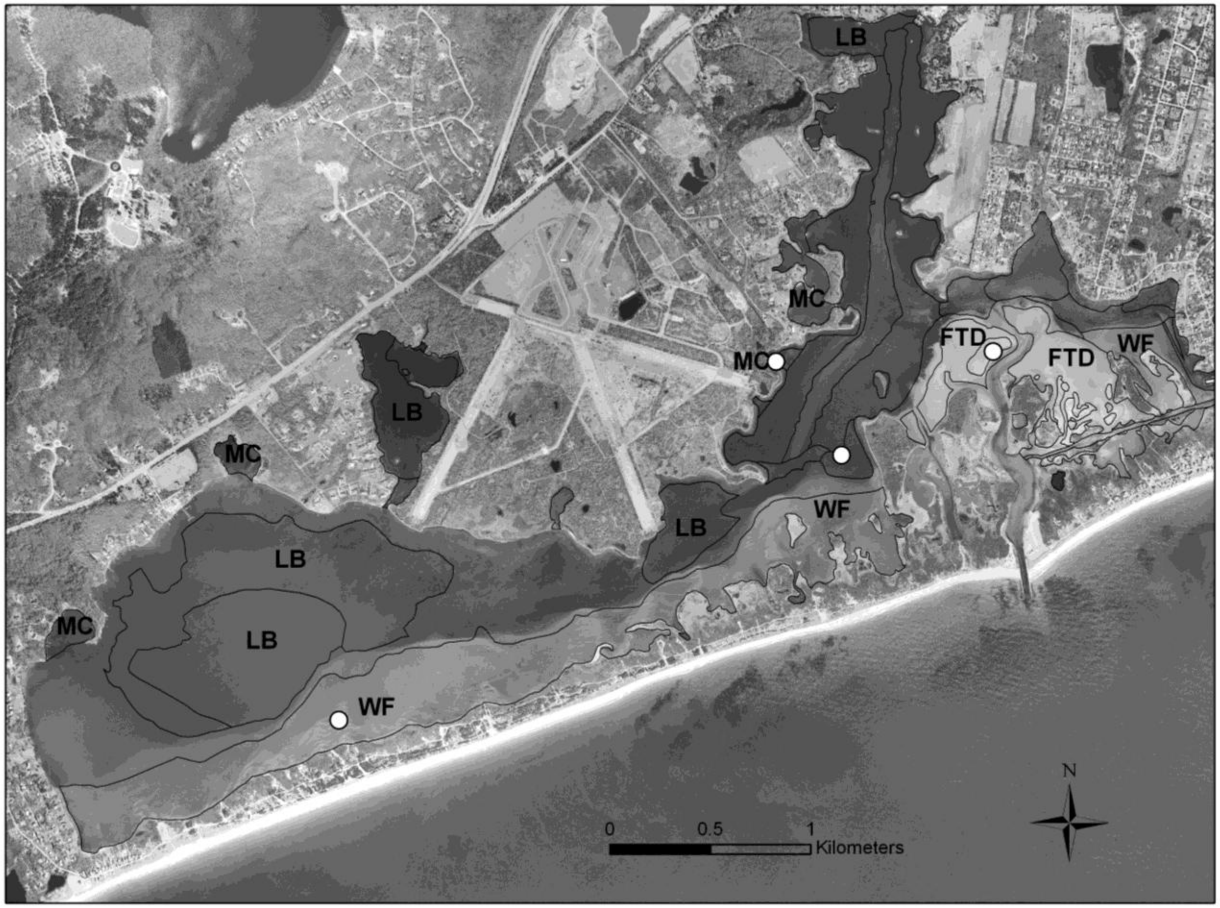


Figure 1.4. Sample locations of simulated dredged material and subaqueous landscape units in Ninigret Pond. Sampled landscapes include: Flood Tidal Delta (FTD), Washover Fan Flat (WF), Lagoon Bottom (LB) and Mainland Cove (MC). .

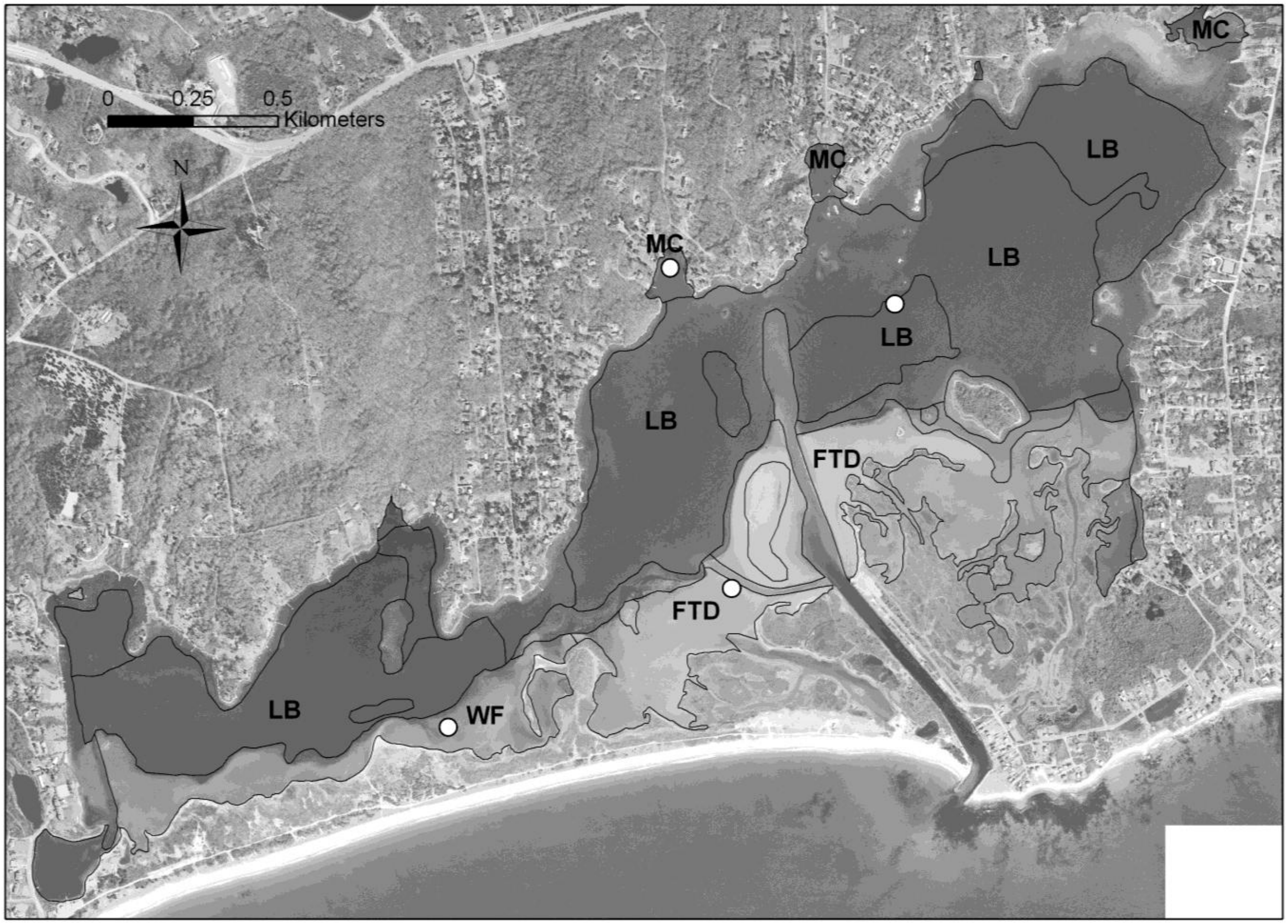


Figure 1.5. Sample locations of simulated dredged material and subaqueous landscape units in Quonochontaug Pond. Sampled landscapes include: Flood Tidal Delta (TFD), Washover Fan Flat (WF), Lagoon Bottom (LB) and Mainland Cove (MC).

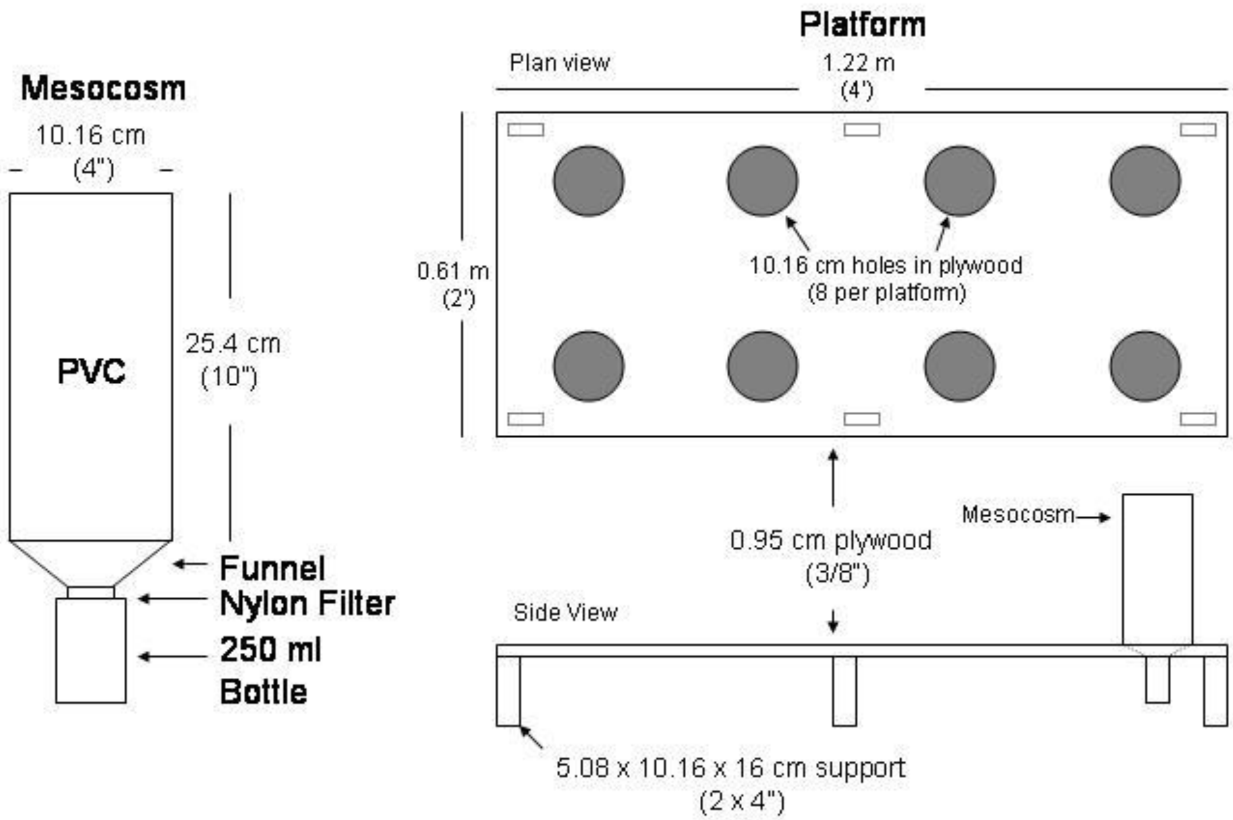


Figure 1.6. Dredged material mesocosms were constructed using PVC pipes (10 x 25cm), a funnel, and nylon filter. Mesocosms stand upright on wood platforms with the top open to accept natural rainfall.

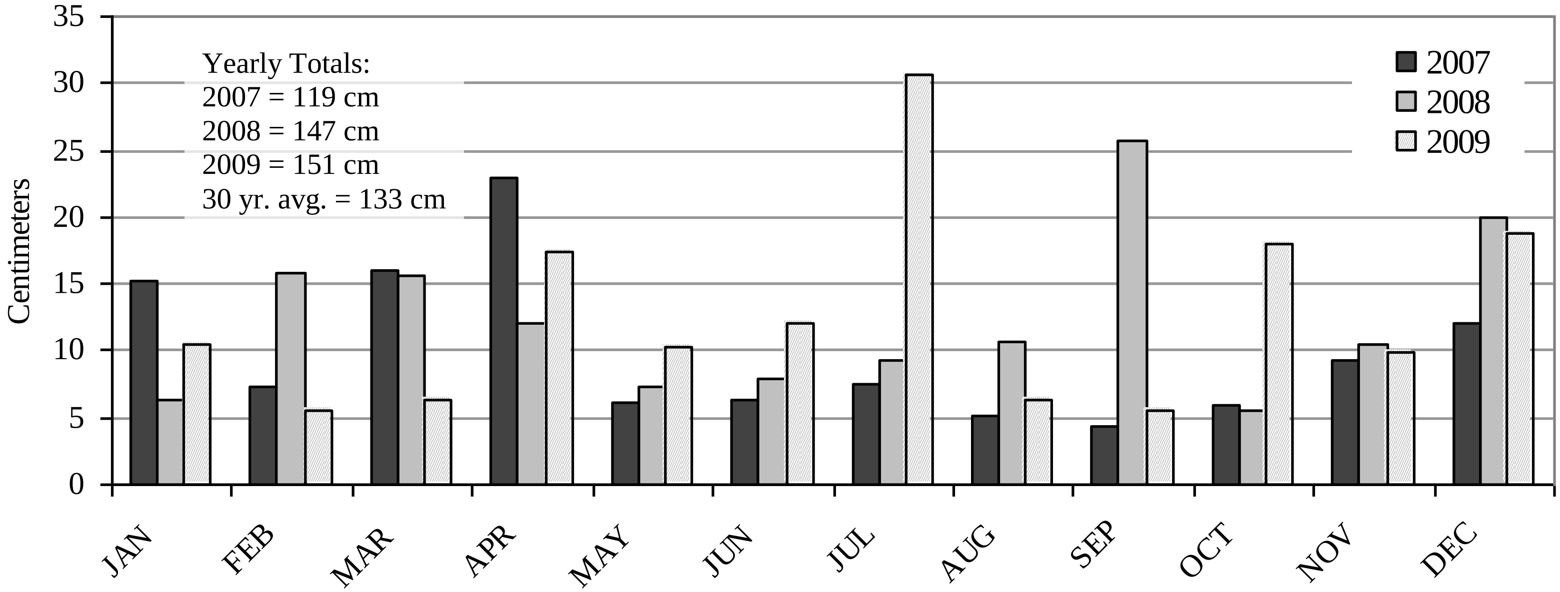


Figure 1.7. Monthly precipitation data from the Kingston, Rhode Island weather station. 2007 was below average in precipitation when compared to the 30 year mean of 133 cm, 2008 and 2009 were above average in the amount of rainfall.

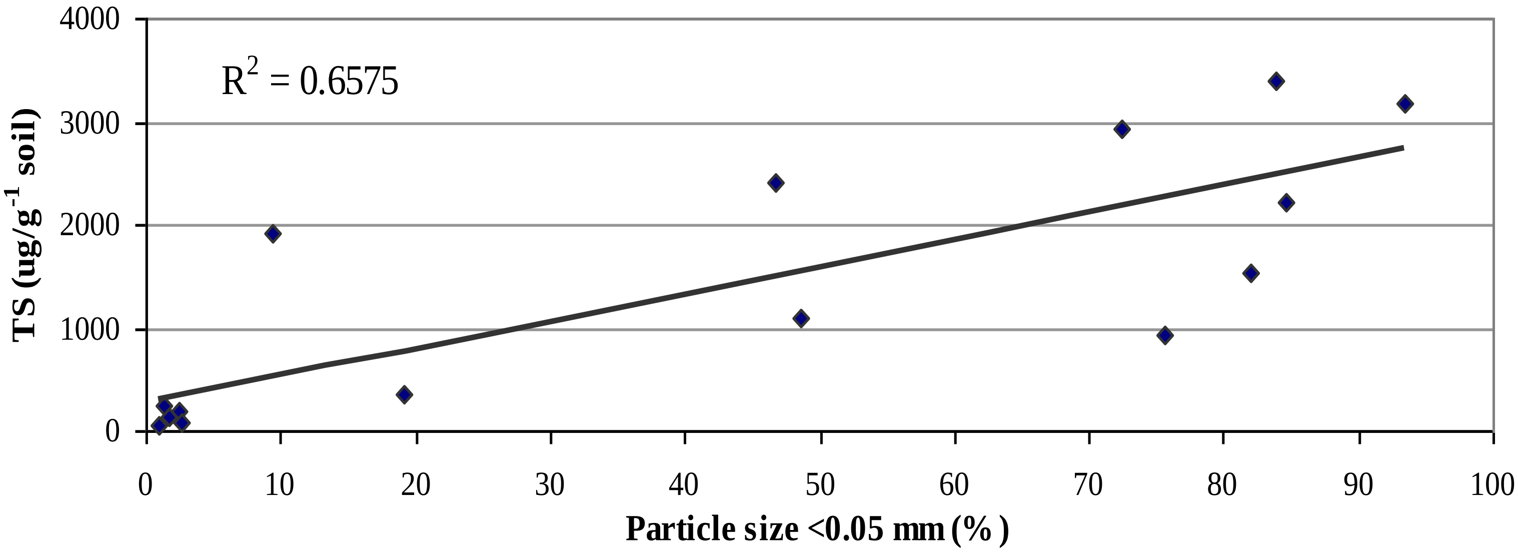


Figure 1.8. Regression analysis of particle size < 0.05 mm (silt + clay) to total inorganic sulfur (AVS + CRS) in simulated dredged materials. Total inorganic sulfur increased with increasing fineness of the soil. Higher sulfide and finer textures are associated with low energy environments such as Bottom, Cove and Bayfloor landscapes units. Sandy landscape units such as Shoal, Spit, Shoreface, Washover Fan and Flood Tidal Delta generally have lower amounts of sulfide and coarser textures.

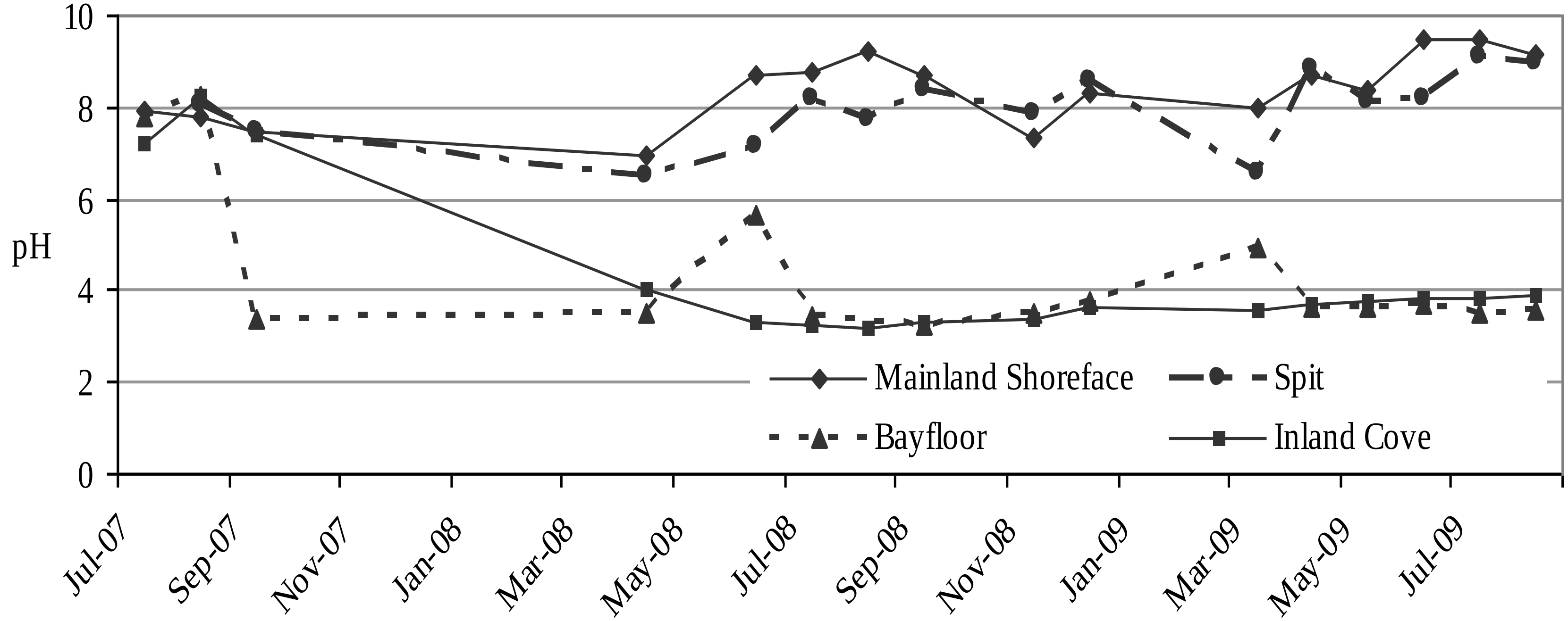


Figure 1.9. Monthly mean leachate pH of Greenwich Bay simulated dredged material. Rainfall leachate was collected and analyzed after a rain event. Leachate was not collected during the winter. Fine textured mesocosms (low energy units) were mixed every spring (April) to break up compacted material.

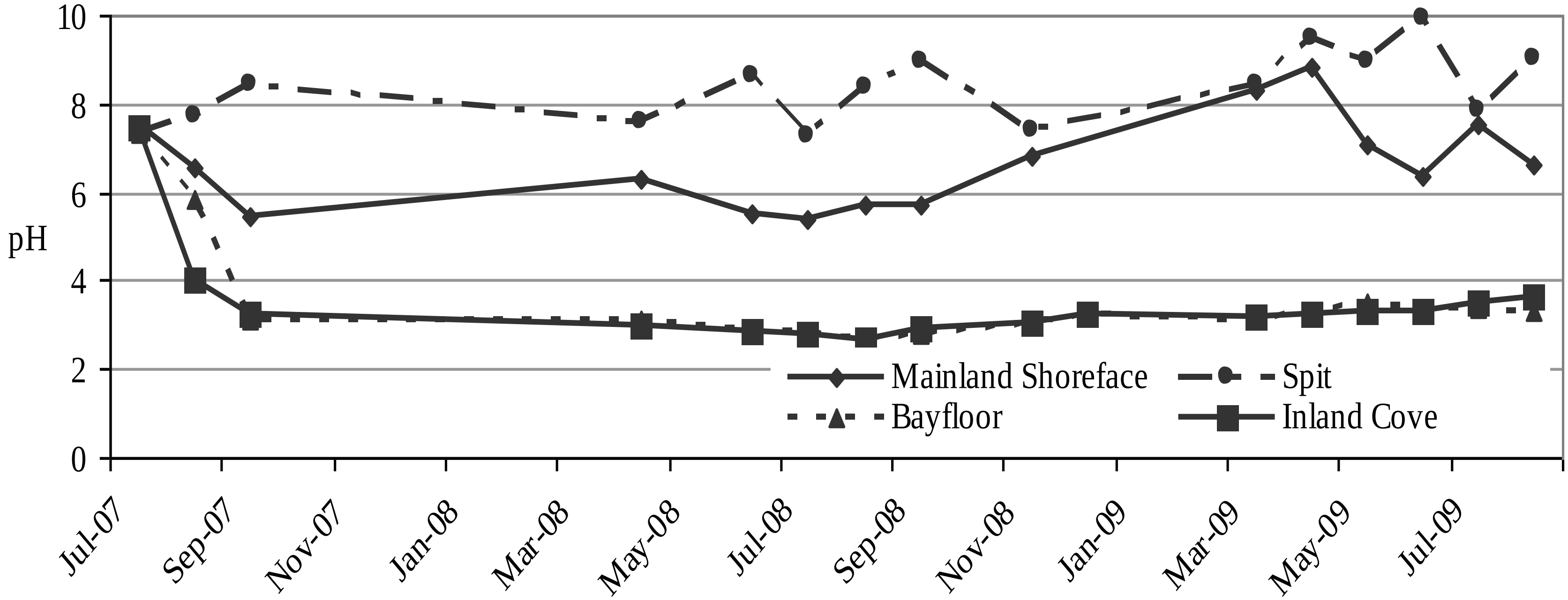


Figure 1.10. Monthly mean leachate pH of Wickford Harbor simulated dredged material. Rainfall leachate was collected and analyzed after a rain event. Leachate was not collected during the winter. Fine textured mesocosms (low energy units) were mixed every spring (April) to break up compacted material.

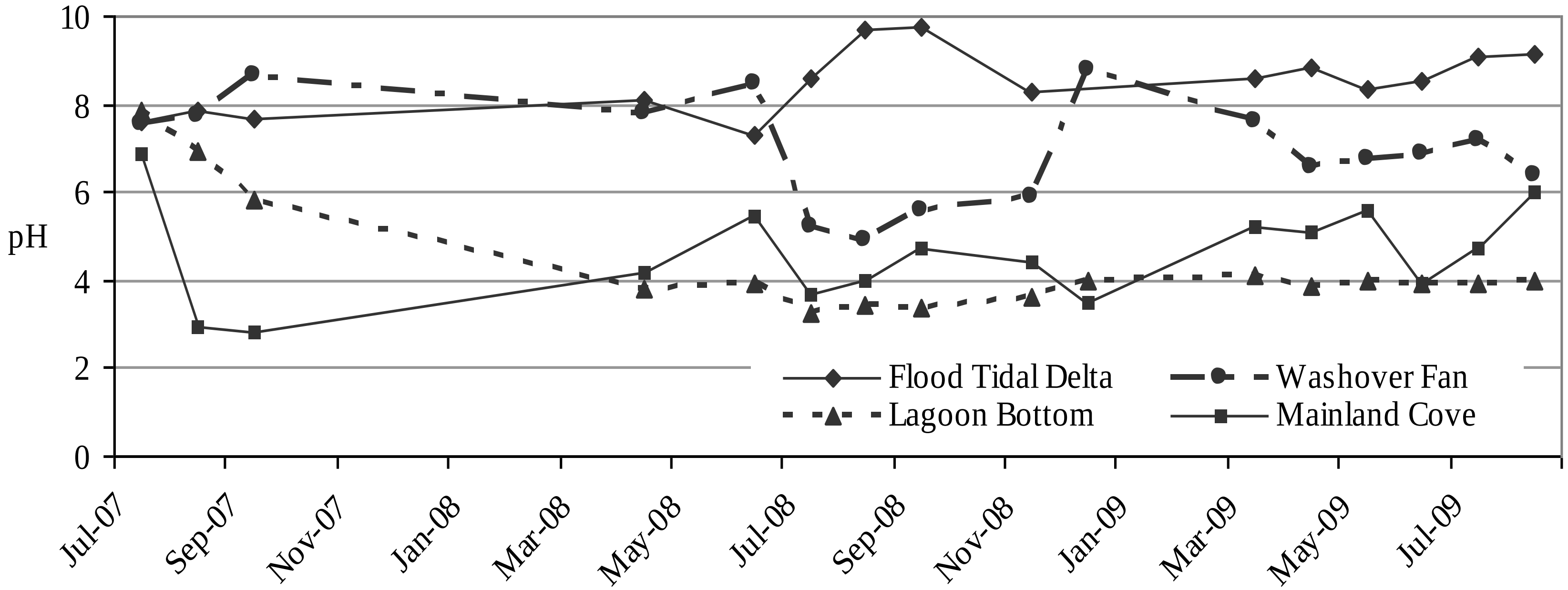


Figure 1.11. Monthly mean leachate pH of Ninigret Pond simulated dredged material. Rainfall leachate was collected and analyzed after a rain event. Leachate was not collected during the winter. Fine textured mesocosms (low energy units) were mixed every spring (April) to break up compacted material.

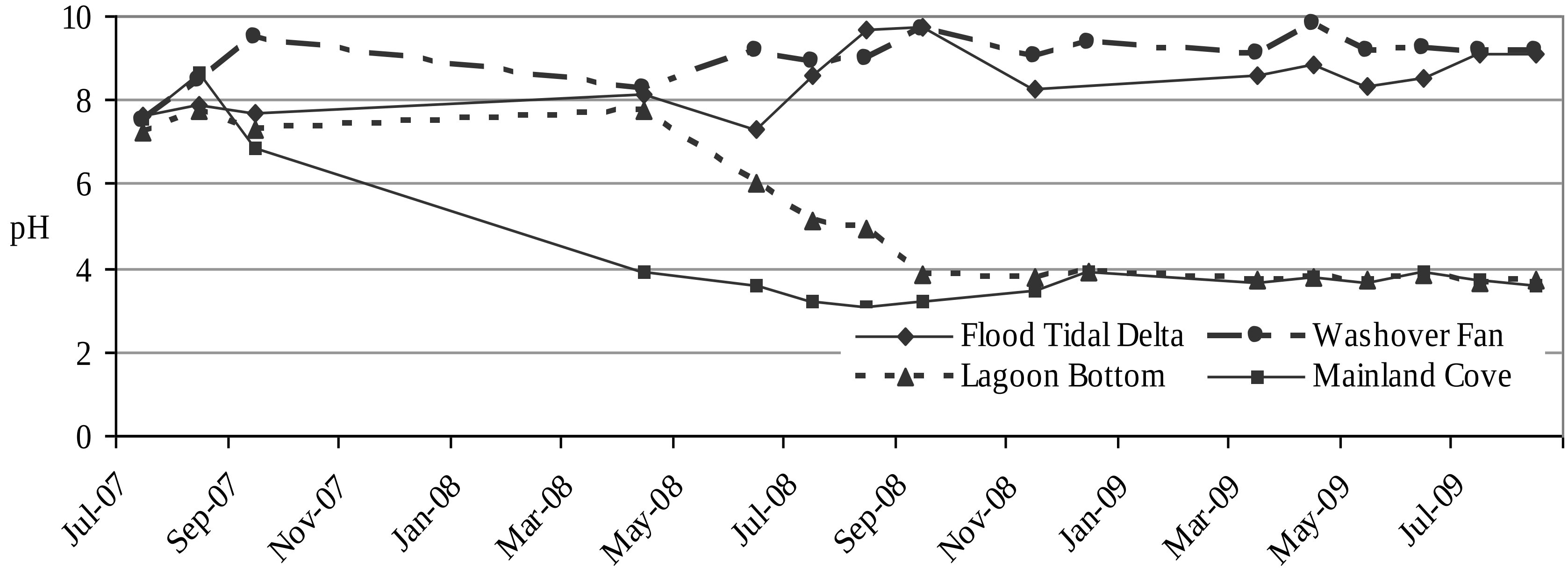


Figure 1.12. Monthly mean leachate pH of Quonochontaug Pond simulated dredged material. Rainfall leachate was collected and analyzed after a rain event. Leachate was not collected during the winter. Fine textured (low energy units) mesocosms were mixed every spring (April) to break up compacted material.

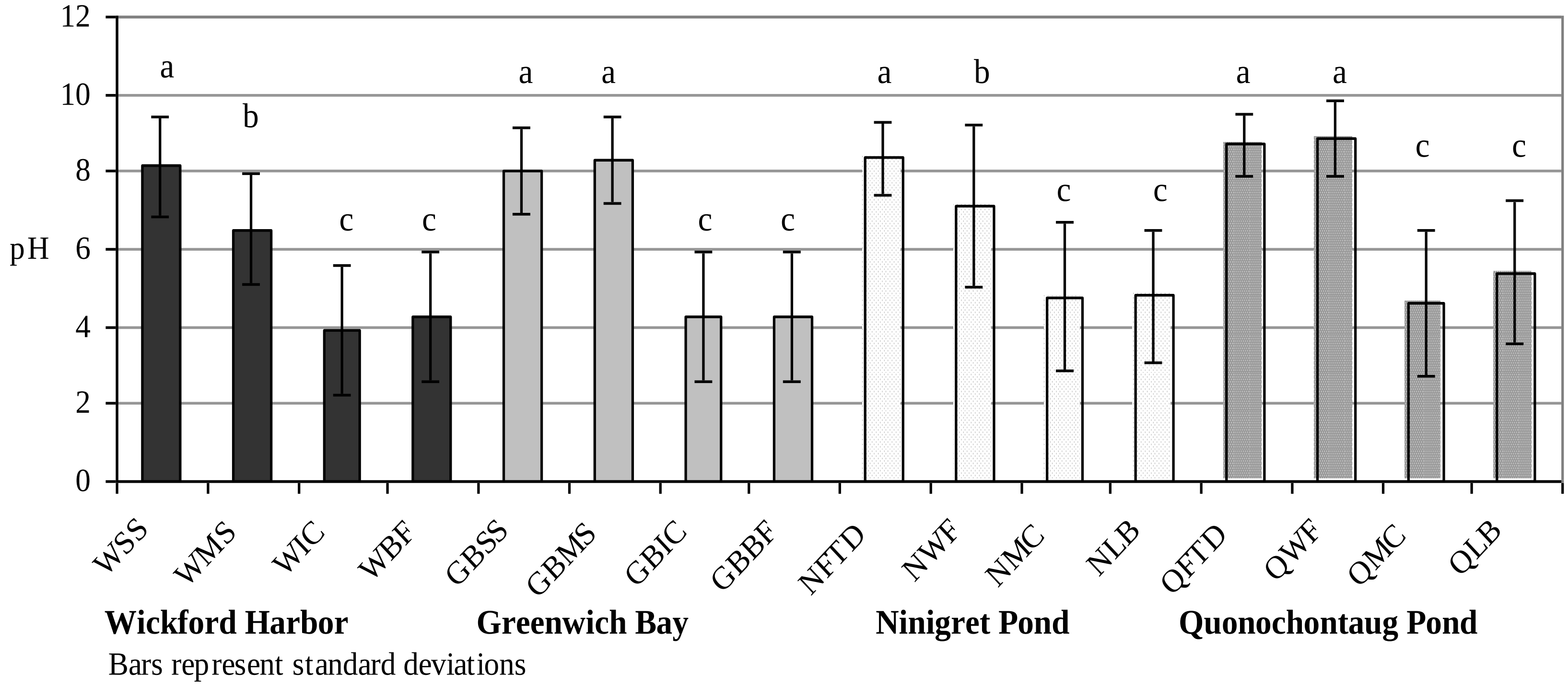


Figure 1.13. Mesocosm monthly mean leachate pH values from simulated dredged materials, 2007-2009. Leachate data follows similar trends to laboratory incubation pH. ANOVA and Bonferroni test of differences among all landscape units. Different letters indicate significant differences ($p < 0.05$) among landscape units. n = 52 - 90 observations per landscape unit. High energy = Spit (SS), Mainland Shoreface (MS), Flood Tidal Delta (FTD), and Washover Fan (WF). Low energy = Mainland Cove (MC), Lagoon Bottom (LB), Inland Cove (IC), and Bayfloor (BF).

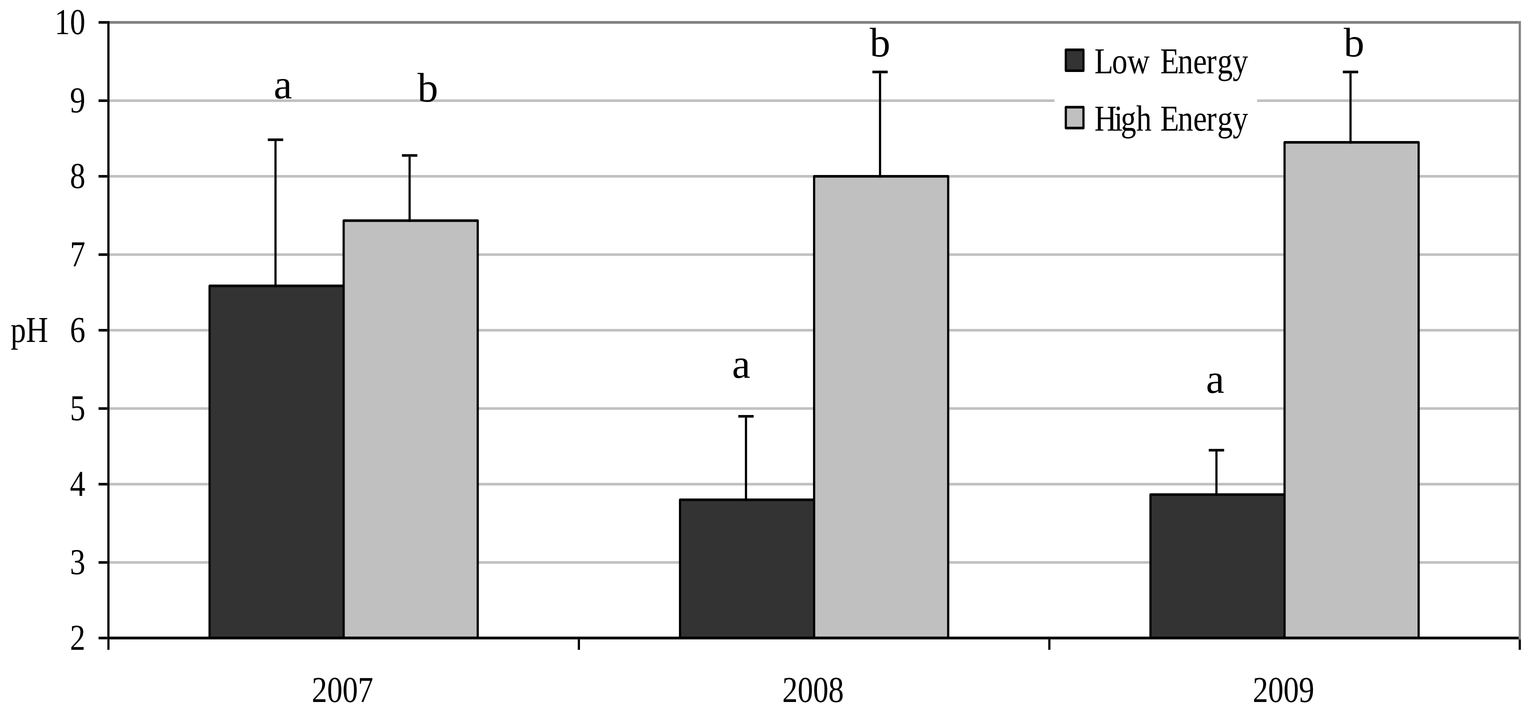


Figure 1.14. Mean mesocosm leachate pH values of high energy and low energy landscape units, grouped by year. Leachate from low energy units showed a drop (<4.0) in the second and third years while high energy units rose in pH. Low energy samples include those from: Cove, Bottom and Bayfloor landscape units. High energy units include those sampled from: Mainland Shoreface, Spit, Flood Tidal Delta and Washover Fan landscape units. Different letters indicate significant differences (t-test; $p < 0.05$) within years.

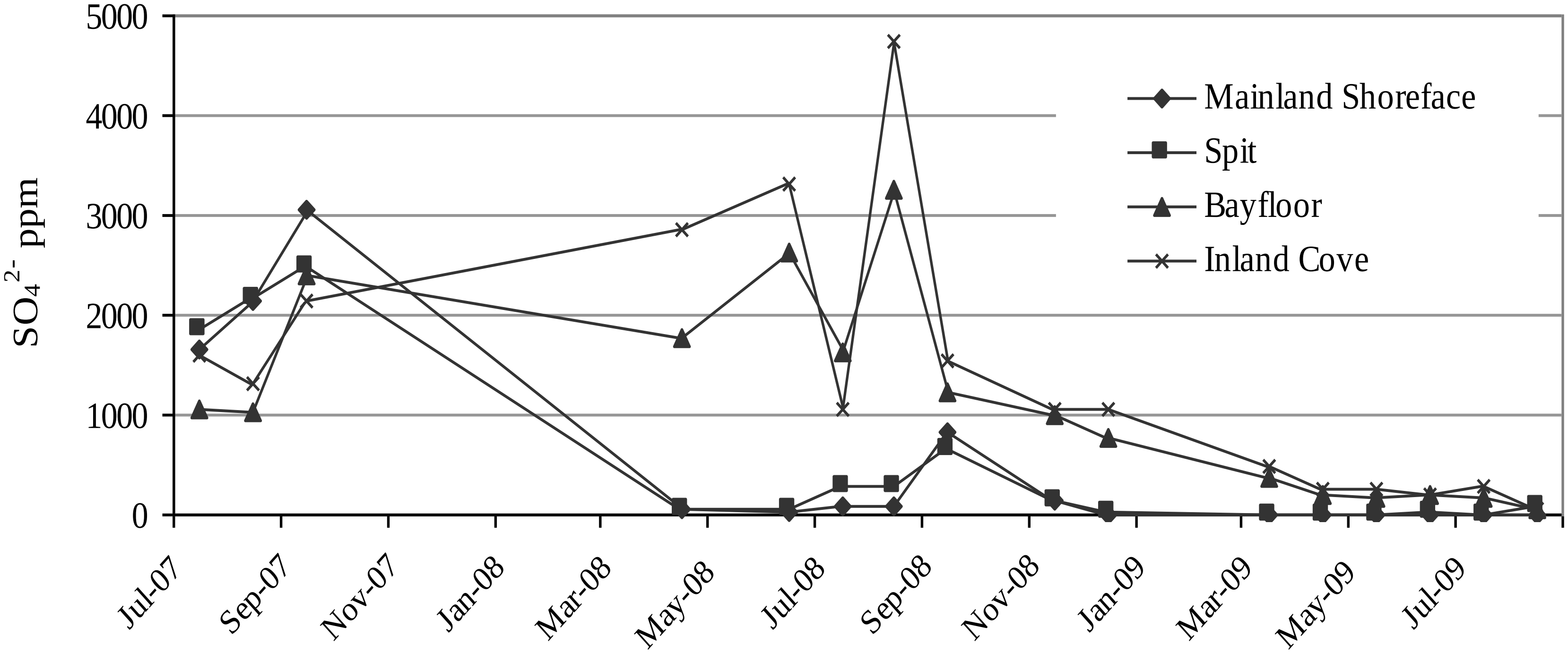


Figure 1.15. Monthly mean leachate sulfate content of Wickford Harbor simulated dredged materials. Rainfall leachate was collected and analyzed after a rain event. Leachate was not collected during the winter. Fine textured mesocosms (low energy units) were mixed every spring (April) to break up compacted material.

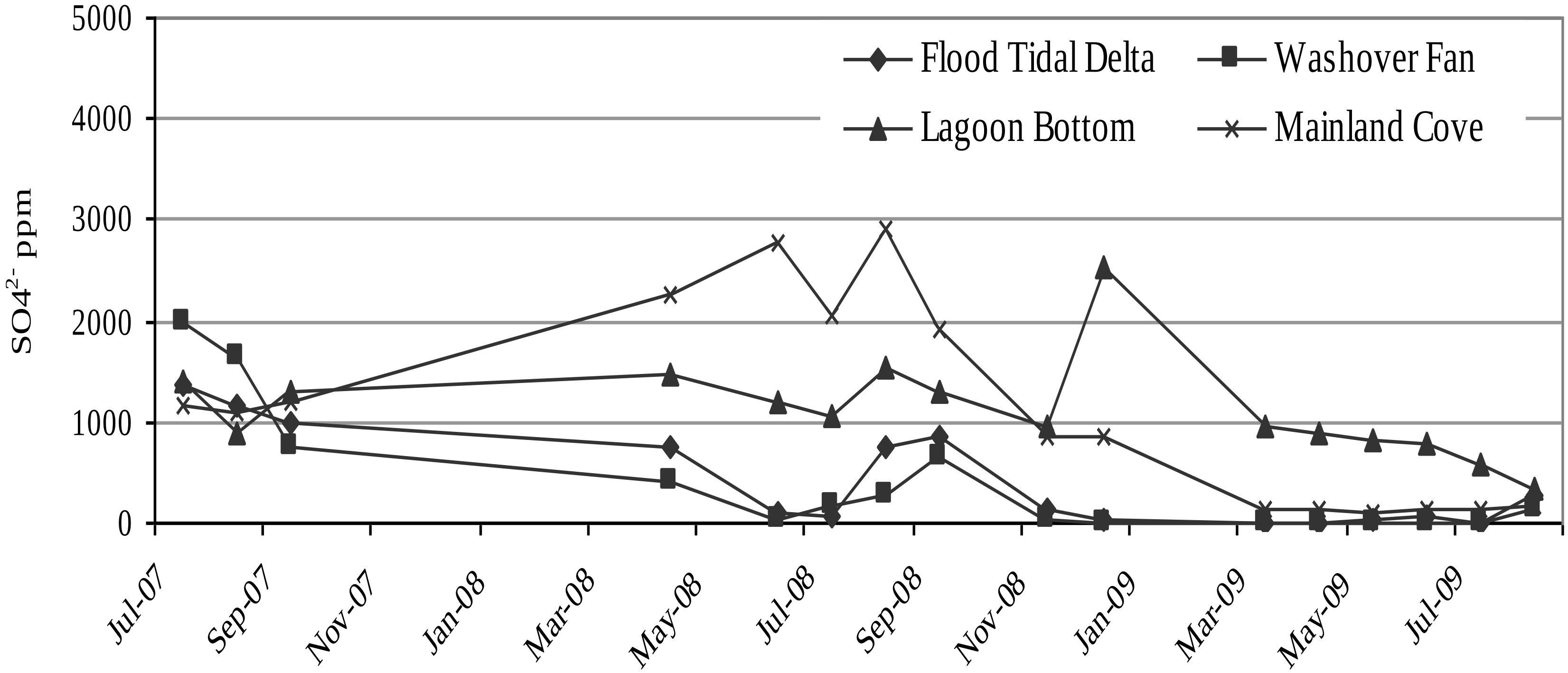


Figure 1.16. Monthly mean leachate sulfate content of Quonochontaug Pond simulated dredged materials. Rainfall leachate was collected and analyzed after a rain event. Leachate was not collected during the winter. Fine textured mesocosms (low energy units) were mixed every spring (April) to break up compacted material.

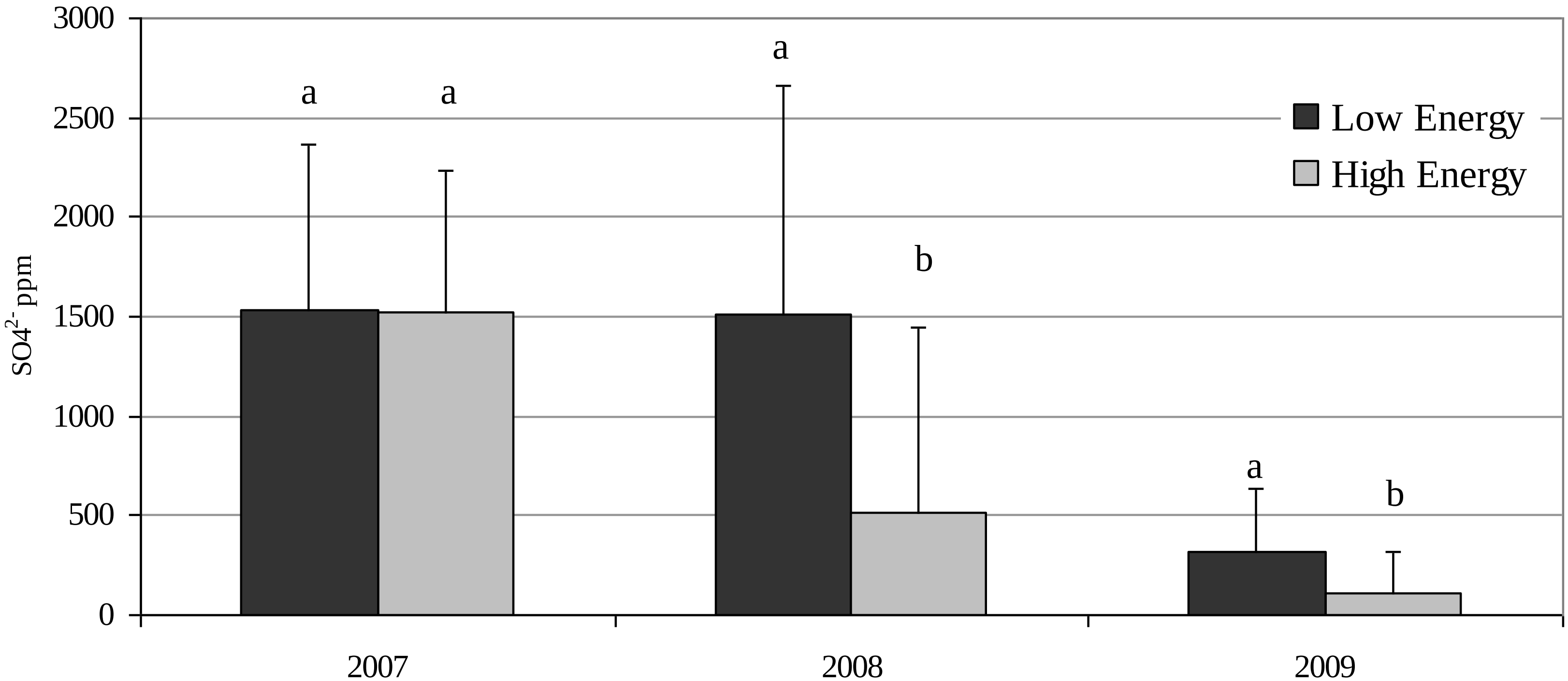


Figure 1.17. Mean sulfate content of high and low energy units grouped by year. Leachate from low energy units had higher sulfate content during the second and third years than high energy units. Low energy units includes material sampled from: Cove, Bottom and Bayfloor landscape units. High energy includes material sampled from: Mainland Shoreface, Spit, Flood Tidal Delta and Washover Fan landscape units. Different letters indicate significant differences(t-test; $p < 0.05$) within years

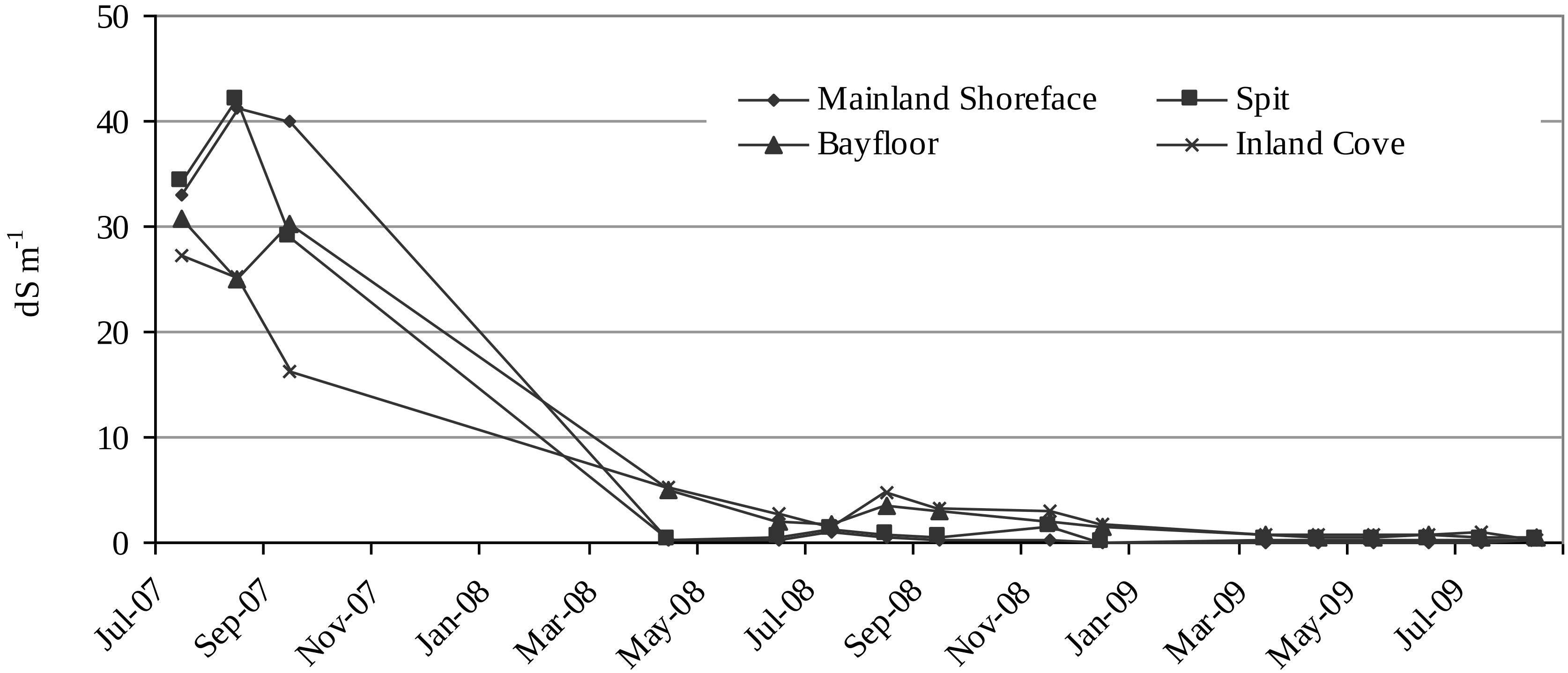


Figure 1.18. Monthly mean leachate conductivity of Wickford Harbor simulated dredged materials. Rainfall leachate was collected and analyzed after a rain event. Leachate was not collected during the winter. Fine textured mesocosms (low energy units) were mixed every spring (April) to break up compacted material.

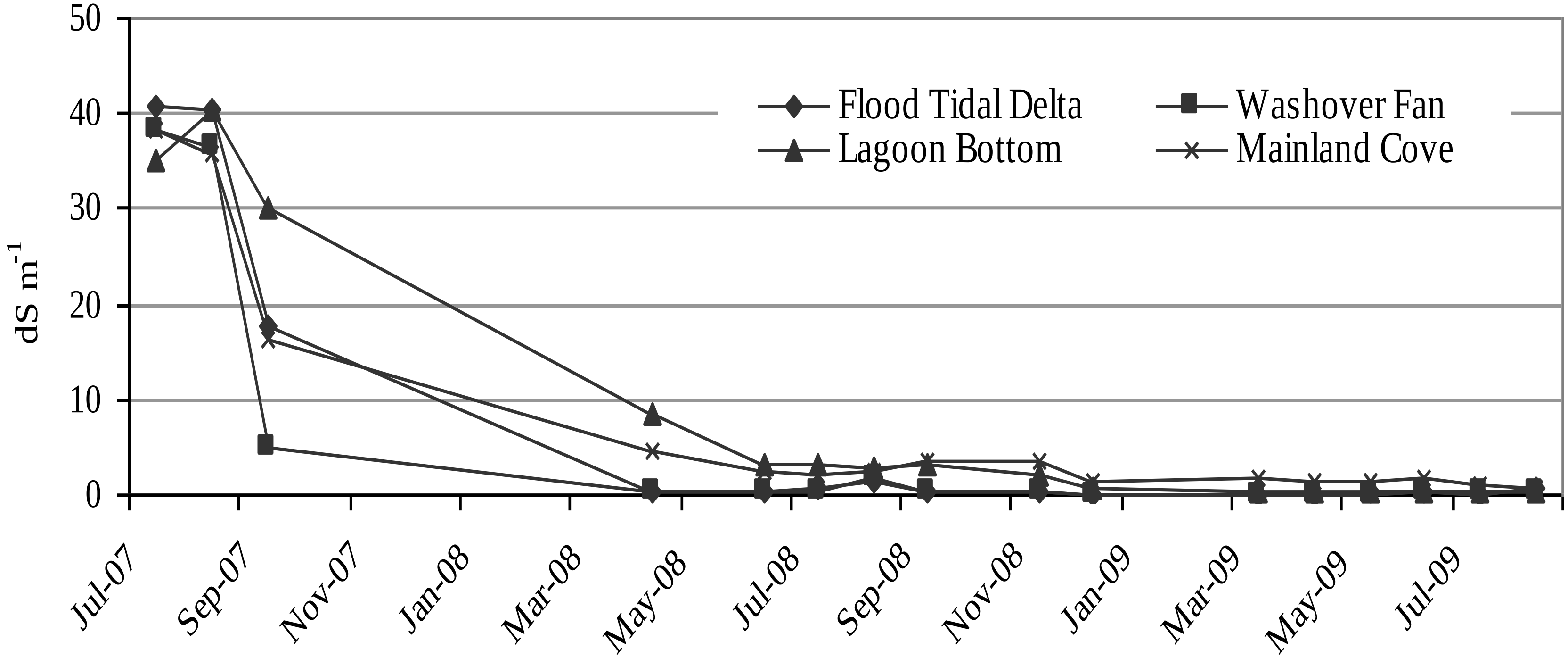


Figure 1.19. Monthly mean leachate conductivity of Quonochontaug Pond simulated dredged materials. Rainfall leachate was collected and analyzed after a rain event. Leachate was not collected during the winter. Fine textured mesocosms (low energy units) were mixed every spring (April) to break up compacted material.

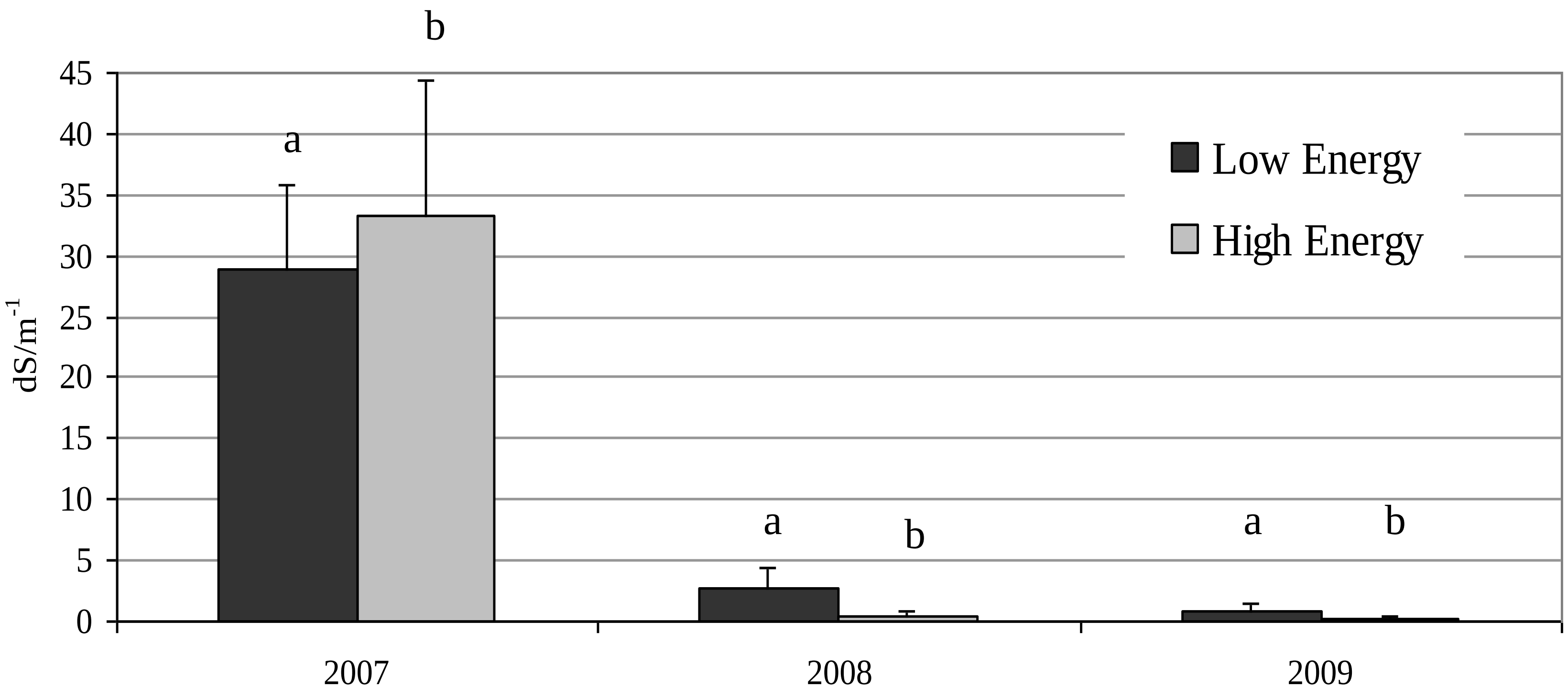


Figure 1.20. Mesocosm mean leachate conductivity content of high and low energy landscape units grouped by year. Coarse textured high energy units initially had higher conductivity possibly due to rapid dewatering resulting from a sandy texture. Low energy environments, having a finer texture had higher conductivity in the second and third years. Low energy units include material sampled from: Cove, Bottom and Bayfloor landscape units. High energy material was sampled from: Mainland Shoreface, Spit, Flood Tidal Delta and Washover Fan landscape units. Different letters indicate significant differences (t-test; $p < 0.05$) within years.

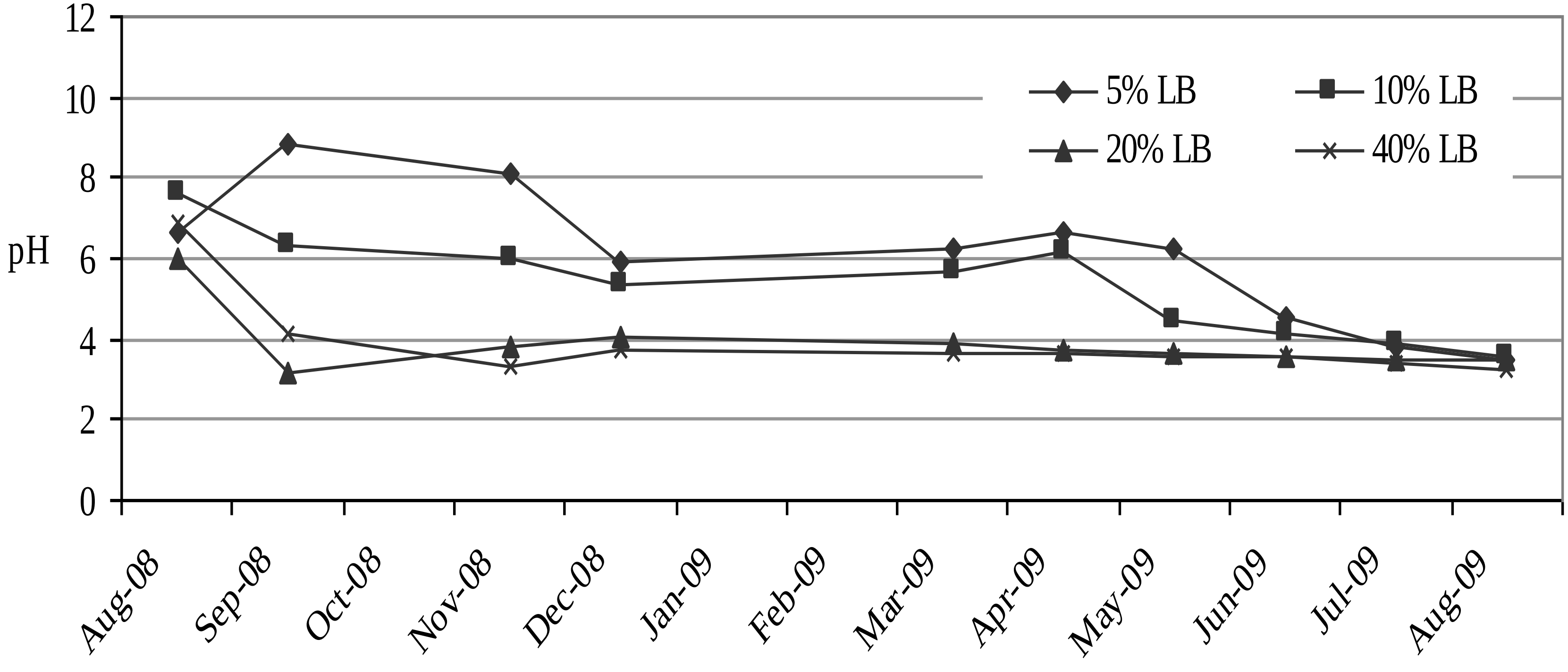


Figure 1.21. Monthly mean leachate pH of mixed dredged materials. Samples were collected from the upper 25 cm of Lagoon bottom (LB), and Washover fan flat (WF) soils in Ninigret Pond, mixed in a bucket at different concentrations by volume. Mixtures consisted of 5% LB : 95% WF; 10% LB : 90% WF; 20% LB : 80% WF; and 40% LB : 60% WF. Leachate was collected after a rain event.

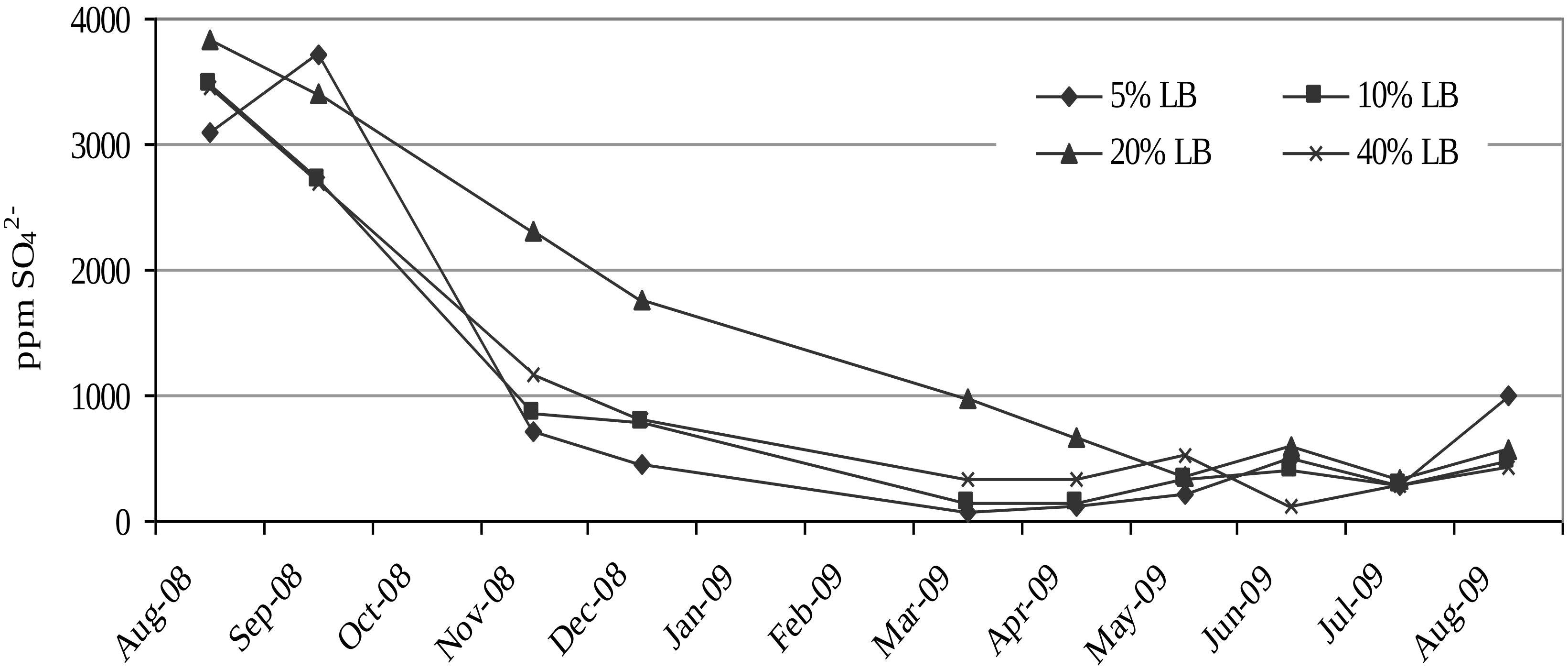


Figure 1.22. Monthly mean leachate sulfate content of the mixed dredged materials. Samples were collected from the upper 25 cm of Lagoon bottom (LB), and Washover fan flat (WF) soils in Ninigret Pond, mixed in a bucket at different concentrations by volume. Mixtures consisted of 5% LB : 95% WF; 10% LB : 90% WF; 20% LB : 80% WF; and 40% LB : 60% WF. Leachate was collected after a rain even

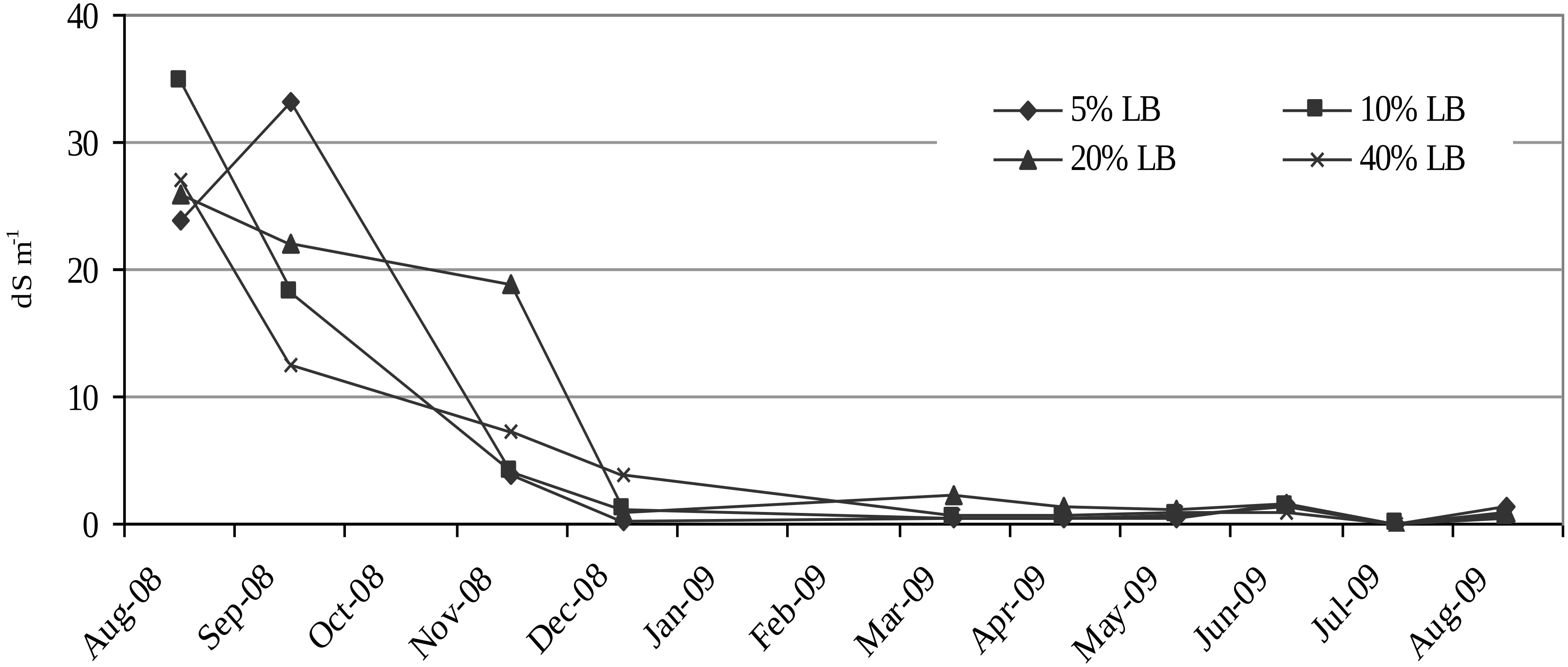


Figure 1.23. Monthly mean leachate conductivity (d S m^{-1}) of the mixed dredged materials. Samples were collected from the upper 25 cm of Lagoon bottom (LB), and Washover fan flat (WF) soils in Ninigret Pond, mixed in a bucket at different concentrations by volume. Mixtures consisted of 5% LB : 95% WF; 10% LB : 90% WF; 20% LB : 80% WF; and 40% LB : 60% WF. Leachate was collected after a rain event.

CHAPTER 2:

SUBAQUEOUS SOIL AND SHELLFISH GROWTH

ABSTRACT

Shellfish aquaculture is a growing industry in Rhode Island. While many aquaculture farms have been established in coastal lagoons and in Narragansett Bay, information regarding the best areas (highest productivity) is lacking to resource managers. Utilization of a subaqueous soil survey and accompanying shellfish productivity interpretations would provide information regarding growth rates, soil type, and bottom acreage of soil- landscape units with the highest shellfish productivity. Relationships between subaqueous soil and shellfish growth were investigated on five different subaqueous soil-landscape units in two coastal lagoons in Rhode Island. Oysters (*Crassostrea* virginica) were grown in trays resting on the bottom while quahogs (hard clam, *Mercenaria mercenaria*) were grown in the soil. Oyster shell height was measured on 90 individuals on each soil type once in early summer, and again in late summer over a 2 year period and growth rates calculated. Quahogs were measured initially and then again after a year period, and growth rates calculated. Biovolume of oysters and quahogs was measured and final live numbers recorded. Chlorophyll *a*, total suspended solids, temperature, salinity, pH, and dissolved oxygen content were measured to assess water quality. I found that oyster growth rates correlated to increases in sand content, while depressed growth occurred on fine textured soils. Quahog growth rates showed similar trends among soils, in that faster growth and decreased mortality occurred on coarse textured subaqueous soils.

No quahogs were recovered from Lagoon Bottom landscape unit in Ninigret Pond due to extensive mortality. Oyster growth rates varied among soils and between years, suggesting environmental factors influenced growth rates. These data suggest that subaqueous soil surveys should be utilized by estuarine resource managers to site the most productive areas for shellfish aquaculture.

INTRODUCTION

Over the last decade the aquaculture industry in Rhode Island has shown dramatic increases. In 2007 the value of Rhode Island aquaculture exceeded one million dollars for the second consecutive year with a value close to $13,000 per acre, representing the 10^{th} double digit increase in 12 years (Alves, 2007). Of the 30 farms in Rhode Island, 123 acres of subtidal land were leased in 2007 with nearly all (99%) of the total aquaculture consisting of the eastern oyster (*Crassostrea virginica*). The hard clam (quahog, *Mercenaria mercenaria*) accounted for the remaining 1% of Rhode Island aquaculture (Alves, 2007). Although shellfish aquaculture appears to be quite successful, there are little data available to farmers for determining the location of aquaculture farms in the most productive areas of the estuary. With the recent addition of subaqueous soil mapping and characterization, a soil interpretation for shellfish aquaculture productivity is needed.

Oysters are viewed as reef forming organisms that exist mostly on sand, hard mud, or reef substrates, and are generally absent from soft mud or areas of high sedimentation rates (Brooks, 1905; Schwind, 1978; Burrell, 1986; Stanley and Sellers, 1986; Harris, 2003). The best oyster habitat appears to be areas of marine estuaries that are generally found with depths from 0.6 - 2 meters, salinities of 10 - 27 ppt, temperatures ranging from 20 – 30 °C, with a clean, hard substrate (preferably oyster shells) (Kennedy et al., 1996; Shumway, 1996; Stanley and Sellers, 1986; Easter Oyster Biological Review Team, 2007). Soft 'mud' as found in Lagoon Bottom and Mainland Cove subaqueous soil-landscape units is generally avoided due to smothering of the oysters due to subsidence in the bottom (Schwind, 1978). Oyster growth is dependent on food supply (seston) and temperature much like other shellfish including the hard clam (Grizzle and Morin, 1989; Kennedy et al., 1996; Rice and Pechenik, 1992).

Many different factors contribute to the growth of shellfish including physical parameters of the water column (temperature, salinity, pH, turbidity) and biological factors such as seston concentration (all suspended particulate matter including plankton and organic detritus) (Grizzle and Morin, 1989; Rice and Pechenik, 1992; Kennedy et al., 1996). A few studies have focused on investigating relationships between shellfish growth, abundance, and sediment type (Pratt, 1953; Pratt and Campbell, 1956; Wells, 1957; Grizzle and Morin, 1989; Grizzle and Lutz, 1989). These studies utilized growth rates and abundance data of the quahog in hopes of correlating growth and other environmental factors such as substrate characteristics (Pratt and Campbell, 1956; Wells, 1957; Grizzle and Morin, 1989).

Pratt (1953) analyzed data from a dredge survey of quahogs (hard clam, *Mercenaria mercenaria*) in Narragansett Bay, Rhode Island to relate abundance and growth to substrate types. Pratt (1953) concluded that quahog abundance was greatest in fine textured sediment. These survey data suggest that the hard clam population density is correlated with the particle size of the bottom sediment (Pratt, 1953). Studying the growth in different substrates, Pratt (1953) calculated that quahogs grew 24% faster in sands than in mud. As a follow up, Pratt and Campbell (1956) conducted growth studies with quahogs over a five year period in Narragansett Bay, Rhode Island in order to identify sediment-shellfish interactions. Different sediment types were transplanted into wooden boxes at one study site (landscape unit) in order to minimize the variability from differences in water quality. Quahogs were placed into these boxes filled with local sediment and also the transplanted sediment. Results corroborated with earlier findings that a negative relationship between growth and particle size existed, with increases in silt-clay content associated with retardation in growth (Pratt, 1953; Pratt and Campbell, 1956). These differences were attributed to feeding mechanisms related to an observed increase in the expulsion of pseudofeces from quahogs in the finer textured material suggesting silt particles inhibited growth (Pratt and Campbell, 1956).

Similar clam abundance experiments were conducted in Chincoteague Bay in Maryland by Wells (1957). Wells (1957) concluded that clam abundance in Chincoteague Bay was highest in sandy bottoms, reflecting opposing findings to those of Pratt (1953) in that densities were highest in silt. These differences as Wells (1957) states "either reflect a difference in classifying the substrate or may reflect the 'muddy' character of the Narragansett Bay bottom". Both Pratt (1953) and Wells (1957) found that densities of quahogs were greatest in substrates that contained shell-sand mixtures.

In more recent studies regarding subaqueous soil and shellfish growth, Grizzle and Morin (1989) transplanted different soil types characterized as either mud, muddy sand, or sand into aluminum cylinders at one site in Great Sound, New Jersey. Quahog growth rate was measured over a 15 week period. No significant differences were found for growth in different sediment types, although faster growth rates were observed in coarser textured material (Grizzle and Morin, 1989). Grizzle and Lutz (1989) concluded that sediment type affects growth under some conditions, but horizontal seston fluxes have a stronger effect on growth. It was determined that horizontal seston fluxes explained growth better than soil type. Horizontal seston flux was defined as the rate of seston (suspended food), flowing horizontally that occurs within the feeding zone of the animal (Grizzle and Lutz, 1989). A moderate horizontal seston flux of 90-130 mg cm^2s^{-1} particulate organic matter and sand attributed to fastest growth in this experiment, while low and high rates showed retardation in growth (Grizzle and Lutz, 1989). Slower growth in finer textured soil results from slower current speeds and greater deposition of particulate organic matter.

Current views on the shellfish-soil relationship are that the increased growth in quahogs associated with sandier sediment in the earlier studies has been reinterpreted to be a secondary result of sandier soil being associated with higher current velocities and thus more food availability (Grizzle and Lutz, 1989; Rice, 1992; Rice and Pechenik, 1992). This suggests that subaqueous soil type may serve as a surrogate for determining areas of favorable seston fluxes, and could thereby be used to predict areas of the subtidal estuary with the highest potentials for shellfish growth. The shellfish-subaqueous soil interpretation provided by a subaqueous soil survey may prove invaluable to future and current shellfish aquaculture and restocking efforts (Demas and Rabenhorst, 1999; Bradley and Stolt, 2003). This study is aimed at determining differences in growth rates of quahogs and oysters on different subaqueous soils in coastal lagoons of Rhode Island.

MATERIALS AND METHODS

Subaqueous soil-shellfish growth relationships were investigated in two coastal lagoons in Rhode Island, Ninigret and Quonochontaug Ponds (Figure 2.1). Four 93 m^2 plots were leased from the Coastal Resources Management Council (CRMC) on four subaqueous-soil landscape units in each pond. In Ninigret Pond, aquaculture lease sites were on Mainland Cove (NMC), Lagoon Bottom (NLB), Washover Fan Slope (NWFS), and Washover Fan Flat (NWF) landscape units (Figure 2.2). In Quonochontaug Pond, shellfish growth rates were investigated on Washover Fan Slope (QWFS), Washover Fan (QWF), Lagoon Bottom (QLB), and Submerged Mainland Beach (QSMB) landscape units (Figure 2.3). In this chapter for each pond, the term ‘landscape unit’ is interchangeable with ‘aquaculture site’, when referring to shellfish growth and water quality measurements, as each landscape unit represents an individual aquaculture site within each pond (Figure 2.2, 2.3).

The Eastern oyster (*Crassostrea virginica*) and quahog (hard clam, *Mercenaria mercenaria*) were used to test growth and subaqueous soil relationships due to their local importance, historical significance, and current aquaculture in the area (Alves, 2007; DeAngelis et al., 2007; Rice et al, 2000). Soils were collected and sampled at each study site with a vibracore (Lanesky et al., 1979; Figures 2.2, 2.3). Descriptions and characterizations were made according to the Soil Survey Manual (Soil Survey Division Staff, 1993) including horizination, horizon depth, color, shell and rock fragments, redoximorphic features, texture, and n-value. All samples were stored in a -15 ºC freezer until analysis.

In June 2008 approximately 11,000 oysters were purchased from a local aquaculturist in Ninigret Pond. Four liters of biovolume of juvenile oysters ($\bar{x}$ = 30 mm height) were placed into twenty four 91 x 47 x 6.4 cm plastic grow-out bags with a mesh size of 0.95 cm. There were approximately 115 live oysters per liter of biovolume. One grow-out bag was transferred to each aquaculture tray at the prospective aquaculture plots. Each plot contained three 1 x 1 x 0.2 meter plastic aquaculture trays (Aquatray® system, purchased from Coastal Aquacultural Supply, Warwick, Rhode Island) that stand 13 cm above the soil surface on PVC legs for a total of 24 Aquatrays® (Figure 2.4).

Approximately 2,400 screened, seed sized quahogs were purchased from the Roger Williams University wet lab. The quahogs used in this study were a recognized subspecies of *Mercenaria mercenaria, Mercenaria mercenaria notata,* having brown-chestnut colored chevron markings on the shell, which aided in identification during retrieval (Rice, 1992; Harte, 2001). Quahog size is typically measured by height (dorso-ventral), length (antero-posterior), width (umbo) or by total body volume (Grizzle et al., 2001). Since legal sized quahogs (25.4 mm) are measured by width in Rhode Island, this dimension was used in this study to determine and measure quahog growth. The mean width of the purchased quahogs was 9.1 mm, with an average of 600 quahogs per liter of biovolume. In August 2008, 0.05 liters of quahog biovolume was placed into the soil in 2 m x 2 m plots at each of the aquaculture sites, and covered with predator netting (0.5 x 0.5 cm mesh) staked to the bottom. One quahog plot was constructed per landscape unit for a total of four plots per lagoon, seven in total. Quonochontaug Lagoon Bottom quahogs were grown in a grow-out bag and placed into the soil. This was done due to the depth of the site (3 meters) and difficulty retrieving the animals without using scuba equipment. Due to the difficulty of retrieving small quahogs, only one measurement was performed in October 2009 to assess growth rates. Quahogs were retrieved using a modified quahog rake to obtain small sized quahogs that did not grow to the minimum hinge width (25.4 mm) for legal harvest. The quahog rake was modified by tying heavy gauge wire in between the steel mesh of the rake, making the minimum opening of the rake 9 mm.

Bi-weekly cleaning of the Aquatrays® and predator netting was performed to remove biofouling using hand brushes while snorkeling. During this time, water quality measurements were taken using a YSI Environmental Model 556 meter (YSI Environmental, Yellow Springs, OH) including water temperature, dissolved oxygen (D.O.), pH, and salinity. Secchi depth readings were also recorded.

Water samples were collected for total suspended solid (TSS) analysis using a one liter Nalgene bottle. Samples were kept cool in a refrigerator until analysis by filtration within 24 hours. Exactly 300 ml of sample water was filtered through a dried (105 ºC) pre-weighed Millipore glass fiber filter using a Buchner glass funnel. TSS was calculated as dry weight (at 105 ºC) after filtration subtracted by initial dry weight. Two replicates were performed for each water sample collected.

Chlorophyll *a* was sampled at the surface using a 150 ml amber glass bottle. Exactly 50 ml of water was filtered immediately after returning from the field through glass-fiber filters. Filters were folded in half, wrapped in foil and kept in a freezer until processing. Two replicates were performed for each water sample. Determination of the chlorophyll *a* collected on the filters was made using spectrophotometric determination of the acetone-extracted chlorophyll (Clesceri et al., 1998; Payne, 2007).

Mean annual water temperature was recorded by iButtons® (Embedded Data Systems, Lawrenceburg, KY) on six landscapes from June 2008 – August 2009 (see Chapter 3). Water temperature was recorded every 4 hours. Mean annual, mean summer, and mean winter water temperatures were calculated. Statistical analyses of water temperatures were carried out using t-tests and analysis of variance (ANOVA)

In July 2008, 30 oysters were randomly sampled by hand from each aquaculture tray and the long axis of the shell was recorded to determine growth rates. These data were pooled for each aquaculture site (consisting of the 3 Aquatrays®) for statistical analysis of a population size of 90 individuals per aquaculture site (landscape unit). Shell measurements were recorded again in October 2008. In 2009, oyster shell size was measured in June, and again after 15 weeks in October.

During the first couple years of growth, oyster growth rates tend to be linear before slowing as they approach their maximum size. Many studies of shellfish growth have utilized a von Bertalanffy (and modified von Bertalanffy) growth curve to compensate for differences in yearly growth (von Bertalanffy, 1938; Jones et al. 1989; Rice et al., 1994; Rice and Pechenik, 1992; Prajneshu and Venugopalan, 1999;

Kraeuter et al., 2007; Henry and Nixon, 2008). I used juvenile oysters and measured growth for two years. During this time, the oysters never reach a point where the growth is best illustrated by a logistic growth model. Thus growth (year to year) was assumed to be linear during the study period, and a von Bertalanffy (and modified von Bertalanffy) growth model was not applied.

For statistical analysis and comparisons among landscape units, mean oyster growth rates were compared among aquaculture plots within study sites. The following equation was used to calculate oyster growth rates on each subaqueous landscape unit:

$$\text{Oyster growth} = (L_2 - L_1) / (t_2 - t_1)$$

Oyster growth equals average shell height of 90 individuals in July 2008 (L_1), subtracted from the average shell height (of 90 individuals) in October 2009 (L_2), and divided by the number of days ($t_2 - t_1$) (Grizzle et al., 2001). Results are recorded as growth in µm day^{-1}. Mean growth rate incorporates late fall, winter, and early spring growth as well as the faster summer growth rates. Summer oyster growth in this study is defined as mean population shell height (of 90 individuals) in June, subtracted from the mean shell height measured in October of that year, divided by the number of growing days. Results are recorded as growth in µm day^{-1} and converted to mm month^{-1} for comparisons to other studies. For comparisons between ponds, mean oyster growth was averaged among landscape units within ponds where the mean growth rate (in each pond) was compared using a t-test.

Total number of live oysters in each aquaculture tray was recorded at the end of the experiment in October 2009. Comparisons among oyster trays and landscape units between ponds were made using ANOVA. Data from the Washover Fan Slope landscape unit in Ninigret Pond was not incorporated within the statistics due to the loss of two oyster trays.

Oyster biovolume was recorded at the end of the experiment in October 2009 at each aquaculture plot. Biovolume was measured using a 12 liter graduated cylinder. Total numbers of live oysters were also recorded at this time to determine an estimate of oyster mortality at each aquaculture plot. Analysis among landscape units between ponds was carried out using analysis of variance (ANOVA). Data from the Washover Fan Slope landscape unit was not used in the statistics due to the loss of two oyster trays.

Quahog growth rate was determined using the following equation:

$$\text{Quahog growth} = (L_2 - L_1) / (t_2 - t_1)$$

Quahog shell growth (hinge width) equals initial and final width (L_1, L_2) divided by the number of days ($t_2 - t_1$) (Grizzle et al., 2001). Initial mean shell width (9.1 mm) and final mean shell width (October 2009) were used as variables for L_2 and L_1 on each subaqueous landscape unit. Quahog growth was calculated as $\mu m\ day^{-1}$ and converted to mm $month^{-1}$ for comparisons to other studies. Statistical analysis of quahog populations (shell sizes) among landscape units between ponds was carried out using ANOVA.

Assessment of growth differences among landscape units was carried out using mean growth and by statistical comparisons of populations using ANOVA and Bonferroni tests using Analyze-it® (Analyze-it Software, Ltd. Leeds UK), Microsoft Excel (Microsoft, 2002) and SAS (SAS 9.1, SAS Institute Inc., Cary, NC, USA).

Pearson's correlation and regression analysis were performed to identify covariance and predictions of shellfish growth based on various soil and water quality parameters. Water quality parameters were analyzed among landscape units within and between ponds and years using non-parametric statistics and t-tests.

RESULTS AND DISCUSSION

Site Characterization

Tidal ranges in Quonochontaug Pond are less than 1 meter while tidal ranges in Ninigret Pond are 7 -16 cm due to constriction from the inlet (Boothroyd et al., 1985). Quonochontaug Pond has a deeper basin, with a larger and deeper inlet to the ocean than Ninigret Pond. Landscape units identified and used in this study consisted of: Lagoon Bottom, Mainland Cove, Washover Fan Flat, Washover Fan Slope and Submerged Mainland Beach. These landscape units represent 76% and 62% the total bottom area in Ninigret and Quonochontaug Ponds, respectively. Water depths of the aquaculture plots in Ninigret Pond ranged from 0.96 - 1.04 meters (Table 2.1). In Quonochontaug Pond, water depth ranged from 0.79 – 1.49 meters in three of the sites, and was over 3 meters at the Lagoon Bottom site (Table 2.1).

Soil textures within 25 cm of the soil surface ranged from coarse sandy loam to silt, across study sites (Table 2.1). Low energy environments such as Mainland Cove and Lagoon Bottom had a finer texture (more silt and clay) than the Washover Fan and Submerged Mainland Beach landscape units. Higher percentages of carbon and carbonates were found in the fine textured soils of Coves and Bottoms (Table 2.2). Lagoon Bottom contained the highest percentages of carbon and carbonates, while

Washover Fan Slope contained the least (Table 2.2). Eelgrass is commonly found growing in Lagoon Bottom and Mainland Cove soils, this vascular plant may provide some of the carbon (Peterson et al., 1984; Bradley, 2001). Sulfidic materials were recognized in the Lagoon Bottom, Mainland Cove, and Washover Fan landscape units in Ninigret Pond and in Lagoon Bottom and Submerged Mainland Beach landscape units in Quonochontaug Pond by laboratory incubation pH < 4.0 (Soil Survey Staff, 2010).

Sulfiwassents and Psammowassents are the most commonly encountered subaqueous soil great groups found in these systems (Bradley, 2001; Mapcoast, 2009; Soil Survey Staff, 2010). These were also the most common great groups found in the aquaculture sites (Table 2.1). At the subgroup level, soils classified as: Typic Sulfiwassents (Lagoon Bottom in Ninigret and Quonochontaug Ponds; Haplic Sulfiwassents (Mainland Cove in Ninigret Pond); Sulfic Psammowassents (Washover Fan in Ninigret Pond); Fluventic Psammowassents (Washover Fan in Quonochontaug Pond); and Aeric Haplowassents (Submerged Mainland Beach in Quonochontaug Pond) (Table 2.1). Landscape unit boundaries typically also define soil type boundaries (Bradley and Stolt, 2003). Therefore, soil types are expected to be the same within each landscape unit.

Water Quality

Water quality parameters were monitored to identify differences among aquaculture plots (landscape units) that may affect shellfish growth. Temperature influences shellfish growth by regulating the rates of metabolic processes thus influencing shell deposition and growth, and is usually highly correlated to shellfish growth (Rice, 1992; Grizzle e al., 2001). Mean annual water temperature was recorded at six aquaculture plots to identify differences between landscape units. Mean annual water temperature was similar across all landscape units with an average of 11.8 ºC (Table 2.3). In Ninigret Pond, Lagoon Bottom was significantly warmer than Washover Fan while in Quonochontaug Pond, Lagoon Bottom was significantly cooler than all other landscape units (Table 2.3). Mean summer water temperatures (June, July, and August) varied over landscape units ranging from 19.5 – 22.3 ºC (Table 2.3). Mean winter water temperature (December, January, and February) was significantly different between Ninigret Washover Fan and Ninigret Lagoon Bottom. Warmer temperatures were recorded in Quonochontaug Pond during the winter than in Ninigret Pond (Table 2.3). Both Lagoon Bottom and Submerged Beach landscape units were significantly warmer than the Washover Fan and Washover Fan Slope landscape units in Quonochontaug Pond (Table 2.3).

Optimum growing temperatures range from 10 – 25 ºC for the quahog with growth ceasing below 9 ºC (Jones et al., 1989; Rice, 1992; Grizzle et al., 2001). In Quonochontaug Pond, there was an average of 151 days < 9 ºC among landscape units, while in Ninigret Pond, there was an average of 152 days < 9 ºC among Washover Fan and Lagoon Bottom landscape units. Oysters can survive a wide range of temperature ranging from -2 – 36 ºC with optimum growing temperatures ranging from 20 - 30 ºC (Stanley and Sellers, 1986; Shumway, 1996; Eastern Oyster Biological Review Team, 2007). With mean summer temperatures ranging from 19.5 – 22.3 ºC (Table 2.3), these sites are within optimum growing temperatures for oysters and quahogs.

Oysters can do well over a wide range of salinities, 0 – 42 ppt (Shumway, 1996), while quahogs thrive in salinities ranging from 18 – 32 ppt (Rice, 1992; Grizzle et al., 2001). Water salinity in Ninigret and Quonochontaug Ponds ranged from 28 - 31 ppt across all aquaculture sites, with Quonochontaug Pond having slightly higher salinities possibly due to better flushing within this lagoon (Table 2.4). Salinities among coastal lagoons are typical of those found in the range for oysters and quahogs, but the higher salinities in these lagoons favors quahog growth, and is one reason why natural oyster populations diminished relative to clams in the coastal lagoons following permanent breachway stabilization (Lee, 1980).

In the coastal lagoons, water pH varied little over time (7.6 – 7.7; Table 2.3). Ocean water pH usually averages 8.2 (Bianchi, 2007). In pH studies using *Crassostrea virginica* and *Mercenaria mercenaria*, Calabrese and Davis (1966), determined that larval stages of both species grew well with water pH's ranging from 6.8 – 9.0 with similar tolerances for adults (Sumway, 1996). Lowered pH has been shown to adversely affect calcifying fauna such as shellfish, and the impact from increased CO_2 concentration has been widely documented (Gazeau et al., 2007; Fabry et al, 2008; Miller et al., 2009). The pH of the water column in the coastal lagoons however, should not be a limiting factor for shellfish growth at the present time.

Dissolved oxygen was measured among aquaculture sites within ponds (Table 2.4). Low oxygen levels or hypoxia in estuarine waters is often defined as D.O. < 2.0 mg/l (Baker and Mann, 1994; Bianchi, 2007). This threshold was not observed during my water quality measurements. Dissolved oxygen among landscape units was similar with a mean concentration of 6.7 mg/l (Table 2.4). Quahog growth is optimal when dissolved oxygen concentrations are above 2.4 mg/l (Rice, 1992; Rice and Pechenik, 1992). Adult oysters have been found to survive anoxic conditions > 28 days at 10 ºC, and 3 – 8 days at 30 ºC (Breitburg et al., 2003), while survival and growth of post-settlement oysters is severely affected by anoxia (Baker and Mann, 1994).

Chlorophyll *a* and total suspended solids were measured as indicators of food supply (phytoplankton abundance) and turbidity (suspended matter) of the water column (Bianchi, 2007). Suspended matter (silt) has been shown to decrease shellfish growth by interfering with feeding mechanisms, although oysters seem to tolerate suspended sediment better (Bricelj et al., 1984; Rice and Pechenik, 1992; Shumway, 1996). Reductions in growth of quahogs have been observed when silt concentrations were above 44 mg/l (Bricelj et al., 1984), while oysters can tolerate suspended silt concentrations up to 0.7 g/l (Mackin and Hopkins, 1961; Shumway, 1996). Chlorophyll *a* concentration (both years) ranged from 3.3 – 5.9 µg/l with a mean concentration of 4.2 µg/l across landscape units (Table 2.4). No significant differences in chlorophyll *a* concentration was found within study sites (Table 2.5, 2.6). These data suggest that phytoplankton abundance (food supply) was similar across sites, although Washover Fan Slope landscape units had had the greatest concentration of chlorophyll (Table 2.4). While working in a similar coastal lagoon in Rhode Island, Rheault and Rice (1996) suggested that continuous sampling of chlorophyll is needed at the same phase of tide to decrease variability in estimates of food concentrations. Total suspended solids (both years) ranged from 27.7 – 36 mg/l with a mean concentration of 29.5 mg/l across all landscape units (Table 2.4). No significant difference in TSS was found between landscape units within ponds (Tables 2.5, 2.6). Since the TSS were < 44 mg/l throughout the study, there did not appear to be any issue with excess suspended solids in the water column.

Statistical analysis of dissolved oxygen, conductivity, salinity, pH, and water depth within Ninigret Pond showed no significant differences among landscape units (Table 2.5). In Quonochontaug Pond, only water depth was significantly different among landscape units (Table 2.6). In order to identify differences of water quality between ponds, water quality parameters were averaged among subaqueous-landscape units and years. Salinity and water depth at the aquaculture plots were significantly different with Quonochontaug Pond having greater depths, and higher salinities (Table 2.7). These differences can be attributed to Quonochontaug Pond having a deeper basin and greater tidal flushing.

In order to identify differences in water quality between years (2008 and 2009), statistical analysis was performed on the averaged values among landscape units within ponds (Table 2.8, 2.9). In Ninigret Pond, no significant differences between 2008 and 2009 were encountered for chlorophyll *a* concentration, total suspended solids, or dissolved oxygen (Table 2.8). In Quonochontaug Pond, total suspended solids and dissolved oxygen were significantly different between 2008 and 2009 ($p < 0.05$) (Table 2.9). Total suspended solid concentration was higher in 2008, as was dissolved oxygen (Table 2.9).

Oyster Growth

I expected faster growth rates on coarser textured soils (Psammowassents) than fine textured, low energy soils (Sulfiwassents). This hypothesis is based on the assumption that coarser textured soils are associated with higher current velocities, and greater food availability (Grizzle and Morin, 1989; Rice, 1995; Rice and Pechenik, 1995). Significant differences in growth rates of oysters grown on different subaqueous landscape units were observed ($p < 0.01$; Figure 2.7). In both ponds, oysters grown on Lagoon Bottom exhibited slower growth than oysters grown on other landscape units (Figure 2.7).

In Ninigret Pond, oyster growth rates ranged from 46 – 98 µm day^{-1}, with an average of 78 µm day^{-1} (July 2008 – October 2009). In Quonochontaug Pond, oyster growth rate ranged from 65 – 109 µm day^{-1} with an average growth of 94 µm day^{-1} (Figure 2.7). Overall oyster growth in Ninigret Pond (78 µm day^{-1}) exhibited slower growth rates than those observed in Quonochontaug Pond (94 µm day^{-1}) ($t = 5.10$; $p < 0.001$) suggesting better growing conditions in Quonochontaug Pond. Oyster growth on Lagoon Bottom in Ninigret Pond was not significantly different from oysters grown on Washover Fan and Mainland Cove, although trends are evident showing depressed growth on the finer textured soil (Figure 2.5; Table 2.1). In Quonochontaug Pond, oyster growth was similar across all landscapes except on Lagoon Bottom, where depressed growth occurred (Figure 2.5).

Oyster growth in my study (both ponds) averaged 86 µm day^{-1} with an annual growth of 31 mm year^{-1} (2.6 mm month^{-1}). Summer oyster growth rates (August – October 2008; June – October 2009) varied between landscapes and years (Figure 2.6). Mean summer growth rates in Ninigret Pond ranged from 100 – 120 µm day^{-1} with an average of 120 µm day^{-1} (3.7 mm month^{-1}) in 2008;102 µm day^{-1} (3.1 mm month^{-1}) in 2009 (Figure 2.6). Excluding Lagoon Bottom data from Quonochontaug

Pond (oyster growth was not recorded in 2008 on this landscape unit) average growth rates were 227 µm day^{-1} in 2008 (6.9 mm $month^{-1}$); 197 µm day^{-1} in 2009 (6.0 mm $month^{-1}$) (Figure 2.6).

Making growth rate comparisons between oysters from different regions becomes a problem due to differences in environmental conditions and mean annual water temperatures. Oyster populations range from the Gulf of Mexico to Canada (Harris, 2003; Eastern Oyster Biological Review Team, 2007; Shumway, 2007). With such a wide range, oysters experience differences in mean annual temperatures, food availability, and overall length of the growing season. Other problems in comparing oyster growth rates (and other shellfish growth rates) between studies lies in the methodology of calculating and describing growth, from shell measurements, biovolume, percent increase in size, and time until market size (Woodruff, 1961; Rheault, 1995; Harris, 2003). Regardless, I compared my growth rates to see if they were similar to what others had found. The oyster growth rates from my study are slower than summer growth rates recorded in previous studies in the Chesapeake Bay. Paynter and Dimichele (1990) reported summer growth rates (June – October) of oysters grown in floating trays ranging from 8 - 15 mm $month^{-1}$ in first and second year oysters in the Chesapeake Bay while Harris (2003), reported overall oyster growth rates of natural populations ranging from 2.0 to 7.8 mm $month^{-1}$. In Florida, maximum linear growth of oysters has been documented above 14 mm $month^{-1}$ (Ingle, 1950).

Oysters in Rhode Island need to be a minimum of 76 mm before they are ready for market. When purchased, oysters averaged 30 mm in shell height (June 2008). In

October 2008, no oysters in Ninigret Pond reached market size, while in Quonochontaug Pond, a few (1-3%) were above market size (Table 2.10). By June 2009, at least 13% of the oysters grown on all of the landscape units with the exception of the Lagoon Bottom had reached 76 mm (Table 2.10). Even after a full season of growing, 99% of the Lagoon Bottom oysters in Ninigret Pond, and 97% of oysters grown on this landscape unit in Quonochontaug Pond, were smaller than legal size (Table 2.10). By October 2009, 24% of oysters grown on Lagoon Bottom in Quonochontaug Pond had reached market size, much better than oysters grown on the same landscape unit in Ninigret Pond (Table 2.10).

By the end of the experiment in October 2009, 44 – 73% of the oysters grown on landscape units other than Lagoon Bottom had reached market size in Ninigret Pond. In Quonochontaug Pond, 61 – 62% of oysters grown on landscape units other than Lagoon Bottom had reached market size. In Quonochontaug Pond all landscape units with the exception of the Lagoon Bottom showed similar results (Table 2.10). Overall, the data suggest that in two growing seasons, more than 50% of oyster populations grown on landscape units other than Lagoon Bottom will reach market size in Rhode Island from an initial shell height of 30 mm. Average time to market size from set varies throughout the oyster range, ranging from 2 years in the Gulf of Mexico, to 4 -5 years in Long Island sound (Carriker, 1959; Shumway, 1996), suggesting that the growth rates I measured are likely representative of this region.

Initially, each aquaculture site contained approximately 1,300 live oysters (115 oysters per liter biovolume, 4 liters per oyster tray, and 3 oyster trays per aquaculture plot). At the end of the experiment there were more oysters alive in Quonochontaug

Pond than in Ninigret Pond (Figure 2.7). The lowest survival was at the Washover Fan Slope (NWFS) site due to vandalism and loss of two oyster trays. Total live oysters in Quonochontaug Pond ranged from 396 at Lagoon Bottom to 685 at the Washover Fan site (Figure 2.7). In Ninigret Pond, total live oysters ranged from 96 – 347 (Figure 2.7). These data represent a 22% survival rate in Ninigret Pond (excluding NWFS), and 38% survival in Quonochontaug Pond. These differences in survival may reflect better environmental conditions for oyster survival in Quonochontaug Pond. This is supported by the higher growth rates in Quonochontaug Pond.

Total live biovolume of oysters by landscape ranged from 5 liters at Lagoon Bottom in Ninigret Pond to 52 liters at Washover Fan Flat in Quonochontaug Pond (Figure 2.8). Quonochontaug Pond had significantly more biovolume than Ninigret Pond ($t = -2.63$; p 0.016 $n = 22$). These data again show a trend where Lagoon Bottom landscapes (low energy environments) exhibited a depression in oyster growth, higher mortality, and lower associated biovolume than coarser textured soils of relatively high energy environments (Psammowassents).

Quahog Growth

Each quahog plot initially contained 0.5 liters biovolume of seed sized quahogs (approximately 300 quahogs). Initial shell sizes (hinge width) averaged 9.1 mm. Final shell sizes ranged from 15.9 – 22.1 mm with a mean of 18.2 mm (Table 2.11). Washover Fan Slope in Ninigret Pond had a significantly larger population than all other landscape units in October 2009. Quahogs grown on Washover Fan were the largest in Quonochontaug Pond while quahogs grown at Lagoon Bottom were the smallest at the end of the study (Table 2.11). Smaller size of the quahogs on the Lagoon Bottom site could possibly be due to my methodology, where these quahogs were grown in a bag due to water depth and problems retrieving them without scuba equipment.

Growth rates of the quahogs were slower than growth rates observed for the oysters (Table 2.11; Figure 2.5). Mean quahog growth rates were 22 µm day^{-1} (excluding Lagoon Bottom in Ninigret Pond) while mean oyster growth rates were 86 µm day^{-1}. On a yearly basis, my quahogs averaged 7.9 mm $year^{-1}$ (0.15 mm $week^{-1}$). Similar growth rates were reported by Littlefield (1991) in Great Salt Pond, Block Island. In Narragansett Bay, young quahogs (1-3 years old) have been reported to grow at rates of 8.3 - 17.6 mm $year^{-1}$ (hinge width) (Henry and Nixon, 2008). In a review of quahog growth along the Eastern U.S., Bricelj (1993) calculated average maximum growth rates of 0.83 mm $week^{-1}$, slightly higher than 0.74 mm $week^{-1}$ average in a review by Grizzle et al. (2001).

There were no quahogs recovered from the Lagoon Bottom site in Ninigret Pond. Macroalgae has been shown to decrease and prevent growth of quahogs (Tyler, 2007). Littlefield (1991) reported annual mortalities of 20% in Great Salt Pond, Block Island due to predation, fouling of the site, and unknown causes. This result is possibly due to adverse water quality (not detected during water quality measurements), or algae and eelgrass detritus that commonly collected at the Lagoon Bottom site. These data suggest that quahog growth rates were less than those observed in Narragansett Bay, but similar to what has been observed on Block Island aquaculture sites.

Shellfish-Subaqueous Soil Relationships

Regression analysis was performed to identify relationships between subaqueous soil and shellfish growth. Oyster growth was correlated to three soil properties: grain size, organic carbon, and carbonates. These variables are collinear because as grain size gets finer, organic matter and carbonates increase, as found in past studies of these systems (Bradley, 2001; Payne 2007) (Table 2.12). Organic matter and calcium carbonates were both negatively correlated to sand content ($r = -0.93$; p 0.0010; $r = -0.89$; p 0.0033 respectively). Oyster growth was not correlated to any water quality or physical site parameter (such as depth). Quahog growth (including Ninigret Lagoon Bottom data) was correlated to sand content and organic matter content of the upper horizon of the soil but not to any water quality parameter (Table 2.12).

Grain size of the surface horizon of the soil (sand) was closely related to oyster growth ($R^2 = 0.85$; $p < 0.01$). Oyster growth exhibits a positive relationship with the sand content of the soil (Figure 2.9). Faster oyster growth was found on sandier, higher energy environments such as Washover Fan. No significant relationships between growth and water quality parameters were found (Table 2.13), although oyster growth was most closely related to dissolved oxygen content ($R^2 = 0.41$; p 0.09). Quahog growth was again related to sand content of the first horizon of the soil and organic matter content (Table 2.13). No relationships between water quality and quahog growth were found (Table 2.13). These results corroborate earlier findings that shellfish growth is related to the grain size of the soils (sediment) due to coarser textures soils being associated with the current speed and depositional environment, and subsequent greater food availability (Pratt and Campbell, 1956; Grizzle and Morin, 1989; Rice and Pechenik, 1992).

While not all subaqueous landscape units were investigated in this study, it should be noted that increases in sand content may not necessarily indicate the best areas of the estuary for shellfish aquaculture. The sandy nature of the Flood Tidal Delta, while having moderate flow rates may have too high a depositional rate for oysters to grow effectively. Oysters are reef forming organisms, but this growth may be hindered by sand deposition, especially on the Flood Tidal Delta where they may become covered with newly deposited sand at each flood tide. Other problems that were not addressed in this study (but were observed) is subsidence of aquaculture equipment in the fine textured, high n-value materials of the Lagoon Bottom and Mainland Cove. The oyster trays tended to sink in this fluid material, cutting off water flow to the bottom of the oyster tray. This may explain some of the slower growth associated with these fine textured landscapes. If oyster aquaculture was performed on-bottom, then there is the possibility of the animals sinking into this material, effectively cutting off their food supply and killing them. These two factors should be investigated further and this information incorporated into the soil survey interpretation for shellfish aquaculture.

SUMMARY AND CONCLUSIONS

The aquaculture industry in Rhode Island has been increasing over the past ten years and is now a million dollar industry. Although many aquaculture farms have been sited in Narragansett Bay and the coastal lagoons, information regarding the best place to site these farms is lacking. In this study, I utilized existing subaqueous soil surveys to relate shellfish growth and the character of the bottom in order to identify areas of the highest productivity for oysters and quahogs. This type of information, commonly called interpretations by soil scientists, would be included with a full subaqueous soil survey. Shellfish growth is determined by several environmental factors such as temperature, salinity, and food availability. Past studies have suggested that temperature and food availability are the most important factors when assessing shellfish growth. Different subaqueous environments (landscapes) and soils are a function of differences in the energies of the system. In this study, I used soil type as a proxy to relate shellfish growth to the energy of the system (food availability). I found that shellfish growth varied on different subaqueous landscapes within and between coastal lagoons. Biovolume and mortality also differed on different soil-landscape units, as well as the percentages of legal sized oysters after two growing seasons. Oyster growth rates increased with increases in sand content of the surface horizon of the soil, while soils having increases in silt-clay contents, showed a relative reduction in growth, as well as decreases in biovolume, and increased mortality. These data suggest that areas of relatively low energy environments of the Coves, and Bottoms will show a depression of shellfish growth. Areas containing increases in sand such as Washover Fans, and Submerged Mainland Beaches showed increases in shellfish growth, more suitable for the fast growth required (and desired) by shellfish aquaculturists. In this study, shellfish followed similar trends among landscape units. Higher growth rates and decreased mortalities were observed on higher energy soil-landscape units than the fine textured Lagoon Bottom and Cove. Incorporating these results in a soil survey would provide managers (such as the CRMC) with data regarding identification of these productive areas as well as spatial extent of subaqueous soils.

Table 2.1. Particle size distribution of samples collected from horizons in the upper 25 cm of soil collected at aquaculture sites (landscape units) in Ninigret and Quonochontaug Ponds. Subgroup soil classification and water depth are also included.

Horizon	Horizon Depth (cm)	vcos (%)	cos (%)	ms (%)	fs (%)	vfs (%)	sand (%)	silt (%)	clay (%)	Texture
Ninigret Pond Washover Fan Slope (NWFS), Typic Fluviwassent, 0.96 m depth										
C1	0-21	20	0	0	53	0	73	27	0	lfs
Cg1	21-35	0	2	2	58	9	71	28	1	fsl
Ninigret Pond Washover Fan (NWF), Sulfic Psammowassent, 1.04 m depth										
A	0-5	1	1	5	55	27	89	8	4	fs
CA1	5-13	0	1	9	61	23	95	3	2	fs
CA2	13-23	0	2	1	58	24	85	12	3	lfs
Ninigret Pond Lagoon Bottom (NLB), Typic Sulfiwassent, 1.00 m depth										
A	0-24	2	1	1	6	13	23	58	18	sil
AC1	24-35	1	2	5	15	22	44	45	11	ls
Ninigret Pond Mainland Cove (NMC), Haplic Sulfiwassent, 1.00 m depth										
A1	0-5	15	22	13	9	3	63	29	9	s
A2	5-19	13	19	16	12	4	64	27	9	cosl
CA	19-40	36	37	10	9	2	94	5	1	cos
Quonochontaug Pond Washover Fan Slope (QWFS), Typic Psammowassent, 1.49 m depth										
Cg1	0-25	7	23	60	8	0	98	1	1	s
Quonochontaug Pond Washover Fan (QWF), Fluventic Psammowassent, 0.79 m depth										
Cg	0-6	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
AC	6-28	16	29	33	18	2	98	2	0	cos
Quonochontaug Pond Lagoon Bottom (QLB), Typic Sulfiwassent, 3.19 m depth										
A	0-27	2	1	2	15	25	45	45	10	l
Quonochontaug Pond Submerged Mainland Beach (QSMB), Aeric Haplowassent, 0.99 m depth										
Cg1	0-13	4	7	35	43	4	92	7	1	s
Cg2	13-23	1	4	25	46	8	83	15	2	ls
Cg3	23-38	2	3	20	49	10	83	15	2	ls

Table 2.2. Chemical soil characteristics of samples collected from horizons in the upper 25 cm of soil at aquaculture sites (landscape units) in Ninigret and Quonochontaug Ponds.

Horizon	Organic Matter (%)	$CaCO_3$ (%)	5:1 Conductivity dS m^{-1}	Incubation pH (16 week)
Ninigret Pond Washover Fan Slope (NWFS)				
C1	1.24	0.50	1.24	7.06
Cg1	0.87	0.50	1.35	7.31
Ninigret Pond Washover Fan (NWF)				
A	2.56	1.56	3.11	3.29
CA1	1.35	0.53	2.30	2.47
CA2	2.16	0.86	2.60	2.58
Ninigret Pond Lagoon Bottom (NLB)				
A	10.62	4.28	4.46	2.35
AC1	10.60	4.05	3.30	2.23
Ninigret Pond Mainland Cove (NMC)				
A1	4.96	3.36	3.47	4.54
A2	6.49	3.75	4.34	3.56
CA	0.87	0.68	2.10	3.51
Quonochontaug Pond Washover Fan Slope (QWFS)				
Cg1	0.23	0.26	0.51	6.58
Quonochontaug Pond Washover Fan (QWF)				
Cg	0.58	0.63	1.47	4.25
AC	0.32	0.52	1.21	6.97
Quonochontaug Pond Lagoon Bottom (QLB)				
A	11.65	4.90	4.43	2.97
Quonochontaug Pond Submerged Mainland Beach (QSMB)				
Cg1	0.61	0.27	1.39	5.93
Cg2	0.73	0.46	1.27	3.59
Cg3	0.46	0.30	1.05	6.16

Table 2.3. Water Temperature (ºC) recorded by iButtons on aquaculture sites between June 2008 and August 2009. Statistical evaluations were evaluated at $\alpha = 0.05$, (t-test; ANOVA, significance $p \leq 0.05$). Different letters adjacent to means indicate significant differences within mean annual, mean summer and mean winter temperature analysis among landscape units within ponds. Mean summer = June, July, August; Mean winter = December, January, February. Temperature was recorded every four hours.

	Water Temperature ºC		
Aquaculture Site	**Mean Annual**	**Mean Summer**	**Mean Winter**
NWFS*	-	22.1	-
NWF	11.5^{a}	23.0^{a}	2.2^{a}
NMC*	-	22.3	-
NLB	12.0^{b}	22.3^{b}	2.8^{b}
QWFS	11.8^{x}	21.5^{x}	3.6^{x}
QWF	12.1^{x}	22.0^{x}	3.5^{x}
QSMB	12.4^{x}	21.8^{x}	4.3^{y}
QLB	11.2^{y}	19.5^{y}	4.2^{y}

* iButton lost, based on YSI data

Table 2.4. Average measures of water quality among landscapes in Ninigret and Quonochontaug Ponds collected during the summer months and averaged between years (2008, 2009). TSS = total suspended solids; D.O. = dissolved oxygen. Standard deviations indicated in ( ).

Landscape unit (Aquaculture site I.D.)	Depth m	Chlorophyll *a* ppb	TSS mg/l	Salinity ‰	D.O. mg/l	pH
NWFS	0.96 (0.16)	5.0 (2.3)	30.1 (14.0)	28.1 (0.8)	6.7 (1.2)	7.7 (0.3)
NWF	1.04 (0.09)	3.9 (2.4)	36.0 (30.0)	28.8 (0.9)	7.1 (1.3)	7.7 (0.2)
NMC	1.00 (0.18)	5.0 (2.7)	27.7 (15.6)	29.5 (1.3)	6.6 (1.0)	7.6 (0.2)
NLB	1.00 (0.11)	4.4 (2.4)	31.0 (20.9)	28.9 (1.0)	6.7 (1.2)	7.6 (0.2)
QWFS	1.49 (0.23)	5.0 (1.9)	26.4 (10.5)	30.9 (1.7)	6.6 (1.2)	7.6 (0.3)
QWF	0.79 (0.24)	4.2 (1.7)	29.0 (7.6)	29.1 (3.8)	6.5 (1.0)	7.6 (0.31)
QSMB	0.99 (0.26)	4.9 (2.2)	27.7 (15.1)	29.1 (4.0)	6.7 (0.7)	7.7 (0.3)
QLB	3.19 (0.21)	3.3 (1.2)	27.7 (12.7)	31.5 (1.8)	6.8 (0.9)	7.7 (0.2)

Table 2.5. Statistical analysis of mean water quality parameters (2008 – 2009) among landscape units within Ninigret Pond. Significance $p \leq 0.05$. Means are provided in Table 2.4.

Parameter Among landscape units	$\chi^{2\dagger}$	**p**	**n**
Chlorophyll *a* (ppb)	2.18	0.54	58
TSS (mg/l)	0.67	0.88	43
D.O. (mg/l)	0.69	0.88	38
Salinity (‰)	6.17	0.10	27
pH	0.11	0.99	51
Water Depth (m)	0.66	0.88	25

† Comparison using a Kruskal-Wallis test $\alpha = 0.05$

Table 2.6. Statistical analysis of mean water quality parameters (2008 - 2009) among landscape units within Quonochontaug Pond. Significance $p \leq 0.05$. Means are provided in Table 2.4.

Parameter Among landscape units	$\chi^{2\dagger}$	**p**	**n**
Chlorophyll *a* (ppb)	6.21	0.10	46
TSS (mg/l)	1.52	0.68	38
D.O. (mg/)	0.21	0.98	32
Salinity (‰)	5.06	0.17	24
pH	0.79	0.85	44
Water Depth (m)	23.38	< 0.0001	29

† Comparison using a Kruskal-Wallis test $\alpha = 0.05$

Table 2.7. Statistical analysis of water quality parameters (averaged among landscapes and years within ponds) between Ninigret and Quonochontaug Ponds. Only water depth and salinity were significantly different between coastal lagoons. Significance $p \leq 0.05$.

Parameter Ninigret vs. Quonochontaug	**Mean Ninigret Pond**	**Mean Quonochontaug Pond**	**t** *	**p**	**n**
Chlorophyll *a* (ppb)	4.6	4.4	0.43	0.67	104
TSS (mg/l)	31.2	27.7	0.96	0.34	81
D.O. (mg/l)	6.8	6.7	0.71	0.48	71
Salinity (‰)	28.9	30.2	2.00	0.05	51
pH	7.7	7.6	0.11	0.92	95
Water Depth (m)	1.00	1.67	3.53	< 0.01	54
iButton Annual Water Temperature ºC	11.6	11.9	0.92	0.36	12288

* Independent t-test with unequal variances using Welch's approximation $\alpha = 0.05$

Table 2.8. Statistical analysis of water quality parameters between years (2008 and 2009) within Ninigret Pond. Significance $p \leq 0.05$.

Parameter	**Mean 2008**	**Mean 2009**	$t^{\dagger}$	**p**	**n**
Chlorophyll *a* (ppb)	4.0	5.1	-1.68	0.10	54
TSS (mg/l)	35.9	26.6	1.66	0.10	47
D.O. (mg/l)	7.0	6.2	0.88	0.39	37

† t-test with Welch's approximation for unequal variances $\alpha = 0.05$

Table 2.9. Statistical analysis of water quality parameters between years (2008 and 2009) within Quonochontaug Pond. Significance $p \leq 0.05$.

Parameter	**Mean 2008**	**Mean 2009**	$t^{\dagger}$	**p**	**n**
Chlorophyll *a* (ppb)	4.2	4.5	-0.55	0.59	46
TSS (mg/l)	32.8	22.8	3.12	< 0.01	42
D.O. (mg/l)	7.0	6.3	2.31	0.03	32

† t-test with Welch's approximation for unequal variances $\alpha = 0.05$

Table 2.10. Percentage of legal sized (76 mm) oysters (*Crassostrea virginica*) by date measured along the long axis in Ninigret and Quonochontaug Ponds. When purchased, oyster averaged 30 mm in height (June 2008). †Vandalism occurred at NWFS (2 oyster trays lost, data from 1 tray used). N = 90 at each landscape unit.

	October 2008	**June 2009**	**October 2009**
Aquaculture Site ID	**% ≥ 76 mm**	**% ≥ 76 mm**	**% ≥ 76 mm**
NWFS	0	20	73†
NWF	0	30	44
NMC	0	13	45
NLB	0	0	1
QWFS	3	19	62
QWF	1	24	62
QSMB	2	16	61
QLB	N/A	3	24

Table 2.11. Quahog (*Mercenaria mercenaria*) growth from initial seed sized purchased from Roger Williams University at aquaculture sites in Ninigret and Quonochontaug Ponds. Quahogs were measured by hinge width upon purchase and again upon collection in October 2009. No quahogs were recovered at Ninigret Pond Lagoon Bottom (NLB). There were 420 growing days in Ninigret Pond, 414 in Quonochontaug Pond. Initial quahog sizes were all 9.1 mm. Different letters indicate significant differences. Ninigret Pond (a, b) $\chi^2 = 62.30$, $p < 0.0001$, $n = 194$; Quonochontaug Pond (x, y, z) $\chi^2 = 50.90$, $p < 0.0001$, $n = 316$.

Aquaculture Site ID	Final Size (mm)	Growth µm/day^{-1}	Number Recovered
NWFS	22.1^{a}	31.0	73
NWF	16.8^{b}	18.3	32
NMC	18.1^{b}	21.4	115
NLB	N/A	N/A	0
QWFS	17.6^{x}	20.6	109
QWF	19.1^{y}	24.3	126
QSMB	18.0^{x}	21.4	47
QLB†	15.9^{z}	16.3	243

†QLB quahogs grown in grow-out bag buried at site

Table 2.12. Pearson's correlation matrix (r) for selected variables (O.M. = organic matter, Chl *a* = Chlorophyll *a* µg/l, TSS = total suspended solids mg/l). Significant correlations in bold ($p \leq 0.05$), n = 8.

Parameter	**Sand >0.05 mm**	**O.M. %**	**$CaCO_3$ %**	**Chl a ppb**	**TSS mg/l**	**D.O. mg/l**	**Water Salinity ‰**	**Depth m**	**Oyster µm/day^{-1}**	**Quahog µm/day^{-1}**
Sand >0.05 mm	1.00									
O.M. %	**0.93 < 0.01**	1.00								
$CaCO_3$ %	**0.89 < 0.01**	**0.97 < 0.01**	1.00							
Chlorophyll *a* ppb	0.28 0.49	-0.58 0.14	-0.54 0.17	1.00						
TSS mg/l	-0.04 0.92	0.03 0.95	0.03 0.95	-0.34 0.41	1.00					
D.O. mg/l	-0.38 0.35	0.41 0.31	0.37 0.36	-0.46 0.25	**0.82 <0.05**	1.00				
Water salinity ‰	-0.09 0.83	0.37 0.37	0.37 0.37	-0.41 0.32	-0.55 0.16	-0.24 0.56	1.00			
Depth m	-0.35 0.39	0.61 0.12	0.56 0.15	-0.66 0.08	-0.30 0.12	0.06 0.88	**0.83 0.02**	1.00		
Oyster µm/day^{-1}	**0.92 < 0.01**	**-0.92 < 0.01**	**-0.88 < 0.01**	0.46 0.26	-0.28 0.50	-0.64 0.09	-0.14 0.75	-0.36 0.37	1.00	
Quahog µm/day^{-1}	**0.71 0.05**	**-0.72 < 0.05**	-0.67 0.07	0.33 0.43	-0.20 0.64	-0.51 0.19	-0.16 0.71	-0.15 0.73	**0.86 < 0.01**	1.00

Table 2.13. Regression matrix (R^2) of shellfish growth, surface horizon soil data, and water quality variables (O.M. = organic matter, , TSS = total suspended solids, D.O. = dissolved oxygen l, W.T. = water temperature. Significance in bold ($p \leq 0.05$), n = 8.

Parameter	Oyster µm/day^{-1}	Quahog µm/day^{-1}
Oyster µm/day^{-1}	1.00	-
Quahog µm/day^{-1}	0.19 0.277	1.00
Sand > 0.05 mm	**0.85** **< 0.01**	**0.50** **0.05**
O.M. %	**0.85** **< 0.01**	**0.52** **0.04**
$CaCO_3$ %	**0.78** **< 0.01**	0.44 0.07
Summer W.T. °C	0.04 0.63	0.00 0.97
Chlorophyll *a* ppb	0.21 0.26	0.11 0.43
TSS mg/l	0.08 0.50	0.04 0.64
D.O. mg/l	0.41 0.09	0.26 0.19
Water Salinity ‰	0.02 0.75	0.02 0.71
Depth m	0.13 0.38	0.02 0.73

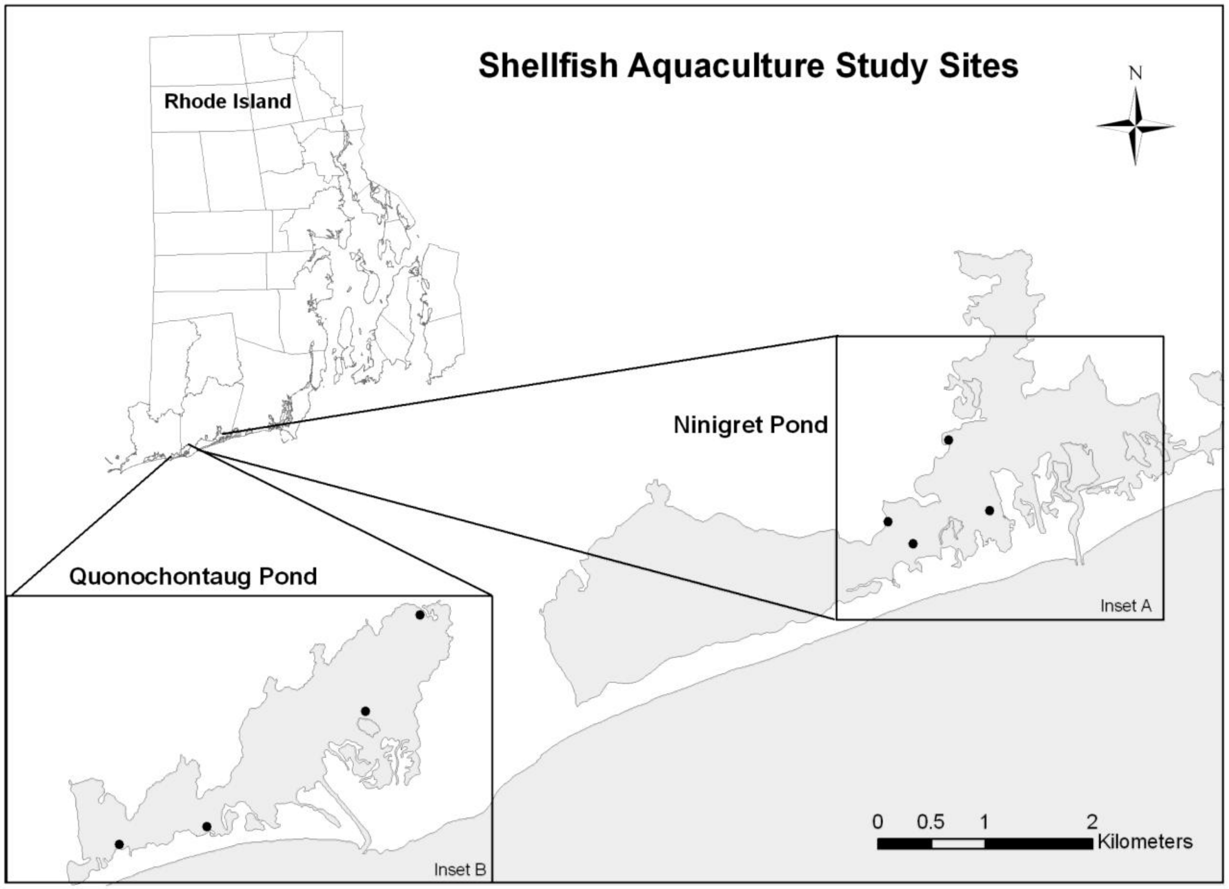


Figure 2.1. Locus map showing study sites for the investigation of shellfish productivity. Ninigret Pond (667 ha; Inset A), and Quonochontaug Pond (312 ha; Inset B).

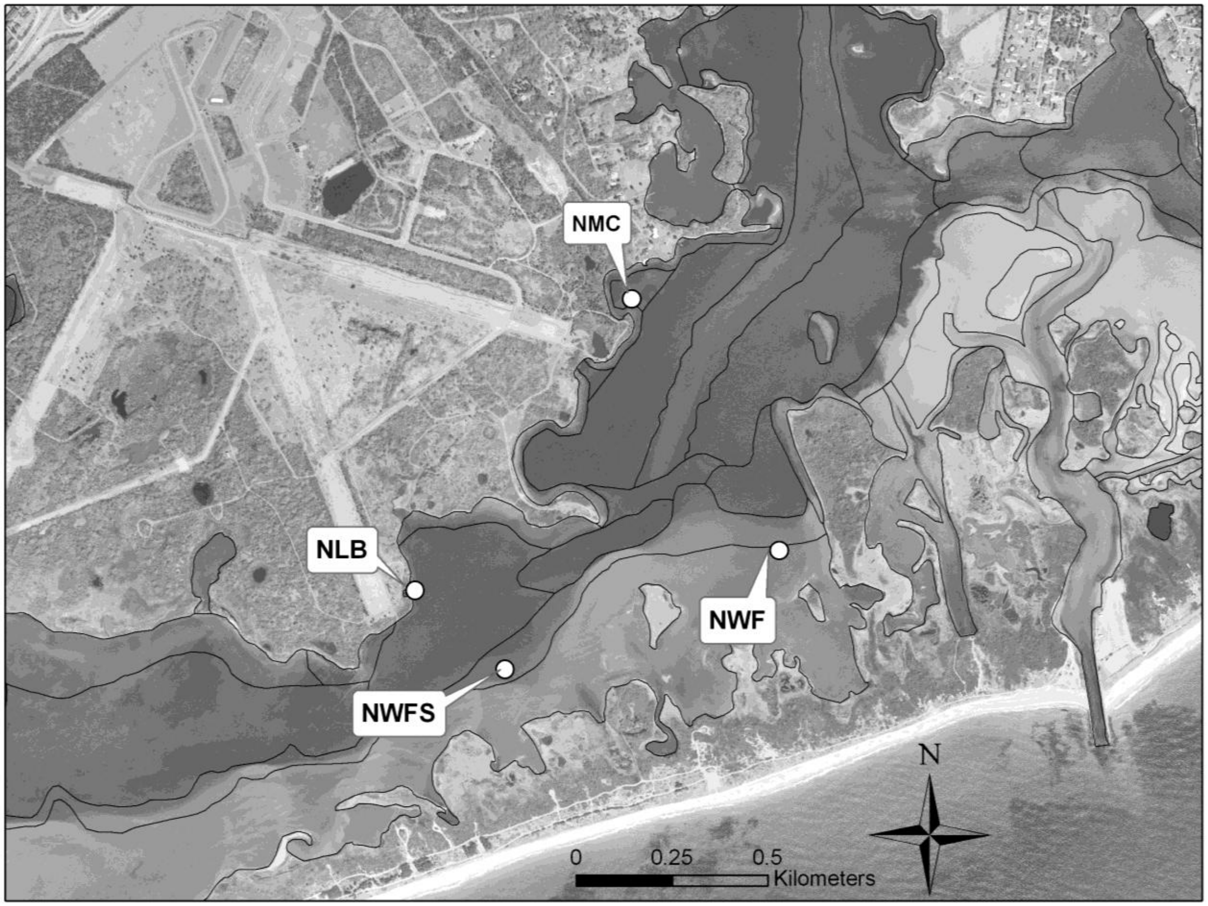


Figure2.2. Aquaculture and soil vibracore locations in Ninigret Pond. Landscape units include: Washover Fan Slope (NWFS), Washover Fan (NWF), Lagoon Bottom (NLB) and Mainland Cove (NMC).

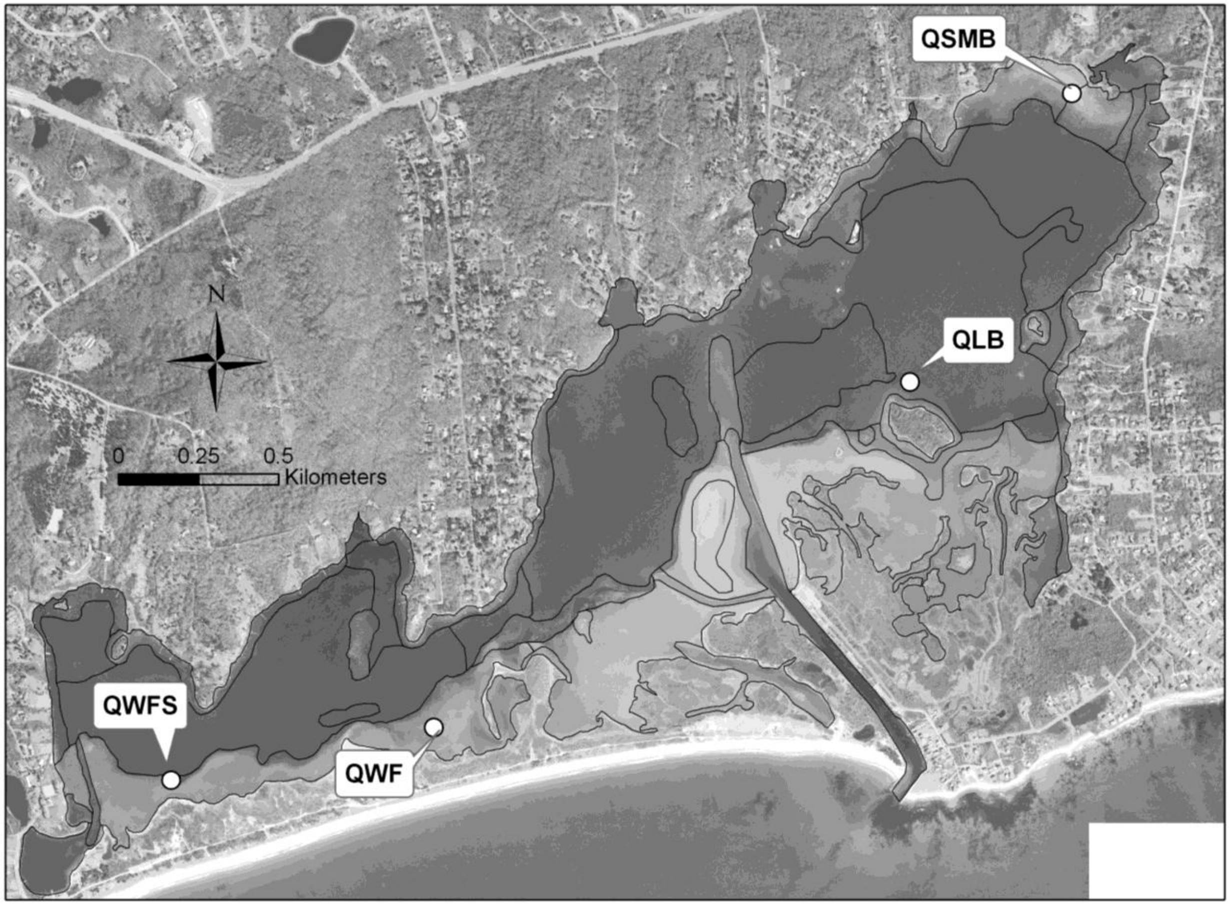


Figure 2.3. Aquaculture and vibracore locations in Quonochontaug Pond. Landscapes include: Washover Fan Slope (QWFS), Washover Fan (QWF), Lagoon Bottom (QLB), and Submerged Mainland Beach (QSMB).

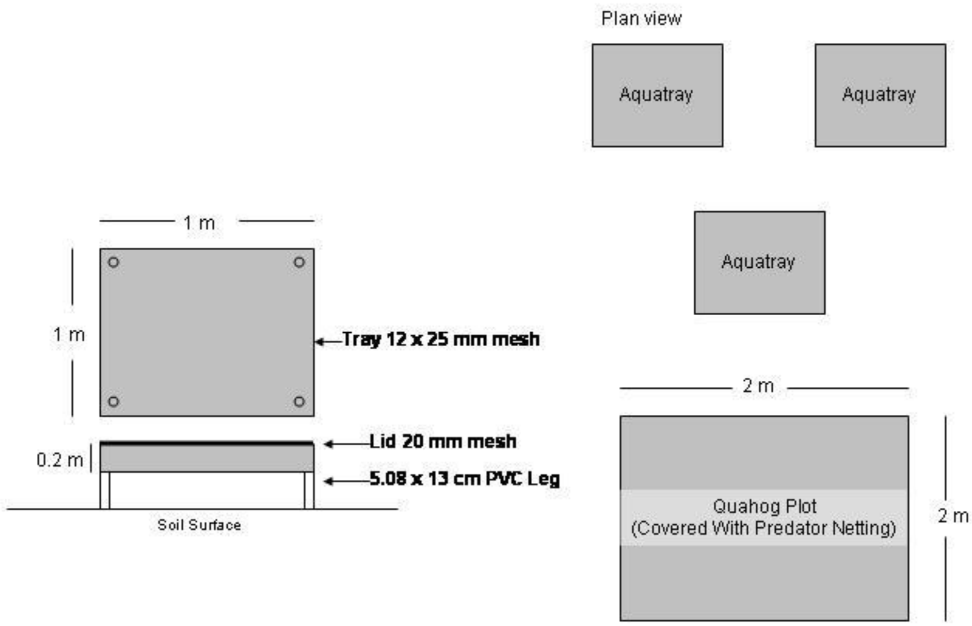


Figure 2.4. Oyster growing trays stand on 13 cm PVC legs resting on the bottom. Each tray initially contained 1 grow-out bag containing 4 liters biovolume of seed sized oysters (115 oysters/liter). Three trays rest at each aquaculture plot for a total of 24 trays (12 in each pond). One quahog plot consisting of 0.5 liters of biovolume (~300 quahogs) is at each aquaculture site covered by 0.25 x 0.25 cm mesh predator netting for a total of 7 quahog plots (4 in each pond; Quonochontaug Lagoon Bottom quahogs were grown in a grow-out bag, placed in the soil due to site depth).

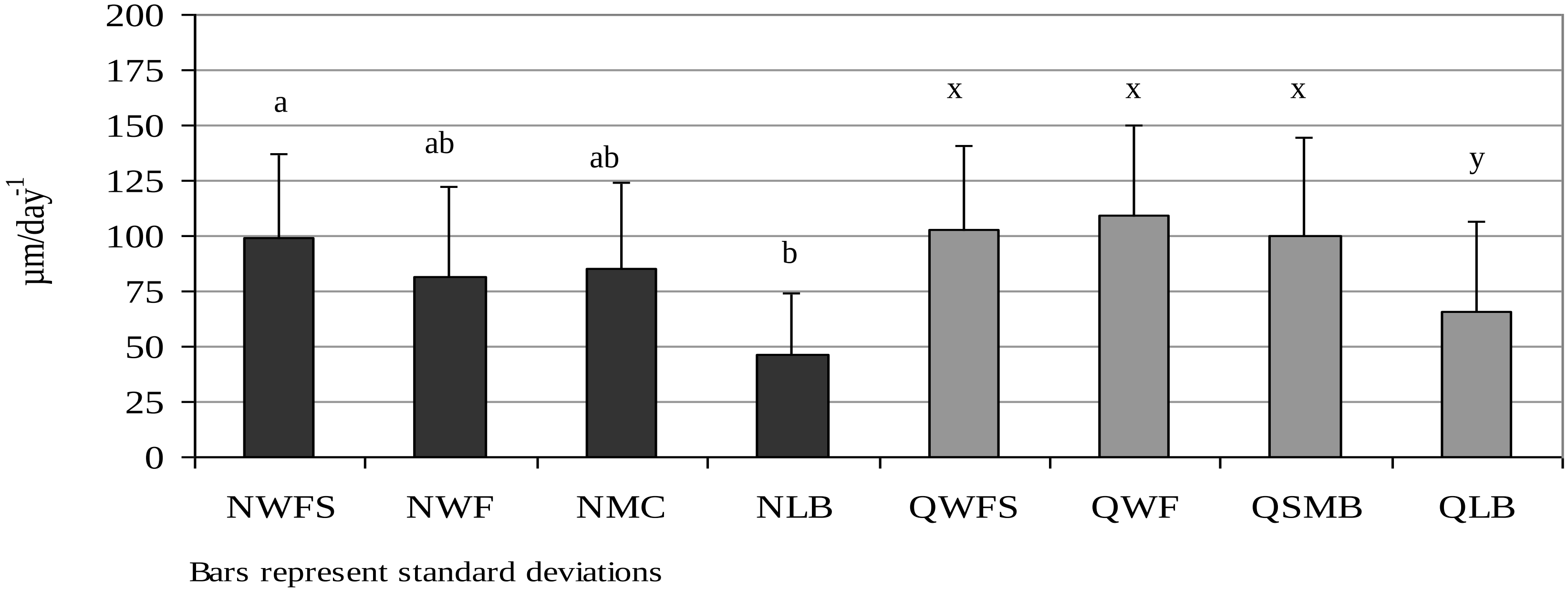
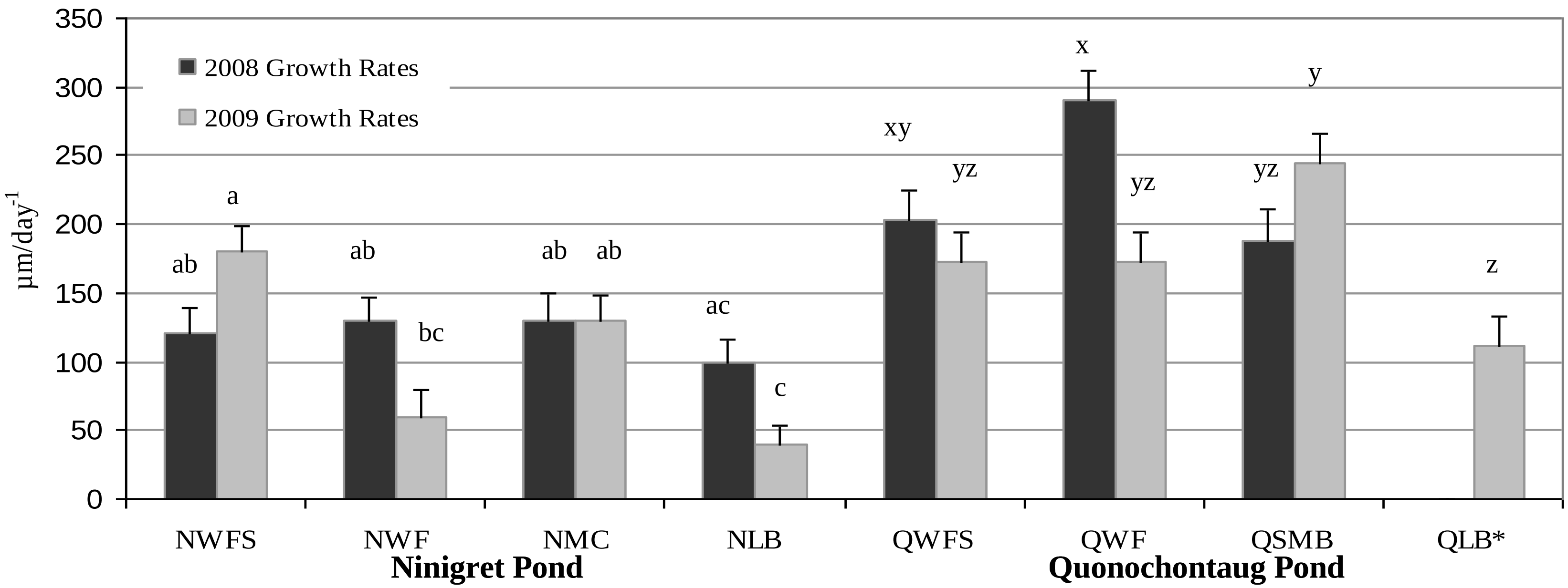


Figure 2.5. Mean oyster growth rates on subaqueous landscape units from 7/22/2008 – 10/8/2009 in Ninigret Pond; 8/1/2008 – 10/2/2009 in Quonochontaug Pond. Different letters indicate significant differences after a ANOVA and Bonferroni contrast, (α = 0.05, n = 90 (each landscape unit)). Note: Vandalism at NWFS site July 2009, unknown amount lost (data was included for one oyster tray at NWFS).



Bars represent standard error

Figure 2.6. Summer oyster growth rates µm/day^{-1} analyzed among landscape units within study sites. Ninigret Pond: July – October 2008 (79 days); June – October 2009 (106 days). Quonochontaug Pond: August 2008 – October 2008 (62 days); June 2009 – October 2009 (98 days). Statistical differences are indicated by different letters $\alpha = 0.05$. Note: Vandalism at NWFS site July 2009, unknown amount lost (data for one oyster tray was used for 2009 growth rates). QLB growth not recorded in 2008. Ninigret Pond data ($F = 6.11$; $p <0.0001$) while xyz represent Quonochontaug Pond data ($F = 6.44$; $p < 0.000$). n = 90 at each landscape unit.

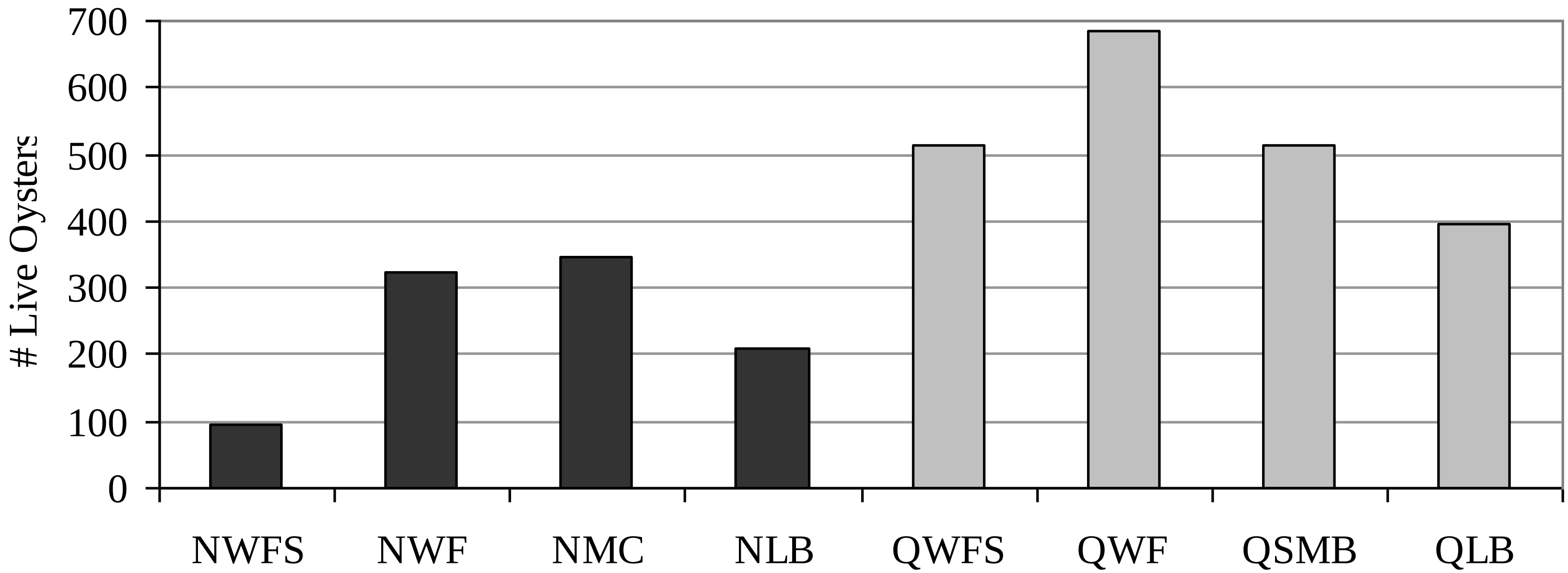


Figure 2.7. Total live number of oysters on aquaculture lease sites in October 2009. There were no significant differences among landscape units within study sties. NWFS data was not included in the statistics due to vandalism in July 2009 (2 oyster trays lost). Ninigret Pond: $F = 2.70$, p 0.15, $n = 9$; Quonochontaug Pond: $F = 1.39$, p 0.31, $n = 12$. Initial numbers = roughly 460 oysters/tray (based on initial biovolume of 4 liters/tray.

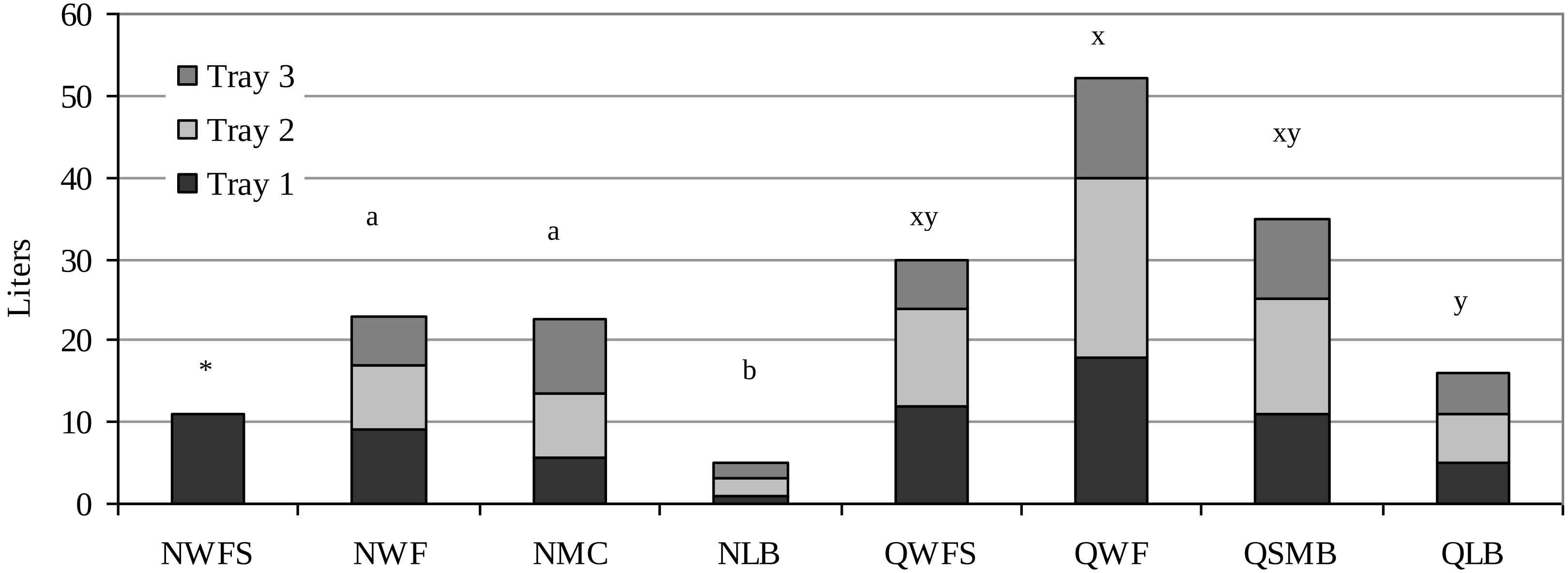


Figure 2.8. Oyster biovolume measured in liters in October 2009. Different letters indicate significant differences between landscape units, a,b represent Ninigret Pond; x,y represent Quonochontaug Pond. $\alpha = 0.05$. Ninigret Pond: $F = 17.76$, p 0.003, $n = 9$; Quonochontaug Pond: $F = 7.01$, p 0.013, $n = 12$. Initial biovolume = 4 liters/tray. Ninigret Pond NWFS data was not included due to vandalism (2 oyster trays were lost).

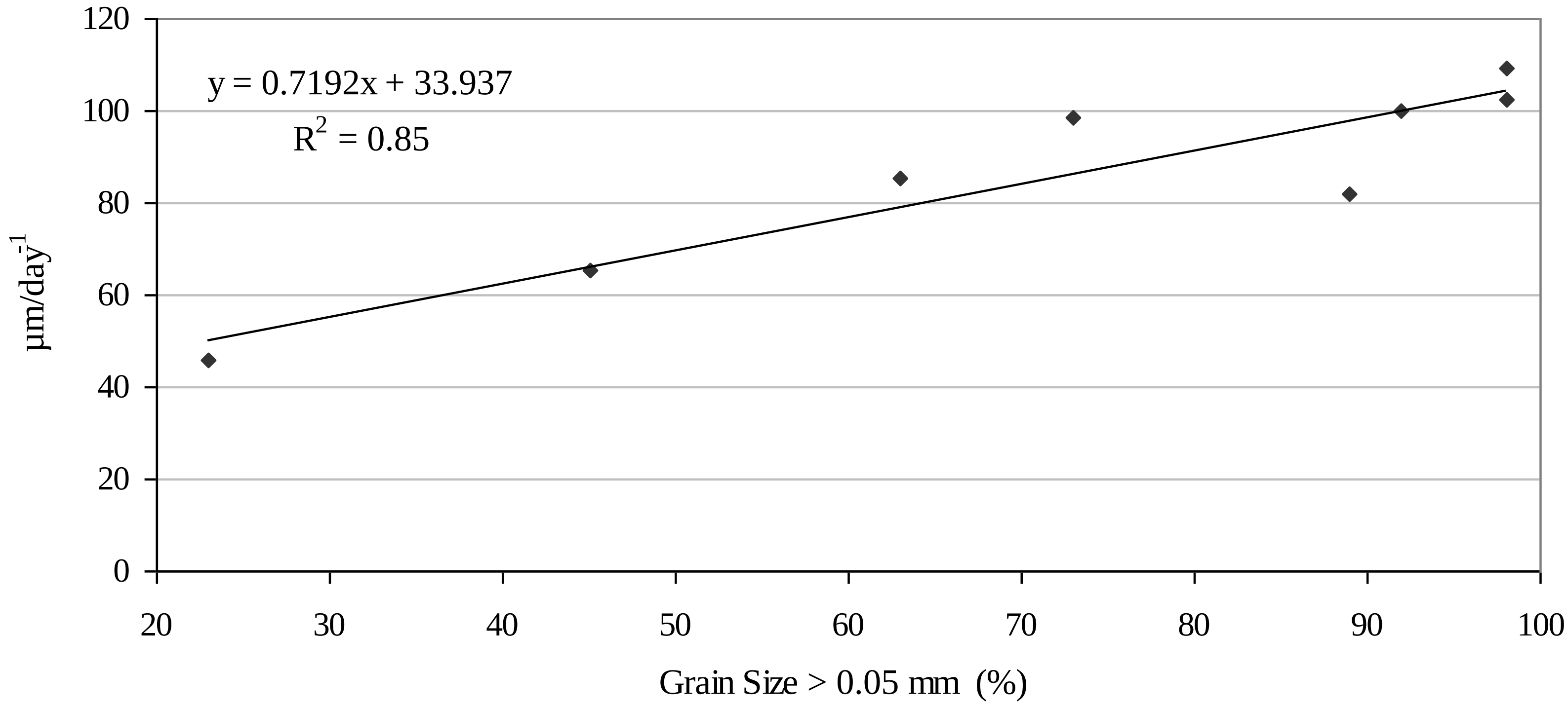


Figure 2.9. Regression analysis of soil particle size (Sand = <0.05 mm) predicting oyster growth on subaqueous landscape units (See Table 2.10). Note the positive slope of the regression.

CHAPTER 3:

SUBAQUEOUS SOIL TEMPERATURE

ABSTRACT

Soil temperature is often recorded because most processes related to soil formation and functions are temperature dependent. Since there are no soil temperature data for estuarine subaqueous soils, this parameter was investigated in two shallow coastal lagoons in Rhode Island. Temperature loggers were placed in the soil at two depths (25 and 50 cm) on three different subaqueous soil-landscape units. Soil temperature was compared among landscape units, overlying water temperature, and a tidal marsh (Pawcatuck series) soil. Subaqueous soil temperature varied slightly among landscape units, and appears to be primarily influenced by water temperature and depth. Soil temperatures at 50 cm below the soil surface showed less fluctuations than temperatures collected at 25 cm from the soil-water column interface or in the water column. Mean annual soil temperatures measured at 50 cm ranged from 12.3 – 12.6 ºC in Washover Fan and Lagoon Bottom soils respectively. Subaqueous soil temperatures were similar to but slightly warmer than the tidal marsh soil. Differences between mean summer and mean winter soil temperatures were greater than 10 ºC and within the mesic soil temperature regime, similar to subaerial soils of Rhode Island.

INTRODUCTION

Soil temperature is often measured due to its importance in many soil functions and processes (Soil Survey Staff, 1999). Soil temperature regulates biological and chemical rates of reactions (Paul and Clark, 1996; Soil Survey Staff, 1999). Below the freezing point of water, biotic activity slows, and between 0 and 5 °C root growth stops or slows for higher level plant species (Soil Survey Staff, 1999; Rabenhorst, 2005). Soil temperature has been used in definitions for biological zero and growing season in soil taxonomy and wetland sciences (USACOE, 1987; Rabenhorst, 2005). For example, oxidation and reduction (redox) reactions are often noted as being temperature dependent (Vaughan et al., 2009). Carbon storage, CO_2 efflux, nutrient availability, and bacterial mineral reduction rates have also been correlated to soil temperature (Abdollahi and Nedwell, 1979; Peterjohn et al., 1994; Schimel et al., 1994; Fang and Moncrieff, 2001; Davidson and Janssens, 2006). Temperature also plays an important role in soil formation, as it is part of the climate which was described by Jenny's (1941) factors of soil formation.

Daily cycles of temperature decrease in amplitude as you go deeper in the soil profile to a depth of about 50 cm, thus a 50 cm depth is typically used to define soil temperature (Soil Survey Division Staff, 1993; Rabenhorst, 2005). For example, in Soil Taxonomy (Soil Survey Staff, 2010), temperature regimes are defined based on data collected at a 50 cm depth. There are five temperature regimes based on average soil temperatures, and an additional four regimes for soils where the mean summer soil temperature minus the mean winter soil temperature is less than 5 ºC, are used to classify soil temperature (Soil Survey Staff, 2010). Mean annual soil temperature can be either recorded or estimated by adding 1 °C to the mean annual air temperature (Fanning and Fanning, 1989; Soil Survey Staff, 1999). Mean summer soil temperature is defined as the temperature of the soil during the three months of summer, June, July and August, while Mean winter soil temperature is defined as the soil temperature during the winter months of December, January, February (Soil Survey Staff, 2010).

Although many factors influence soil temperature, it is air temperature, or water temperature in the case of subaqueous soils, that contribute the most influence (Soil Survey Division Staff, 1993). While most subaerial soils have an estimate or direct readings of soil temperature, no information regarding subaqueous soil temperature taken at different depths and soil-landscape units is published. This research looks at the mean annual, mean summer, and mean winter soil temperature of subaqueous soils recorded at different landscape units and depths in coastal lagoons of Rhode Island.

MATERIALS AND METHODS

Ninigret and Quonochontaug Ponds were chosen as study sites for the investigation of subaqueous soil temperature (See Figure 2.1). Thermochron iButtons® model 1921G (Embedded Data Systems, Lawrenceburg, KY) were used to record soil and water temperature. The iButton was placed in a water-proof container made from a 10.5 x 3 cm plastic centrifuge tube, a number 6 rubber stopper, drierite, clean loamy sand soil material, and cotton balls. Approximately 2 cm of the bottom of the centrifuge tube was filled with drierite. Five centimeters of clean, dry, loamy sand soil material was then poured into the tube. A Cotton ball was then placed into the centrifuge tube and the iButton placed on top. A second cotton ball was then pushed down on top of the iButton, filing the rest of the tube with clean loamy sand soil material and stoppered with a rubber stopper. Hot glue was then used to glue the rubber stopper to the centrifuge bottle to ensure no leakage. Recent discussions have suggested changing the depth for measuring soil temperature for defining the growing season in wetlands to 25 cm (USACOE, 200X), so the iButtons were buried at varying depths of 25 and 50 cm using a bucket auger. A line attached the iButton to a cinder block on the soil surface where a second iButton was tied to record the water temperature.

Two subaqueous landscape units were chosen in Ninigret Pond for the investigation of subaqueous soil temperature. Two different Lagoon Bottom sites were selected on in Ninigret Pond, while one site was used on the Washover Fan. At the Lagoon Bottom sites, iButtons were buried in the soil at 25 cm (NLB 25 cm), and at 50 cm (NLB 50 cm) (Table 3.1). At the Washover Fan site, iButtons were buried in at 50 cm (NWF 25 cm; NWF 50 cm) (Table 3.1). Water temperature was recorded at all sites by attaching an iButton to a cinderblock resting on the soil surface. Water depths ranged from 1.00 – 1.50 meters (Table 3.1). The iButtons in Ninigret Pond were placed in the field in September 2008, set to record temperature every 4 hours starting at noon, and retrieved in August 2009.

In Quonochontaug Pond, soil temperature was measured on Washover Fan, Lagoon Bottom, and Submerged Mainland Beach subaqueous soils. All iButtons were buried at a depth of 25 cm. Water temperature was also recorded at each site. Water depths in Quonochontaug Pond ranged from 0.79 – 3.19 meters (Table 3.1). The iButtons were placed in the field in July 2008, set to record temperature every four hours starting at noon, and retrieved in June 2009. For comparison, soil temperature data collected from November 2008 – August 2009 was obtained from a tidal marsh soil (Pawcatuck series). Mean annual soil temperature, mean summer soil temperature, and mean winter soil temperature were calculated as defined by Soil Taxonomy (Soil Survey Staff, 2010).

RESULTS

In Ninigret Pond, mean annual soil temperature varied little (12.3 – 12.6 ºC) regardless of temperature logger depth (25 or 50 cm), or subaqueous landscape unit (Table 3.1). These values are similar (albeit warmer) than the mean annual soil temperatures recorded in Quonochontaug Pond on Washover Fan (QWF 25 cm), and Submerged Mainland Beach sites (QSMB 25 cm) (Both 12.1 ºC) (Table 3.1). The one exception was the mean annual soil temperature recorded at Lagoon Bottom in Quonochontaug Pond (QLB 25 cm; 10.8 ºC). The mean annual soil temperature of the tidal marsh soil was noticeably lower (8.7 ºC) than subaqueous soil temperature (Table 3.1). Mean annual soil temperatures were similar to water temperatures (Table 3.1), although at a daily or a weekly basis, fluctuations in water temperature were much greater than soil temperature (Figure 3.1). In general, daily, weekly and seasonal fluctuations in soil temperature were greater in the Washover Fan than in the Lagoon Bottom soils (Figure 3.2, 3.3).

Mean annual water temperatures were similar with respect to soil temperature (11.5 – 12.4 ºC) (Table 3.1). This suggests that mean annual water temperature would serve as good surrogate for mean annual soil temperature.

Mean summer soil temperatures varied among landscape units and between depths (Table 3.1). All of the subaqueous soils had mean summer soil temperatures that were warmer than the mean summer temperature (16.8 ºC) of the tidal marsh soil (Table 3.1). Both fine textured soils from Lagoon Bottom (Ninigret and Quonochontaug Ponds) had the lowest mean summer soil temperatures (Table 3.1). Temperatures recorded at 50 cm (NLB 50 cm; NWF 50 cm) had cooler mean summer temperatures than soil temperatures within sites recorded at 25 cm (NLB 25 cm; NWF 25 cm), more variability in temperature was recorded at 25 cm than at 50 cm (Table 3.1; Figures 3.2, 3.3). Summer water temperatures were slightly warmer than summer soil temperatures (Table 3.1).

Mean winter soil temperature exhibited a wide variation in temperature much like mean summer temperature, ranging from 2.9 – 7.6 ºC (Table 3.1). The mean winter soil temperature of the tidal marsh soil was 4.5 ºC. Sandy, Washover Fan subaqueous soils had the lowest winter soil temperatures, while Lagoon Bottom and Submerged Mainland Beach landscape units were slightly warmer (Table 3.1). In both cases, winter soil temperature taken at 50 cm was warmer in Washover Fan and Lagoon Bottom soils than winter temperatures taken at 25 cm (Table 3.1).

Differences between mean summer and mean winter soil temperatures ranged from 10.3 – 18.8 ºC (Table 3.1). Smaller differences between mean summer and mean winter soil temperatures were observed on Lagoon Bottom soil (Table 3.1). Depth of soil recordings also affected differences in summer and winter temperatures, where differences were smaller among the deeper buried iButtons (NWF 50 cm and NLB 50 cm) (Table 3.1).

DISCUSSION

Differences in subaqueous soil temperature among soil-landscape units, seems to be largely controlled by a couple of factors. First, subaqueous soils exist at different water column depths. Water temperature varied among sites, with deeper depths having the lowest water temperatures in the summer, and cooler temperatures in the winter. Since water temperature, like air temperature in subaerial soils is the greatest controlling factor, soil temperature showed ties to water temperature effects.

A controlling factor in the fluctuation of water temperature was water depth. At deeper depths, less fluctuation in water temperature was observed due to increases in the distance of the air-water interface. While large fluctuations in air temperature may affect shallow sites and the subaqueous soils underneath, deep water buffers these daily and weekly variations. The effect of water depth can be clearly seen when comparing water temperatures at Lagoon Bottom and Washover Fan in Quonochontaug Pond where the deeper site shows less variability and cooler summer temperatures (Figure 3.4). Buffering of the water temperature clearly affects soil temperature (Figure 3.5).

Soil texture may also affect subaqueous soil temperature fluctuations. For example, although in Ninigret Pond at the Lagoon Bottom 25 cm site and Washover Fan site have equal water depths, and equivalent water temperatures, there are differences in mean summer and winter soil temperatures (Table 3.1). The coarser textured soil (Washover Fan) is warmer in the summer and cooler in the winter than the finer textured Lagoon Bottom. This suggests that the coarser textured soil appears to be more influenced by the overlying water column temperature, being affected by water temperature earlier than the Lagoon Bottom Soil (Figure 3.2).

There were several other factors that may contribute to subaqueous soil temperature that I was not able to test. Tidal range, vegetation, distance from the inlet, ground water inputs, and flow rates all may affect subaqueous soil temperature indirectly through changes in water temperature. In some cases, tidal cycling may influence the temperature of the water by bringing in cooler water on the flood tide, while solar radiation warms the shallow water during the ebb tide. These fluctuations can be seen in water temperature data from Quonochontaug Pond, where cycling is evident (Figure 3.4.). Eelgrass may serve as a buffer to changes in daily temperature, further affecting subaqueous soil temperature. It should be noted that the Lagoon Bottom sites used in this study had nearly 100% eelgrass cover, while every other soil investigated (in Ninigret and Quonochontaug Pond) had no, or sparse (<1%) eelgrass cover. In order to test this hypothesis, temperature loggers should have been placed at different locations within landscape units on varying densities of eelgrass cover.

Subaerial soils in Rhode Island classify within the mesic temperature regime (Soil Survey Staff, 2010). The subaqueous soils I studied in these coastal lagoons also meet the requirements for a mesic temperature regime. Mean annual subaqueous soil temperature can be estimated by using the mean annual water temperature at the soil-water interface. Mean summer and winter temperatures however, change with respect to water temperature, with soil temperatures generally being warmer in the winter and cooler in the summer.

Table 3.1. Subaqueous soil and water temperatures recorded by iButton at various landscape units and depths recorded by iButton September 20, 2008 – August 27, 2009. Sample rate = 4 hours. Landscape units include Ninigret Pond Lagoon Bottom (NLB), Ninigret Pond Washover Fan (NWF), Quonochontaug Pond Washover Fan (QWF), Quonochontaug Pond Lagoon Bottom (QLB), and Quonochontaug Submerged Mainland Beach (QSMB).

Soil Temperatures (ºC)

Site (iButton depth)	Annual	Summer	Winter	Summer - Winter	Water Depth (m)
NWF (25 cm)	12.3	22.3	3.5	18.8	1.04
NWF (50 cm)	12.3	20.5	4.9	15.6	"
NLB (25 cm)	12.5	19.8	6.3	13.5	1.00
NLB (50 cm)*	12.6	17.9	7.6	10.3	1.50
QWF (25 cm)	12.1	21.6	3.5	18.3	0.79
QSMB (25 cm)	12.1	20.7	4.7	16.0	0.99
QLB (25 cm)	10.8	16.9	5.6	11.4	3.19
Pawcatuck (40 cm)	8.7	16.8	4.5	12.3	-
Water Temperatures (ºC)					
NWF	11.5	23.0	2.2	19.7	1.04
NLB	12.0	22.3	2.8	19.5	1.00
NLB*	12.0	20.5	4.4	16.1	1.50
QWF	12.1	22.0	3.5	18.5	0.79
QSMB	12.4	21.8	4.3	17.5	0.99
QLB	11.2	19.5	4.2	15.3	3.19

* Second Lagoon Bottom site in Ninigret Pond

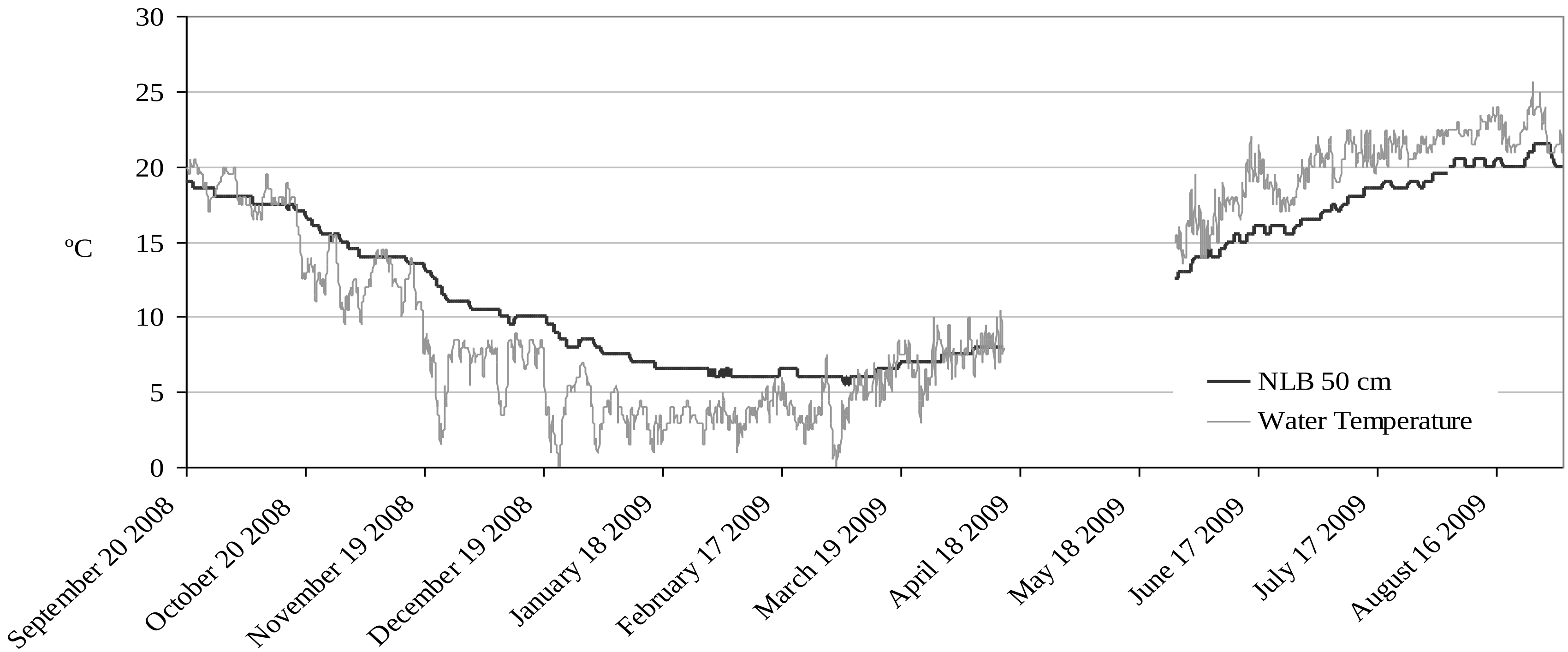


Figure 3.1. Ninigret Lagoon Bottom (NLB) soil temperature taken at 50 cm from September 20, 2008 – August 27 2009. Water temperature measured at the soil-water interface is also included.

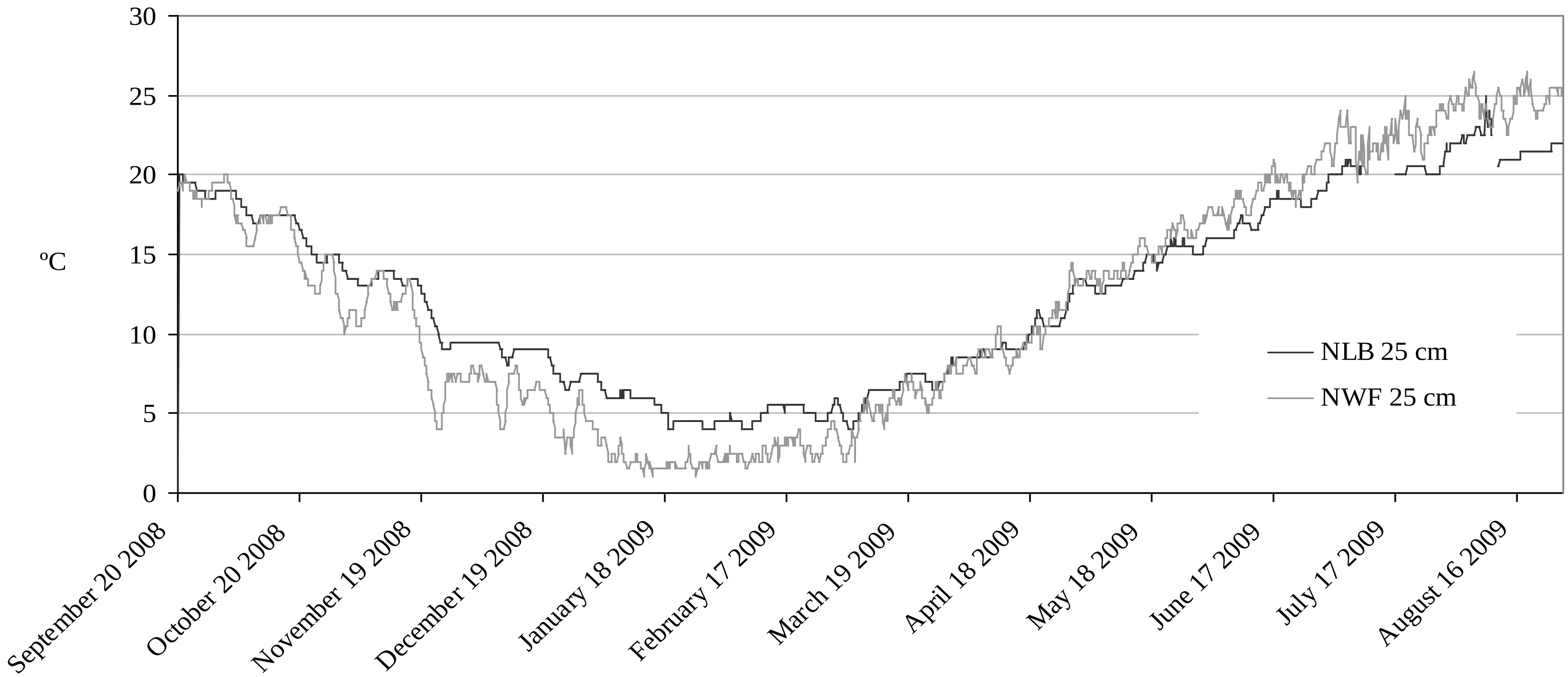


Figure 3.2. Soil temperatures collected from iButtons buried at 25 cm in Ninigret Pond Lagoon Bottom (NLB) and Ninigret Pond Washover Fan (NWF) sites. Both sites have similar water depths (1.00; 1.04 m). The coarser textured soil (NWF) has higher summer temperatures and lower winter temperatures suggesting a texture effect on soil temperature.

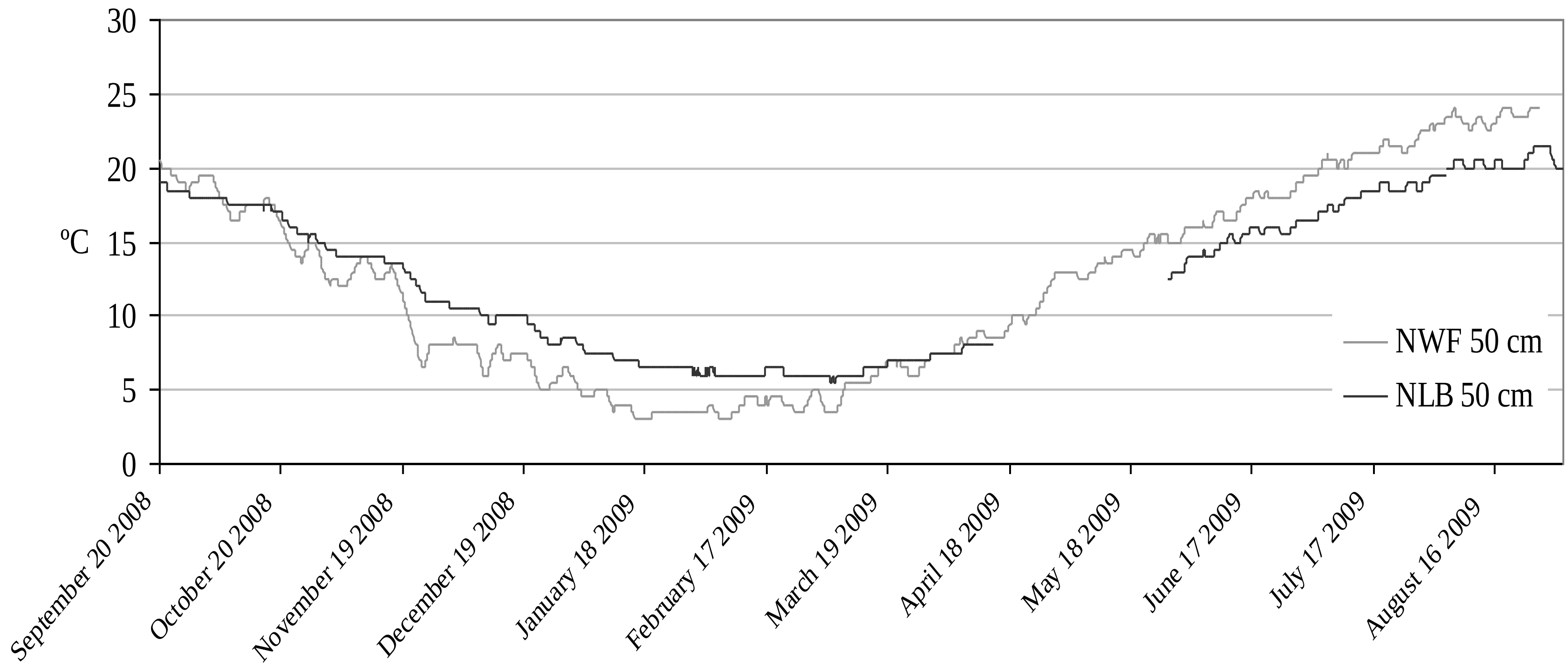


Figure 3.3. Soil temperatures recorded at 50 cm from September 20, 2008 – August 27, 2009 Ninigret Pond Washover Fan (NWF) and Ninigret Pond Lagoon Bottom (NLB) sites.

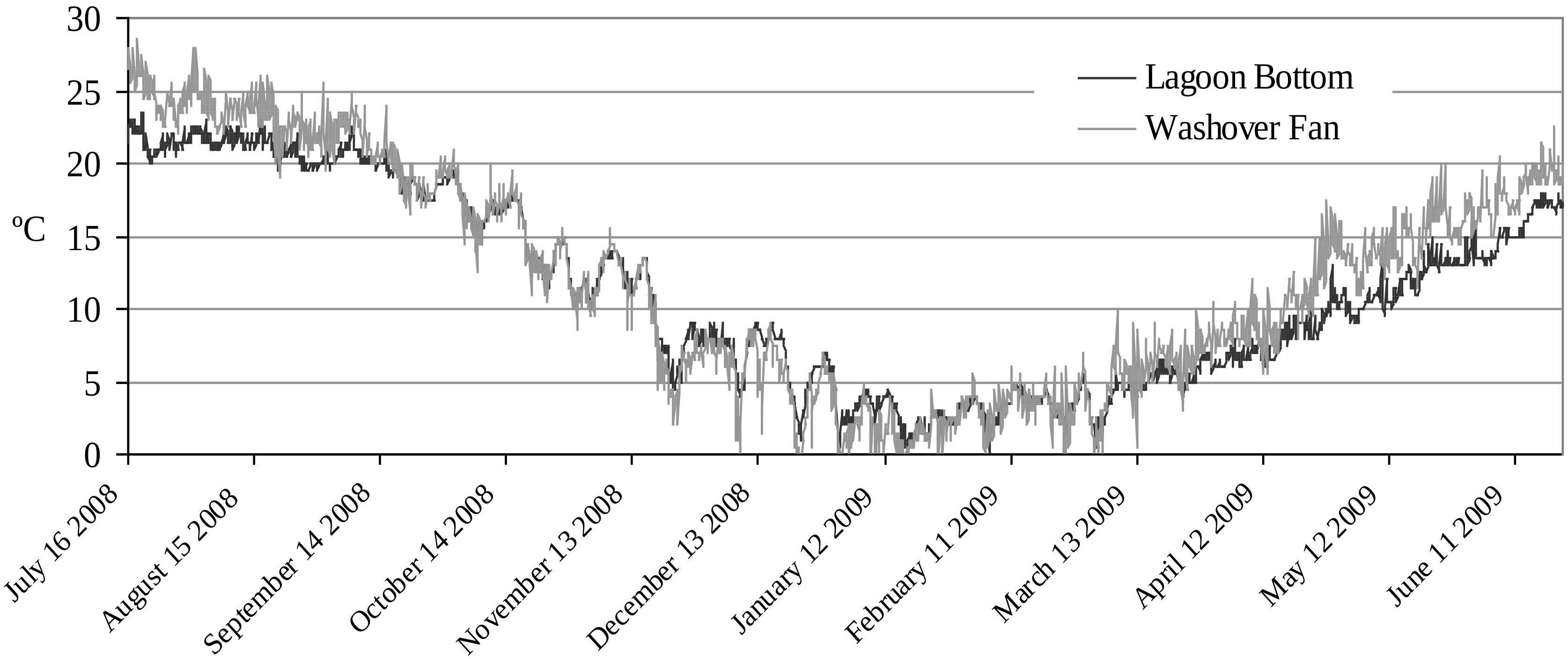


Figure 3.4. Water temperature fluctuations in Quonochontaug Pond. Water temperature fluxes decreased with increasing water depth as can be seen between Washover Fan (0.79 meters deep) and Lagoon Bottom (3.19 meters deep).

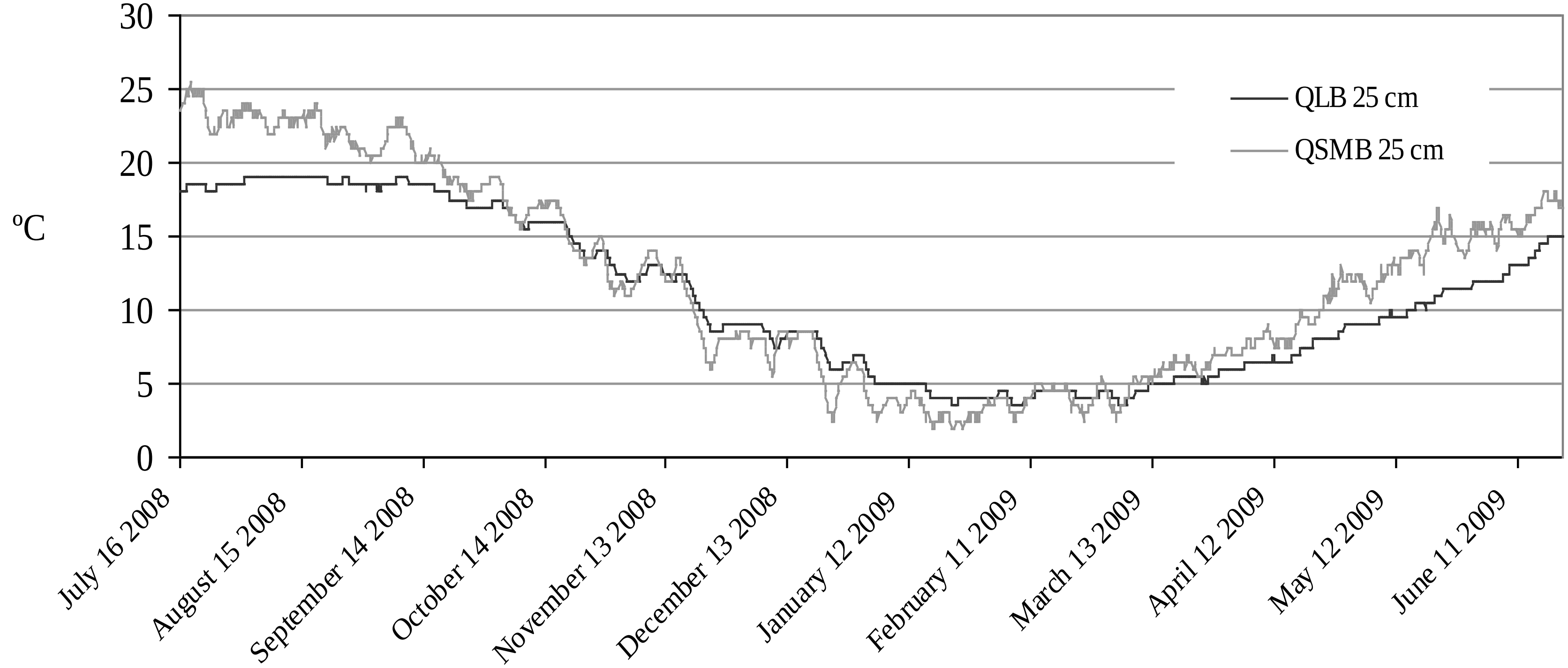


Figure 3.5. Soil temperature data collected in Quonochontaug Pond on Lagoon Bottom (QLB) and Submerged Mainland Beach (QSMB) landscape units. QLB was taken at a site with a water depth of 3.19 meters while QSMB was taken at a site with a water depth of 1.0 meters.

APPENDIX 1: SUBAQUEOUS SOI L INTERPRETATIONS

Table A.1. Users of Subaqueous soil survey data for specific resource management (King, 2003).

Resource Managers

US-EPA, MD-DNR, MDE
Chesapeake Bay Program
DE Inland Bay Program
Maryland Coastal Bays Program
Egg Harbor, NJ
Baltimore Harbor/Bay Dredging US-ACE
US-ACE, US-DI
Pamlico-Albermarle Sound NEP Program
NOAA
US-ACE, MD-DNR, Wor SWCD,
DI Assateague Island National Park
Private Aquaculture Industry
Shellfish Harvest Industry
NRCS, RCD, DE CIB, DNREC
DE Sierra Club
DNREC

Specific Soil Resource Based Interpretations

SAV Restoration
Crab Habitat
Clam Stocking
Management for Sustainable Production Clam, Oyster, and Scallop
Nutrient Reduction
Pathogens Pfesteria Cyst Residence Sites
Benthic Preservation Site Identification
Wildlife Management
Wading Shore Birds, Migratory Waterfowl, Nurseries and Spawning Areas
Habitat Protection for Horseshoe Crab and Diamondback Terrapin
Dredging Island Creation
Tidal Marsh Protection and Creation
Bathymetric Map
Navigational Channel Creation/Maintenance
Effects of Dredging on Benthic Ecology
Off Site Disposal of Dredge Spoil
Acid-Sulfate Weathering Hazards
Dune Maintenance/Replenishment

APPENDIX 2: MONTHLY MEAN MESOCOSM LEACHATE pH

Monthly mean mesocosm leachate pH

Greenwich Bay

Landscape: **GBMS**

Date	pH	σ		C*v*	SE
7/30/07	**7.95**	0.24	2	3.02	0.17
8/13/07	**7.80**	1.55	7	19.93	0.59
9/15/07	**7.44**	1.23	7	16.57	0.47
4/29/08	**6.95**	0.85	4	12.19	0.42
6/25/08	**8.72**	0.37	5	4.23	0.17
7/24/08	**8.76**	0.46	4	5.27	0.23
8/7/08	**9.20**	0.78	3	8.53	0.45
9/29/08	**8.69**	1.03	6	11.89	0.42
11/16/08	**7.34**	0.76	4	10.38	0.38
12/16/08	**8.30**	1.10	4	13.30	0.55
3/30/09	**8.00**	0.20	4	2.48	0.10
4/21/09	**8.67**	0.43	3	4.96	0.25
5/31/09	**8.36**	1.38	4	16.52	0.69
6/23/09	**9.48**	0.60	4	6.38	0.30
7/26/2009	**9.49**	0.69	3	7.31	0.40
8/31/2009	**9.19**	0.93	3	10.14	0.54

Monthly mean mesocosm leachate pH

Greenwich Bay

Landscape: **GBSS**

Date	pH	σ		C*v*	SE
7/30/07	**-**	-	-	-	-
8/13/07	**8.05**	0.39	3	4.85	0.23
9/15/07	**7.50**	0.19	3	2.54	0.11
4/29/08	**6.50**	1.38	4	21.27	0.69
6/25/08	**7.14**	0.36	2	5.05	0.25
7/24/08	**8.17**	0.83	3	10.15	0.48
8/7/08	**7.75**	0.00	1	0.00	0.00
9/29/08	**8.41**	0.87	7	10.38	0.33
11/16/08	**7.85**	1.29	2	16.49	0.91
12/16/08	**8.55**	0.84	4	9.83	0.42
3/30/09	**6.53**	1.91	4	29.29	0.96
4/21/09	**8.83**	0.92	4	10.44	0.46
5/31/09	**8.09**	0.64	4	7.96	0.32
6/23/09	**8.16**	0.60	4	7.39	0.30
7/26/2009	**9.10**	0.32	4	3.56	0.16
8/31/2009	**8.98**	0.79	3	8.83	0.46

APPENDIX 2: MONTHLY MEAN MESOCOSM LEACHATE pH

Monthly mean mesocosm leachate pH

Greenwich Bay

Landscape: **GBBF**

Date	pH	σ	n	C*v*	SE
7/30/07	**7.79**	0.89	2	11.44	0.63
8/13/07	**8.24**	0.42	6	5.09	0.17
9/15/07	**3.38**	0.47	7	13.86	0.18
4/29/08	**3.49**	0.23	5	6.47	0.10
6/25/08	**5.62**	1.08	3	19.14	0.62
7/24/08	**3.47**	0.11	4	3.06	0.05
8/7/08	**-**	-	-	-	-
9/29/08	**3.23**	0.21	7	6.47	0.08
11/16/08	**3.49**	0.19	2	5.48	0.13
12/16/08	**3.75**	0.08	4	2.04	0.04
3/30/09	**4.93**	2.35	3	47.70	1.36
4/21/09	**3.62**	0.05	4	1.51	0.03
5/31/09	**3.67**	0.05	4	1.35	0.02
6/23/09	**3.67**	0.06	4	1.60	0.03
7/26/2009	**3.52**	0.14	4	3.89	0.07
8/31/2009	**3.58**	0.15	3	4.24	0.09

Monthly mean mesocosm leachate pH

Greenwich Bay

Landscape: **GBIC**

Date	pH	σ		C*v*	SE
7/30/07	**7.19**	0.00	1	1.00	0.00
8/13/07	**8.23**	0.44	7	5.34	0.17
9/15/07	**7.40**	0.50	4	6.78	0.25
4/29/08	**4.02**	0.63	5	15.80	0.28
6/25/08	**3.29**	0.13	4	3.98	0.07
7/24/08	**3.23**	0.07	4	2.05	0.03
8/7/08	**3.19**	0.10	4	3.26	0.05
9/29/08	**3.34**	0.15	8	4.37	0.05
11/16/08	**3.39**	0.07	3	2.04	0.04
12/16/08	**3.62**	0.04	4	1.14	0.02
3/30/09	**3.60**	0.11	4	3.02	0.05
4/21/09	**3.71**	0.08	4	2.17	0.04
5/31/09	**3.76**	0.09	4	2.50	0.05
6/23/09	**3.85**	0.12	4	3.24	0.06
7/26/2009	**3.85**	0.15	4	4.01	0.08
8/31/2009	**3.88**	0.12	4	3.19	0.06

APPENDIX 2: MONTHLY MEAN MESOCOSM LEACHATE pH

Monthly mean mesocosm leachate pH

Wickford Harbor

Landscape: **WMS**

Date	pH	σ		C*v*	SE
7/30/07	**7.52**	0.38	10	5.08	0.12
8/13/07	**6.58**	1.48	5	22.41	0.66
9/15/07	**5.45**	1.66	8	30.52	0.59
4/29/08	**6.29**	1.50	4	23.87	0.75
6/25/08	**5.50**	1.38	5	25.11	0.62
7/24/08	**5.40**	0.57	4	10.49	0.28
8/7/08	**5.72**	1.05	4	18.46	0.53
9/29/08	**5.69**	1.65	8	29.00	0.58
11/16/08	**6.80**	0.60	4	8.75	0.30
12/16/08	**-**	-	-	-	-
3/30/09	**8.31**	2.26	2	27.23	1.60
4/21/09	**8.82**	1.07	4	12.13	0.53
5/31/09	**7.08**	0.36	4	5.04	0.18
6/23/09	**6.38**	0.28	4	4.37	0.14
7/26/2009	**7.56**	1.13	4	14.95	0.57
8/31/2009	**6.64**	0.15	3	2.19	0.08

Monthly mean mesocosm leachate pH

Wickford Harbor

Landscape: **WSS**

Date	pH	σ		C*v*	SE
7/30/07	**7.32**	0.51	18	7.04	0.12
8/13/07	**7.73**	0.36	6	4.68	0.15
9/15/07	**8.45**	0.85	8	10.03	0.30
4/29/08	**7.58**	0.81	5	10.64	0.36
6/25/08	**8.64**	1.71	3	19.85	0.99
7/24/08	**7.29**	1.86	4	25.47	0.93
8/7/08	**8.40**	2.59	4	30.88	1.30
9/29/08	**8.97**	1.08	7	12.04	0.41
11/16/08	**7.39**	2.79	3	37.72	1.61
12/16/08	**-**	-	-	-	-
3/30/09	**8.41**	1.10	4	13.07	0.55
4/21/09	**9.46**	0.28	3	2.94	0.16
5/31/09	**8.98**	1.19	4	13.21	0.59
6/23/09	**9.92**	0.49	3	4.94	0.28
7/26/2009	**7.85**	1.14	3	14.54	0.66
8/31/2009	**9.06**	0.52	2	5.70	0.37

APPENDIX 2: MONTHLY MEAN MESOCOSM LEACHATE pH

Monthly mean mesocosm leachate pH

Wickford Harbor

Landscape: **WBF**

Date	pH	σ		C*v*	SE
7/30/07	**7.34**	0.60	11	8.12	0.18
8/13/07	**5.84**	2.31	3	39.59	1.34
9/15/07	**3.11**	0.19	8	6.23	0.07
4/29/08	**3.13**	0.37	8	11.84	0.13
6/25/08	**2.86**	0.34	5	11.96	0.15
7/24/08	**2.87**	0.20	4	6.87	0.10
8/7/08	**2.67**	0.05	4	1.98	0.03
9/29/08	**2.81**	0.12	8	4.16	0.04
11/16/08	**3.04**	0.02	4	0.63	0.01
12/16/08	**3.24**	0.00	1	0.00	0.00
3/30/09	**3.14**	0.15	3	4.76	0.09
4/21/09	**3.31**	0.22	4	6.72	0.11
5/31/09	**3.49**	0.29	4	8.34	0.15
6/23/09	**3.39**	0.22	4	6.51	0.11
7/26/2009	**3.35**	0.20	3	5.92	0.11
8/31/2009	**3.34**	0.09	4	2.55	0.04

Monthly mean mesocosm leachate pH

Wickford Harbor

Landscape: **WIC**

Date	pH	σ		C*v*	SE
7/30/07	**7.47**	0.43	13	5.77	0.12
8/13/07	**4.00**	0.95	6	23.83	0.39
9/15/07	**3.23**	0.22	7	6.82	0.08
4/29/08	**3.00**	0.42	7	13.97	0.16
6/25/08	**2.89**	0.33	6	11.45	0.13
7/24/08	**2.81**	0.11	4	3.80	0.05
8/7/08	**2.69**	0.07	4	2.49	0.03
9/29/08	**2.90**	0.10	8	3.44	0.04
11/16/08	**3.04**	0.05	4	1.67	0.03
12/16/08	**3.22**	0.00	1	0.00	0.00
3/30/09	**3.17**	0.06	3	1.92	0.04
4/21/09	**3.23**	0.06	2	1.75	0.04
5/31/09	**3.30**	0.12	2	3.65	0.08
6/23/09	**3.29**	0.03	2	0.86	0.02
7/26/2009	**3.51**	0.33	4	9.39	0.16
8/31/2009	**3.63**	0.27	4	7.39	0.13

APPENDIX 2: MONTHLY MEAN MESOCOSM LEACHATE pH

Monthly mean mesocosm leachate pH

Ninigret Pond

Landscape: NFTD

Date	pH	σ		C*v*	SE
7/30/07	**7.64**	0.31	10	4.01	0.10
8/13/07	**7.87**	0.51	4	6.47	0.25
9/15/07	**7.67**	0.67	8	8.71	0.24
4/29/08	**8.11**	0.73	6	8.94	0.30
6/25/08	**7.32**	1.20	5	16.38	0.54
7/24/08	**8.57**	0.87	3	10.12	0.50
8/7/08	**9.71**	0.33	3	3.36	0.19
9/29/08	**9.75**	0.59	6	6.10	0.24
11/16/08	**8.27**	0.85	4	10.26	0.42
12/16/08	**-**	-	-	-	-
3/30/09	**8.58**	0.00	1	0.00	0.00
4/21/09	**8.85**	0.23	4	2.60	0.12
5/31/09	**8.31**	0.66	3	7.92	0.38
6/23/09	**8.54**	0.53	4	6.19	0.26
7/26/2009	**9.07**	0.28	4	3.08	0.14
8/31/2009	**9.11**	0.22	4	2.37	0.11

Monthly mean mesocosm leachate pH

Ninigret Pond

Landscape: NWF

Date	pH	σ		C*v*	SE
7/30/07	**7.55**	0.64	17	8.53	0.16
8/13/07	**7.70**	0.80	8	10.34	0.28
9/15/07	**8.68**	0.75	8	8.63	0.26
4/29/08	**7.82**	0.59	8	7.60	0.21
6/25/08	**8.49**	0.75	5	8.87	0.34
7/24/08	**5.22**	2.43	4	46.59	1.22
8/7/08	**4.89**	1.82	4	37.23	0.91
9/29/08	**5.57**	2.80	8	50.20	0.99
11/16/08	**5.88**	2.73	4	46.53	1.37
12/16/08	**8.80**	1.39	2	15.84	0.98
3/30/09	**7.58**	3.31	3	43.70	1.91
4/21/09	**6.56**	2.79	4	42.50	1.39
5/31/09	**6.76**	3.12	4	46.21	1.56
6/23/09	**6.85**	3.06	4	44.77	1.53
7/26/2009	**7.18**	2.70	4	37.61	1.35
8/31/2009	**6.36**	3.37	3	52.99	1.95

APPENDIX 2: MONTHLY MEAN MESOCOSM LEACHATE pH

Monthly mean mesocosm leachate pH

Ninigret Pond

Landscape: NLB

Date	pH	σ	n	C*v*	SE
7/30/07	**7.86**	0.33	14	4.23	0.09
8/13/07	**6.95**	0.27	4	3.86	0.13
9/15/07	**5.80**	1.29	7	22.24	0.49
4/29/08	**3.80**	0.50	8	13.11	0.18
6/25/08	**3.93**	0.52	5	13.24	0.23
7/24/08	**3.28**	0.14	3	4.32	0.08
8/7/08	**3.41**	0.48	4	14.15	0.24
9/29/08	**3.36**	0.20	8	5.89	0.07
11/16/08	**3.63**	0.11	4	2.99	0.05
12/16/08	**3.96**	0.10	2	2.50	0.07
3/30/09	**4.08**	0.40	3	9.77	0.23
4/21/09	**3.87**	0.12	4	3.08	0.06
5/31/09	**4.00**	0.12	4	2.94	0.06
6/23/09	**3.91**	0.35	4	9.00	0.18
7/26/2009	**3.95**	0.16	4	3.94	0.08
8/31/2009	**3.96**	0.05	4	1.26	0.02

Monthly mean mesocosm leachate pH

Ninigret Pond

Landscape: NMC

Date	pH	σ		C*v*	SE
7/30/07	**6.89**	1.47	13	21.38	0.41
8/13/07	**2.96**	0.20	4	6.72	0.10
9/15/07	**2.81**	0.26	8	9.27	0.09
4/29/08	**4.19**	0.76	8	18.18	0.27
6/25/08	**5.49**	1.65	6	30.11	0.67
7/24/08	**3.71**	0.88	3	23.77	0.51
8/7/08	**3.98**	1.66	4	41.72	0.83
9/29/08	**4.70**	1.85	7	39.38	0.70
11/16/08	**4.42**	1.51	4	34.26	0.76
12/16/08	**3.48**	0.00	1	0.00	0.00
3/30/09	**5.24**	2.52	3	48.06	1.45
4/21/09	**5.07**	2.45	4	48.33	1.22
5/31/09	**5.58**	2.43	3	43.63	1.40
6/23/09	**3.92**	0.13	3	3.21	0.07
7/26/2009	**4.71**	1.84	4	39.12	0.92
8/31/2009	**5.98**	2.68	3	44.77	1.55

APPENDIX 2: MONTHLY MEAN MESOCOSM LEACHATE pH

Monthly mean mesocosm leachate pH

Quonochontaug Pond

Landscape: **QFTD**

Date	pH	σ		C*v*	SE
7/30/07	**7.64**	0.31	3	4.01	0.18
8/13/07	**7.87**	0.51	5	6.47	0.23
9/15/07	**7.67**	0.67	8	8.71	0.24
4/29/08	**8.11**	0.73	5	8.94	0.32
6/25/08	**7.32**	1.20	4	16.38	0.60
7/24/08	**8.57**	0.87	4	10.12	0.43
8/7/08	**9.71**	0.33	4	3.36	0.16
9/29/08	**9.75**	0.59	6	6.10	0.24
11/16/08	**8.27**	0.85	3	10.26	0.49
12/16/08	**-**	-	-	-	-
3/30/09	**8.58**	0.00	2	0.00	0.00
4/21/09	**8.85**	0.23	4	2.60	0.12
5/31/09	**8.31**	0.66	4	7.92	0.33
6/23/09	**8.54**	0.53	4	6.19	0.26
7/26/2009	**9.07**	0.28	4	3.08	0.14
8/31/2009	**9.11**	0.22	4	2.37	0.11

Monthly mean mesocosm leachate pH

Quonochontaug Pond

Landscape: **QWF**

Date	pH	σ		C*v*	SE
7/30/07	**7.47**	0.37	8	4.91	0.13
8/13/07	**8.49**	0.44	8	5.13	0.15
9/15/07	**9.51**	1.07	8	11.24	0.38
4/29/08	**8.27**	0.44	6	5.38	0.18
6/25/08	**9.14**	1.12	3	12.29	0.65
7/24/08	**8.90**	0.25	3	2.81	0.14
8/7/08	**8.99**	1.22	3	13.56	0.70
9/29/08	**9.68**	0.91	5	9.36	0.41
11/16/08	**9.06**	0.86	3	9.52	0.50
12/16/08	**9.36**	0.48	2	5.14	0.34
3/30/09	**9.10**	0.47	2	5.21	0.34
4/21/09	**9.78**	0.74	3	7.56	0.43
5/31/09	**9.15**	1.08	3	11.81	0.62
6/23/09	**9.25**	1.32	3	14.23	0.76
7/26/2009	**9.18**	0.82	3	8.98	0.48
8/31/2009	**9.17**	1.05	3	11.49	0.61

APPENDIX 2: MONTHLY MEAN MESOCOSM LEACHATE pH

Monthly mean mesocosm leachate pH

Quonochontaug Pond

Landscape: QLB

Date	pH	σ	n	C*v*	SE
7/30/07	**7.24**	0.42	9	5.81	0.14
8/13/07	**7.76**	0.53	6	6.79	0.22
9/15/07	**7.33**	0.29	5	3.99	0.13
4/29/08	**7.78**	0.60	6	7.74	0.25
6/25/08	**6.00**	2.09	5	34.83	0.94
7/24/08	**5.14**	1.82	3	35.44	1.05
8/7/08	**4.97**	1.84	4	37.02	0.92
9/29/08	**3.87**	0.26	7	6.66	0.10
11/16/08	**3.80**	0.23	4	5.97	0.11
12/16/08	**3.92**	0.01	2	0.18	0.00
3/30/09	**3.74**	0.11	3	2.89	0.06
4/21/09	**3.79**	0.13	4	3.47	0.07
5/31/09	**3.74**	0.26	3	6.97	0.15
6/23/09	**3.85**	0.26	4	6.69	0.13
7/26/2009	**3.63**	0.28	4	7.75	0.14
8/31/2009	**3.71**	0.22	3	5.91	0.13

Monthly mean mesocosm leachate pH

Quonochontaug Pond

Landscape: QMC

Date	pH	σ		C*v*	SE
7/30/07	**7.58**	0.71	7	9.40	0.27
8/13/07	**8.65**	0.34	6	3.97	0.14
9/15/07	**6.89**	0.79	6	11.49	0.32
4/29/08	**3.89**	0.48	6	12.22	0.19
6/25/08	**3.60**	0.49	4	13.63	0.24
7/24/08	**3.21**	0.09	4	2.73	0.04
8/7/08	**3.09**	0.19	4	6.00	0.09
9/29/08	**3.18**	0.28	7	8.74	0.11
11/16/08	**3.44**	0.12	4	3.37	0.06
12/16/08	**3.89**	0.18	4	4.64	0.09
3/30/09	**3.67**	0.19	4	5.23	0.10
4/21/09	**3.78**	0.13	4	3.39	0.06
5/31/09	**3.67**	0.23	4	6.37	0.12
6/23/09	**3.89**	0.10	4	2.63	0.05
7/26/2009	**3.74**	0.09	4	2.41	0.05
8/31/2009	**3.60**	0.10	4	2.70	0.05

APPENDIX 2: MONTHLY MEAN MESOCOSM LEACHATE pH

Monthly mean mesocosm leachate pH
Mixed Mesocosms LB% to WF% by Volume
Ninigret Pond

Mixture	**5% LB**					**10% LB**				
Date	**pH**	**σ**		**C*v***	**SE**	**pH**	**σ**		**C*v***	**SE**
8/7/08	**6.68**	2.92	3	43.70	1.69	**7.58**	0.84	3	11.12	0.49
9/29/08	**8.87**	0.00	1	0.00	0.00	**6.29**	1.29	4	20.47	0.64
11/16/08	**8.13**	0.00	1	0.00	0.00	**5.99**	2.43	2	40.52	1.72
12/16/08	**5.89**	2.52	2	42.90	1.79	**5.39**	1.48	2	27.44	1.05
3/30/09	**6.21**	2.13	2	34.30	1.51	**5.70**	2.24	2	39.36	1.59
4/21/09	**6.68**	3.22	2	48.27	2.28	**6.19**	2.98	2	48.21	2.11
5/31/09	**6.28**	2.51	2	40.00	1.78	**4.49**	0.30	2	6.78	0.22
6/23/09	**4.52**	0.26	2	5.79	0.18	**4.13**	0.25	2	6.16	0.18
7/26/09	**3.85**	0.41	2	10.65	0.29	**3.89**	0.11	2	2.73	0.08
8/31/09	**3.47**	0.00	1	0.00	0.00	**3.58**	0.08	2	2.18	0.05

Mixture	**20% LB**					**40% LB**				
Date	**pH**	**σ**		**C*v***	**SE**	**pH**	**σ**		**C*v***	**SE**
8/7/08	**6.00**	1.35	4	22.48	0.67	**6.87**	0.49	4	7.13	0.25
9/29/08	**3.17**	0.15	4	4.57	0.07	**4.14**	0.56	3	13.61	0.33
11/16/08	**3.84**	0.51	2	13.26	0.36	**3.36**	0.01	2	0.42	0.01
12/16/08	**4.09**	0.00	1	0.00	0.00	**3.76**	0.18	2	4.89	0.13
3/30/09	**3.93**	0.11	2	2.70	0.08	**3.67**	0.04	2	1.16	0.03
4/21/09	**3.71**	0.02	2	0.57	0.02	**3.64**	0.13	2	3.50	0.09
5/31/09	**3.63**	0.00	1	0.00	0.00	**3.56**	0.11	2	2.98	0.08
6/23/09	**3.60**	0.11	2	2.95	0.08	**3.58**	0.00	1	0.00	0.00
7/26/09	**3.48**	0.12	2	3.46	0.09	**3.39**	0.11	2	3.34	0.08
8/31/09	**3.48**	0.00	1	0.00	0.00	**3.28**	0.17	2	5.17	0.12

APPENDIX 3: MONTHLY MEAN MESOCOSM LEACHATE CONDUCTIVITY

Monthly mean mesocosm leachate Conductivity (dS $^{m-1}$)

Greenwich Bay

Landscape: **GBMS**

Date	dS m^{-1}	σ		C*v*	SE
7/30/07	**33.70**	1.13	2	3.36	0.80
8/13/07	**35.70**	1.99	7	5.58	0.75
9/15/07	**34.60**	3.87	7	11.20	1.46
4/29/08	**0.55**	0.04	4	7.82	0.02
6/25/08	**0.56**	0.22	5	38.72	0.10
7/24/08	**0.81**	0.29	4	36.37	0.15
8/7/08	**0.83**	0.20	3	24.33	0.12
9/29/08	**0.40**	0.39	6	97.48	0.16
11/16/08	**0.60**	0.25	4	41.60	0.13
12/16/08	**0.19**	0.08	4	43.54	0.04
3/30/09	**0.20**	0.04	4	22.88	0.02
4/21/09	**0.23**	0.07	3	33.08	0.04
5/31/09	**0.36**	0.14	4	39.00	0.07
6/23/09	**0.28**	0.03	4	10.80	0.01
7/26/2009	**0.70**	0.29	2	41.79	0.21
8/31/2009	**0.36**	0.07	3	18.72	0.04

Monthly mean mesocosm leachate Conductivity (dS $^{m-1}$)

Greenwich Bay

Landscape: **GBSS**

Date	dS m^{-1}	σ		C*v*	SE
7/30/07	**-**	-	-	-	-
8/13/07	**33.43**	1.05	3	3.14	0.61
9/15/07	**35.77**	9.56	3	26.72	5.52
4/29/08	**0.50**	0.29	4	58.39	0.14
6/25/08	**0.31**	0.23	2	72.37	0.16
7/24/08	**0.61**	0.34	3	55.60	0.20
8/7/08	**0.73**	0.00	1	0.00	0.00
9/29/08	**0.60**	0.40	7	66.79	0.15
11/16/08	**0.54**	0.05	2	8.43	0.03
12/16/08	**0.25**	0.15	4	60.41	0.08
3/30/09	**0.19**	0.02	4	7.88	0.01
4/21/09	**0.22**	0.07	4	31.53	0.04
5/31/09	**0.41**	0.13	4	31.78	0.06
6/23/09	**0.39**	0.04	4	9.99	0.02
7/26/2009	**0.50**	0.09	2	19.06	0.07
8/31/2009	**0.45**	0.11	3	24.06	0.06

APPENDIX 3: MONTHLY MEAN MESOCOSM LEACHATE CONDUCTIVITY

Monthly mean mesocosm leachate Conductivity (dS $^{m-1}$)

Greenwich Bay

Landscape: GBBF

Date	dS m^{-1}	σ	n	C*v*	SE
7/30/07	**26.35**	0.49	2	1.88	0.35
8/13/07	**25.90**	4.53	6	17.48	1.85
9/15/07	**22.03**	6.66	7	30.21	2.52
4/29/08	**2.56**	1.09	5	42.50	0.49
6/25/08	**0.42**	0.25	3	58.27	0.14
7/24/08	**1.77**	0.64	4	36.05	0.32
8/7/08	**-**	-	-	-	-
9/29/08	**3.20**	0.46	7	14.35	0.17
11/16/08	**2.54**	0.06	2	2.23	0.04
12/16/08	**1.52**	0.15	4	9.61	0.07
3/30/09	**1.79**	0.06	3	3.24	0.03
4/21/09	**1.49**	0.24	4	16.19	0.12
5/31/09	**1.31**	0.54	4	40.94	0.27
6/23/09	**2.09**	0.50	4	23.67	0.25
7/26/2009	**0.88**	0.41	2	46.39	0.29
8/31/2009	**1.28**	0.24	3	18.68	0.14

Monthly mean mesocosm leachate Conductivity (dS $^{m-1}$)

Greenwich Bay

Landscape: GBIC

Date	dS m^{-1}	σ		C*v*	SE
7/30/07	**29.50**	0.00	1	0.00	0.00
8/13/07	**31.39**	5.58	7	17.79	2.11
9/15/07	**31.41**	9.73	4	30.97	4.86
4/29/08	**5.44**	1.91	5	35.07	0.85
6/25/08	**3.91**	0.91	4	23.33	0.46
7/24/08	**3.30**	1.02	4	30.79	0.51
8/7/08	**5.00**	0.60	4	11.92	0.30
9/29/08	**3.23**	0.90	8	27.82	0.32
11/16/08	**3.05**	0.52	3	17.17	0.30
12/16/08	**1.47**	0.38	4	25.52	0.19
3/30/09	**1.93**	0.22	4	11.55	0.11
4/21/09	**1.47**	0.18	4	12.45	0.09
5/31/09	**1.43**	0.18	4	12.84	0.09
6/23/09	**1.65**	0.12	4	7.10	0.06
7/26/2009	**1.45**	0.18	4	12.70	0.09
8/31/2009	**0.76**	0.33	4	43.59	0.17

APPENDIX 3: MONTHLY MEAN MESOCOSM LEACHATE CONDUCTIVITY

Monthly mean mesocosm leachate Conductivity (dS $^{m-1}$)

Wickford Harbor

Landscape: **WMS**

Date	dS m-1	σ		C*v*	SE
7/30/07	**32.98**	3.25	10	9.85	1.03
8/13/07	**41.14**	3.28	5	7.98	1.47
9/15/07	**40.13**	3.67	8	9.15	1.30
4/29/08	**0.16**	0.07	4	42.77	0.03
6/25/08	**0.22**	0.08	5	34.75	0.03
7/24/08	**0.94**	1.37	4	146.52	0.69
8/7/08	**0.40**	0.18	4	43.35	0.09
9/29/08	**0.32**	0.15	8	48.76	0.05
11/16/08	**0.21**	0.10	4	48.81	0.05
12/16/08	**-**	-	-	-	-
3/30/09	**0.10**	0.02	2	23.24	0.02
4/21/09	**0.12**	0.02	4	15.23	0.01
5/31/09	**0.12**	0.04	4	38.03	0.02
6/23/09	**0.12**	0.05	4	40.94	0.02
7/26/2009	**0.12**	0.04	4	31.80	0.02
8/31/2009	**0.18**	0.05	3	30.30	0.03

Monthly mean mesocosm leachate Conductivity (dS $^{m-1}$)

Wickford Harbor

Landscape: **WSS**

Date	dS m-1	σ		C*v*	SE
7/30/07	**34.37**	4.90	18	14.26	1.16
8/13/07	**41.88**	4.08	6	9.74	1.67
9/15/07	**29.04**	9.65	8	33.22	3.41
4/29/08	**0.25**	0.14	5	53.99	0.06
6/25/08	**0.45**	0.14	3	30.67	0.08
7/24/08	**1.32**	1.00	4	75.98	0.50
8/7/08	**0.64**	0.43	4	66.92	0.21
9/29/08	**0.41**	0.21	7	52.32	0.08
11/16/08	**1.60**	2.27	3	141.29	1.31
12/16/08	**-**	-	-	-	-
3/30/09	**0.14**	0.08	4	55.72	0.04
4/21/09	**0.25**	0.13	3	51.40	0.07
5/31/09	**0.25**	0.11	4	41.85	0.05
6/23/09	**0.22**	0.01	3	3.77	0.00
7/26/2009	**0.27**	0.15	3	55.54	0.09
8/31/2009	**0.31**	0.12	2	37.10	0.08

APPENDIX 3: MONTHLY MEAN MESOCOSM LEACHATE CONDUCTIVITY

Monthly mean mesocosm leachate Conductivity (dS $^{m-1}$)

Wickford Harbor

Landscape: **WBF**

Date	dS m-1	σ		C*v*	SE
7/30/07	**30.87**	6.22	11	20.14	1.87
8/13/07	**24.98**	8.39	3	33.58	4.84
9/15/07	**30.36**	12.79	8	42.13	4.52
4/29/08	**5.03**	2.23	8	44.29	0.79
6/25/08	**2.06**	1.92	5	92.90	0.86
7/24/08	**1.67**	1.43	4	85.90	0.72
8/7/08	**3.47**	0.50	4	14.43	0.25
9/29/08	**2.96**	1.04	8	35.26	0.37
11/16/08	**1.98**	0.25	4	12.72	0.13
12/16/08	**1.51**	0.00	1	0.00	0.00
3/30/09	**0.72**	0.26	3	36.06	0.15
4/21/09	**0.58**	0.22	4	37.84	0.11
5/31/09	**0.58**	0.18	4	31.80	0.09
6/23/09	**0.81**	0.27	4	32.85	0.13
7/26/2009	**0.51**	0.17	3	32.35	0.10
8/31/2009	**0.41**	0.12	4	30.05	0.06

Monthly mean mesocosm leachate Conductivity (dS $^{m-1}$)

Wickford Harbor

Landscape: **WIC**

Date	dS m-1	σ		C*v*	SE
7/30/07	**27.31**	4.83	13	17.69	1.34
8/13/07	**25.30**	6.61	6	26.14	2.70
9/15/07	**16.28**	11.30	7	69.43	4.27
4/29/08	**5.17**	2.93	7	56.73	1.11
6/25/08	**2.80**	1.36	5	48.41	0.61
7/24/08	**1.49**	0.53	4	35.14	0.26
8/7/08	**4.74**	1.01	4	21.27	0.50
9/29/08	**3.21**	1.21	8	37.77	0.43
11/16/08	**2.92**	0.14	4	4.95	0.07
12/16/08	**1.76**	0.00	1	0.00	0.00
3/30/09	**0.78**	0.34	3	44.09	0.20
4/21/09	**0.72**	0.13	2	17.55	0.09
5/31/09	**0.68**	0.08	2	12.33	0.06
6/23/09	**0.81**	0.09	2	10.60	0.06
7/26/2009	**1.11**	0.73	4	66.42	0.37
8/31/2009	**0.26**	0.16	4	59.66	0.08

APPENDIX 3: MONTHLY MEAN MESOCOSM LEACHATE CONDUCTIVITY

Monthly mean mesocosm leachate Conductivity (dS $^{m-1}$)
Ninigret Pond
Landscape: NFTD

Date	dS m^{-1}	σ		C*v*	SE
7/30/07	**36.47**	7.05	10	19.33	2.23
8/13/07	**52.50**	0.80	4	1.52	0.40
9/15/07	**50.13**	3.60	8	7.19	1.27
4/29/08	**0.28**	0.07	6	24.60	0.03
6/25/08	**0.33**	0.06	5	19.92	0.03
7/24/08	**1.11**	0.95	3	85.31	0.55
8/7/08	**0.53**	0.10	3	19.38	0.06
9/29/08	**0.28**	0.16	6	56.85	0.06
11/16/08	**0.28**	0.09	4	31.81	0.04
12/16/08	**-**	-	-	-	-
3/30/09	**0.11**	0.00	1	0.00	0.00
4/21/09	**0.18**	0.04	4	23.71	0.02
5/31/09	**0.20**	0.05	3	26.78	0.03
6/23/09	**0.26**	0.04	4	13.83	0.02
7/26/2009	**0.21**	0.05	4	24.39	0.03
8/31/2009	**0.25**	0.14	4	58.26	0.07

Monthly mean mesocosm leachate Conductivity (dS $^{m-1}$)
Ninigret Pond
Landscape: NWF

Date	dS m^{-1}	σ		C*v*	SE
7/30/07	**31.79**	3.23	17	10.17	0.78
8/13/07	**24.22**	6.25	8	25.80	2.21
9/15/07	**3.84**	2.03	8	52.73	0.72
4/29/08	**0.33**	0.16	8	48.86	0.06
6/25/08	**0.48**	0.10	5	21.15	0.04
7/24/08	**1.00**	0.47	4	46.72	0.23
8/7/08	**0.74**	0.10	4	13.77	0.05
9/29/08	**0.44**	0.25	8	56.24	0.09
11/16/08	**0.34**	0.06	4	18.82	0.03
12/16/08	**0.12**	0.07	2	56.46	0.05
3/30/09	**0.17**	0.06	3	33.48	0.03
4/21/09	**0.16**	0.04	4	27.12	0.02
5/31/09	**0.16**	0.07	4	41.99	0.03
6/23/09	**0.23**	0.09	4	40.79	0.05
7/26/2009	**0.15**	0.08	4	53.01	0.04
8/31/2009	**0.24**	0.09	3	39.51	0.05

APPENDIX 3: MONTHLY MEAN MESOCOSM LEACHATE CONDUCTIVITY

Monthly mean mesocosm leachate Conductivity (dS $^{m-1}$)
Ninigret Pond
Landscape: NLB

Date	dS m^{-1}	σ	n	C*v*	SE
7/30/07	**29.86**	2.99	14	10.02	0.80
8/13/07	**21.25**	5.52	4	25.99	2.76
9/15/07	**20.55**	4.67	7	22.72	1.77
4/29/08	**1.43**	1.72	8	120.36	0.61
6/25/08	**1.53**	0.74	5	48.71	0.33
7/24/08	**2.21**	0.26	3	11.85	0.15
8/7/08	**2.29**	0.66	4	28.79	0.33
9/29/08	**1.80**	0.79	8	43.94	0.28
11/16/08	**0.73**	0.22	4	29.73	0.11
12/16/08	**0.34**	0.01	2	1.87	0.00
3/30/09	**0.17**	0.05	3	31.22	0.03
4/21/09	**0.23**	0.03	4	14.46	0.02
5/31/09	**0.25**	0.03	4	12.79	0.02
6/23/09	**0.34**	0.10	4	28.07	0.05
7/26/2009	**0.28**	0.05	4	18.05	0.02
8/31/2009	**0.27**	0.02	4	7.53	0.01

Monthly mean mesocosm leachate Conductivity (dS $^{m-1}$)
Ninigret Pond
Landscape: NMC

Date	dS m^{-1}	σ		C*v*	SE
7/30/07	**30.91**	3.82	13	12.36	1.06
8/13/07	**29.30**	3.88	4	13.23	1.94
9/15/07	**24.18**	6.85	8	28.32	2.42
4/29/08	**0.37**	0.24	8	65.60	0.08
6/25/08	**0.34**	0.33	6	95.26	0.13
7/24/08	**1.23**	0.12	3	9.58	0.07
8/7/08	**1.40**	0.30	4	21.71	0.15
9/29/08	**0.46**	0.26	7	55.99	0.10
11/16/08	**0.36**	0.04	4	10.60	0.02
12/16/08	**0.83**	0.00	1	0.00	0.00
3/30/09	**0.16**	0.02	3	14.72	0.01
4/21/09	**0.16**	0.02	4	15.37	0.01
5/31/09	**0.19**	0.06	3	29.85	0.03
6/23/09	**0.30**	0.02	3	7.83	0.01
7/26/2009	**0.31**	0.16	4	50.73	0.08
8/31/2009	**0.40**	0.27	3	68.80	0.16

APPENDIX 3: MONTHLY MEAN MESOCOSM LEACHATE CONDUCTIVITY

Monthly mean mesocosm leachate Conductivity (dS $^{m-1}$)
Quonochontaug Pond

Landscape: QFTD

Date	dS m-1	σ		C*v*	SE
7/30/07	**40.87**	4.22	3	10.32	2.44
8/13/07	**40.26**	3.24	5	8.04	1.45
9/15/07	**17.69**	12.13	8	68.59	4.29
4/29/08	**0.22**	0.12	5	56.78	0.05
6/25/08	**0.48**	0.13	4	28.05	0.07
7/24/08	**0.76**	0.79	4	104.20	0.40
8/7/08	**1.27**	1.48	4	116.17	0.74
9/29/08	**0.28**	0.08	6	29.79	0.03
11/16/08	**0.49**	0.21	3	43.34	0.12
12/16/08	**0.16**	0.04	3	27.40	0.02
3/30/09	**0.16**	0.00	2	2.24	0.00
4/21/09	**0.17**	0.02	4	13.05	0.01
5/31/09	**0.27**	0.11	4	40.20	0.06
6/23/09	**0.28**	0.07	4	24.52	0.03
7/26/2009	**0.15**	0.01	2	5.39	0.01
8/31/2009	**0.57**	0.09	4	14.98	0.04

Monthly mean mesocosm leachate Conductivity (dS $^{m-1}$)
Quonochontaug Pond

Landscape: QWF

Date	dS m-1	σ		C*v*	SE
7/30/07	**38.31**	2.80	8	7.30	0.99
8/13/07	**36.35**	4.59	8	12.63	1.62
9/15/07	**4.83**	2.65	8	54.92	0.94
4/29/08	**0.25**	0.12	6	46.98	0.05
6/25/08	**0.45**	0.15	3	33.03	0.08
7/24/08	**0.52**	0.27	3	53.17	0.16
8/7/08	**1.83**	2.29	3	124.98	1.32
9/29/08	**0.27**	0.12	5	43.58	0.05
11/16/08	**0.27**	0.03	3	9.54	0.02
12/16/08	**0.10**	0.02	2	20.95	0.02
3/30/09	**0.16**	0.03	2	20.94	0.02
4/21/09	**0.14**	0.03	3	19.16	0.02
5/31/09	**0.17**	0.02	3	9.30	0.01
6/23/09	**0.26**	0.07	3	24.74	0.04
7/26/2009	**0.18**	0.07	2	38.06	0.05
8/31/2009	**0.39**	0.15	3	38.05	0.09

APPENDIX 3: MONTHLY MEAN MESOCOSM LEACHATE CONDUCTIVITY

Monthly mean mesocosm leachate Conductivity (dS $^{m-1}$)

Quonochontaug Pond

Landscape: QLB

Date	dS m-1	σ	n	C*v*	SE
7/30/07	**35.17**	3.05	9	8.67	1.02
8/13/07	**40.45**	12.00	6	29.65	4.90
9/15/07	**30.28**	5.39	5	17.80	2.41
4/29/08	**8.36**	3.29	6	39.34	1.34
6/25/08	**3.27**	1.46	5	44.60	0.65
7/24/08	**3.35**	0.69	3	20.67	0.40
8/7/08	**2.98**	1.80	4	60.33	0.90
9/29/08	**3.34**	1.27	7	37.85	0.48
11/16/08	**2.07**	0.85	4	40.95	0.42
12/16/08	**0.66**	0.40	2	59.63	0.28
3/30/09	**0.41**	0.27	3	65.43	0.15
4/21/09	**0.42**	0.20	4	47.69	0.10
5/31/09	**0.34**	0.15	3	42.42	0.08
6/23/09	**0.52**	0.13	4	24.62	0.06
7/26/2009	**0.27**	0.06	2	23.61	0.05
8/31/2009	**0.42**	0.07	3	16.28	0.04

Monthly mean mesocosm leachate Conductivity (dS $^{m-1}$)

Quonochontaug Pond

Landscape: QMC

Date	dS m-1	σ		C*v*	SE
7/30/07	**38.31**	1.98	7	5.18	0.75
8/13/07	**35.75**	1.78	6	4.98	0.73
9/15/07	**16.14**	8.64	6	53.55	3.53
4/29/08	**4.45**	4.12	6	92.52	1.68
6/25/08	**2.50**	0.72	4	28.94	0.36
7/24/08	**2.30**	0.52	4	22.50	0.26
8/7/08	**2.37**	1.19	4	50.28	0.59
9/29/08	**3.42**	0.65	7	19.07	0.25
11/16/08	**3.59**	0.59	4	16.32	0.29
12/16/08	**1.41**	0.02	4	1.10	0.01
3/30/09	**1.73**	0.39	4	22.63	0.20
4/21/09	**1.52**	0.08	4	5.20	0.04
5/31/09	**1.39**	0.33	4	23.70	0.16
6/23/09	**1.87**	0.38	4	20.19	0.19
7/26/2009	**1.18**	0.21	2	17.39	0.15
8/31/2009	**0.69**	0.22	4	32.13	0.11

APPENDIX 3: MONTHLY MEAN MESOCOSM LEACHATE CONDUCTIVITY

Monthly mean mesocosm leachate conductivity
Mixed Mesocosms LB% to WF% by Volume
Ninigret Pond

Mixture	**5% LB**					**10% LB**				
Date	**dS m^{-1}**	**σ**		**C*v***	**SE**	**dS m^{-1}**	**σ**		**C*v***	**SE**
8/7/08	**23.86**	17.82	3	74.70	10.29	**34.77**	4.20	3	12.09	2.43
9/29/08	**33.20**	0.00	1	0.00	0.00	**18.23**	15.41	4	84.55	7.70
11/16/08	**3.87**	0.00	1	0.00	0.00	**4.20**	0.95	2	22.56	0.67
12/16/08	**0.34**	0.00	1	0.00	0.00	**1.19**	0.34	2	28.74	0.24
3/30/09	**0.37**	0.02	2	6.35	0.02	**0.44**	0.25	2	57.08	0.18
4/21/09	**0.35**	0.14	2	39.89	0.10	**0.54**	0.01	2	2.61	0.01
5/31/09	**0.51**	0.20	2	37.97	0.14	**0.64**	0.06	2	9.07	0.04
6/23/09	**1.54**	1.21	2	78.40	0.86	**1.36**	0.16	2	12.05	0.12
7/26/09	-	-	-	-	-	-	-	-	-	-
8/31/09	**1.35**	0.00	1	0.00	0.00	**0.37**	0.41	2	110.59	0.29

Mixture	**20% LB**					**40% LB**				
Date	**dS m^{-1}**	**σ**		**C*v***	**SE**	**dS m^{-1}**	**σ**		**C*v***	**SE**
8/7/08	**25.82**	8.38	4	32.47	4.19	**26.97**	6.06	4	22.46	3.03
9/29/08	**22.15**	6.88	3	31.08	3.97	**12.58**	4.45	4	35.37	2.22
11/16/08	**18.88**	7.95	2	42.15	5.63	**7.23**	2.25	2	31.10	1.59
12/16/08	**1.01**	0.00	3	0.00	0.00	**3.92**	0.76	2	19.48	0.54
3/30/09	**2.27**	1.86	2	82.01	1.31	**0.68**	0.25	2	36.29	0.18
4/21/09	**1.34**	0.62	2	46.19	0.44	**0.73**	0.40	2	54.71	0.28
5/31/09	**1.06**	0.00	1	0.00	0.00	**0.92**	0.45	2	48.78	0.32
6/23/09	**1.50**	0.14	2	9.21	0.10	**0.84**	0.00	1	0.00	0.00
7/26/09	-	-	-	-	-	-	-	-	-	-
8/31/09	**0.97**	0.00	1	0.00	0.00	**0.74**	0.18	2	23.94	0.12

APPENDIX 4: MONTHLY MEAN MESOCOSM LEACHATE SULFATE CONTENT

Monthly mean mesocosm leachate Sulfate Content (ppm SO_4^{2-})
Greenwich Bay
Landscape: GBMS

Date	ppm SO_4^{2-}	σ		C*v*	SE
7/30/07	**1359.16**	240.78	2	17.72	170.26
8/13/07	**1038.03**	226.32	7	21.80	85.54
9/15/07	**1199.01**	821.88	7	68.55	310.64
4/29/08	**611.77**	1085.95	4	177.51	542.98
6/25/08	**147.75**	63.83	5	43.20	28.54
7/24/08	**291.46**	196.88	4	67.55	98.44
8/7/08	**380.91**	176.10	3	46.23	101.67
9/29/08	**421.31**	571.48	4	135.64	285.74
11/16/08	**157.49**	72.18	4	45.83	36.09
12/16/08	**39.82**	32.35	4	81.24	16.18
3/30/09	**23.53**	30.66	4	130.31	15.33
4/21/09	**41.84**	46.74	3	111.73	26.99
5/31/09	**25.64**	24.64	4	0.00	12.32
6/23/09	**13.88**	10.86	4	78.26	5.43
7/26/09	**66.37**	35.86	3	54.03	20.70
8/31/09	**117.86**	52.69	3	44.70	30.42

Monthly mean mesocosm leachate Sulfate Content (ppm SO_4^{2-})
Greenwich Bay
Landscape: GBSS

Date	ppm SO_4^{2-}	σ		C*v*	SE
7/30/07	**-**	-	-	-	-
8/13/07	**1213.92**	623.13	3	51.33	359.77
9/15/07	**1955.40**	495.16	4	25.32	247.58
4/29/08	**952.28**	658.75	4	69.18	329.37
6/25/08	**37.51**	53.05	2	141.42	37.51
7/24/08	**234.70**	180.89	3	77.07	104.44
8/7/08	**253.94**	0.00	1	0.00	0.00
9/29/08	**751.11**	1043.51	7	138.93	394.41
11/16/08	**120.68**	47.79	2	39.60	33.79
12/16/08	**79.05**	91.96	4	116.33	45.98
3/30/09	**9.35**	4.86	4	52.01	2.43
4/21/09	**22.63**	28.08	4	124.12	14.04
5/31/09	**67.58**	32.35	4	0.00	16.18
6/23/09	**173.48**	269.63	4	155.43	134.82
7/26/09	**56.12**	32.60	4	58.09	16.30
8/31/09	**202.34**	69.94	3	34.56	40.38

APPENDIX 4: MONTHLY MEAN MESOCOSM LEACHATE SULFATE CONTENT

Monthly mean mesocosm leachate Sulfate Content (ppm SO_4^{2-})
Greenwich Bay
Landscape: GBBF

Date	ppm SO_4^{2-}	σ	n	C*v*	SE
7/30/07	**934.97**	179.56	2	19.21	126.97
8/13/07	**565.60**	141.42	6	25.00	57.73
9/15/07	**2586.04**	1028.32	7	39.76	388.67
4/29/08	**668.33**	963.33	5	144.14	430.82
6/25/08	**384.76**	497.46	3	129.29	287.21
7/24/08	**2537.97**	2252.92	4	88.77	1126.46
8/7/08	**-**	-	-	-	-
9/29/08	**1350.51**	820.55	7	60.76	310.14
11/16/08	**761.82**	16.32	2	2.14	11.54
12/16/08	**815.21**	61.33	4	7.52	30.66
3/30/09	**1238.28**	758.01	3	61.21	437.64
4/21/09	**1002.55**	129.03	4	12.87	64.51
5/31/09	**870.52**	274.04	4	0.00	137.02
6/23/09	**453.76**	399.62	4	88.07	199.81
7/26/09	**734.94**	218.04	4	29.67	109.02
8/31/09	**882.17**	59.76	3	6.77	34.50

Monthly mean mesocosm leachate Sulfate Content (ppm SO_4^{2-})
Greenwich Bay
Landscape: GBIC

Date	ppm SO_4^{2-}	σ		C*v*	SE
7/30/07	**1148.51**	0.00	1	0.00	0.00
8/13/07	**854.99**	218.05	7	25.50	82.42
9/15/07	**1151.59**	781.20	4	67.84	390.60
4/29/08	**2493.24**	2140.43	5	85.85	957.23
6/25/08	**3686.48**	1280.66	4	34.74	640.33
7/24/08	**3083.37**	1445.75	4	46.89	722.88
8/7/08	**4201.58**	952.35	4	22.67	476.17
9/29/08	**1481.81**	1005.77	4	67.87	502.88
11/16/08	**1099.45**	412.18	2	37.49	291.46
12/16/08	**780.40**	409.36	4	52.46	204.68
3/30/09	**1118.23**	624.81	4	55.87	312.41
4/21/09	**817.61**	137.46	4	16.81	68.73
5/31/09	**860.15**	257.68	4	29.96	128.84
6/23/09	**377.73**	413.81	4	109.55	206.90
7/26/09	**519.53**	218.69	4	42.09	109.34
8/31/09	**404.58**	229.70	4	56.78	114.85

APPENDIX 4: MONTHLY MEAN MESOCOSM LEACHATE SULFATE CONTENT

Monthly mean mesocosm leachate Sulfate Content (ppm SO_4^{2-})
Wickford Harbor
Landscape: WMS

Date	ppm SO_4^{2-}	σ		Cv	SE
7/30/07	**1670.24**	704.33	5	42.17	314.99
8/13/07	**2134.26**	280.56	5	13.15	125.47
9/15/07	**3056.49**	918.27	6	30.04	374.88
4/29/08	**51.94**	53.99	5	103.93	24.14
6/25/08	**40.40**	55.36	5	137.02	24.76
7/24/08	**73.59**	101.33	4	137.70	50.66
8/7/08	**90.90**	104.88	4	115.38	52.44
9/29/08	**815.93**	1685.29	8	206.55	595.84
11/16/08	**153.87**	260.57	4	169.35	130.28
12/16/08	**8.75**	3.99	4	45.57	1.99
3/30/09	**1.81**	0.85	2	47.14	0.60
4/21/09	**2.11**	1.16	4	54.71	0.58
5/31/09	**0.00**	0.00	4	0.00	0.00
6/23/09	**1.21**	0.99	4	81.65	0.49
7/26/09	**0.60**	1.21	4	200.00	0.60
8/31/09	**1.21**	2.09	3	173.21	1.21

Monthly mean mesocosm leachate Sulfate Content (ppm SO_4^{2-})
Wickford Harbor
Landscape: WSS

Date	ppm SO_4^{2-}	σ		Cv	SE
7/30/07	**1844.37**	750.02	18	40.67	176.78
8/13/07	**2159.47**	507.38	6	23.50	207.14
9/15/07	**2474.92**	1090.85	8	44.08	385.68
4/29/08	**66.95**	90.12	5	134.60	40.30
6/25/08	**46.17**	61.08	3	132.29	35.26
7/24/08	**288.57**	145.01	4	50.25	72.51
8/7/08	**274.14**	411.82	4	150.22	205.91
9/29/08	**660.83**	1187.13	7	179.64	448.69
11/16/08	**146.83**	144.62	3	98.50	83.50
12/16/08	**17.20**	6.18	4	35.95	3.09
3/30/09	**6.64**	7.79	4	117.36	3.89
4/21/09	**2.01**	1.84	3	91.65	1.06
5/31/09	**0.00**	0.00	4	0.00	0.00
6/23/09	**16.49**	10.12	3	61.36	5.84
7/26/09	**13.27**	15.41	3	116.06	8.90
8/31/09	**92.92**	76.80	2	82.65	54.31

APPENDIX 4: MONTHLY MEAN MESOCOSM LEACHATE SULFATE CONTENT

Monthly mean mesocosm leachate Sulfate Content (ppm SO_4^{2-})
Wickford Harbor
Landscape: WBF

Date	ppm SO_4^{2-}	σ		C*v*	SE
7/30/07	**1069.36**	360.85	7	33.74	136.39
8/13/07	**1017.69**	268.50	3	26.38	155.02
9/15/07	**2409.26**	1243.57	8	51.62	439.67
4/29/08	**1775.43**	1435.00	8	80.83	507.35
6/25/08	**2642.15**	2162.37	5	81.84	967.04
7/24/08	**1621.76**	1307.70	4	80.63	653.85
8/7/08	**3246.41**	891.58	4	27.46	445.79
9/29/08	**1230.75**	1188.10	8	96.53	420.06
11/16/08	**997.55**	308.02	4	30.88	154.01
12/16/08	**777.62**	282.82	4	36.37	141.41
3/30/09	**359.22**	187.98	3	52.33	108.53
4/21/09	**200.33**	125.29	4	62.54	62.65
5/31/09	**180.42**	95.35	4	0.00	47.68
6/23/09	**212.40**	155.50	4	73.21	77.75
7/26/09	**170.56**	160.56	3	94.14	92.70
8/31/09	**45.56**	21.98	4	48.24	10.99

Monthly mean mesocosm leachate Sulfate Content (ppm SO_4^{2-})
Wickford Harbor
Landscape: WIC

Date	ppm SO_4^{2-}	σ		C*v*	SE
7/30/07	**1598.68**	1744.51	13	109.12	483.84
8/13/07	**1313.96**	645.92	6	49.16	263.70
9/15/07	**2132.49**	1385.02	7	64.95	523.49
4/29/08	**2868.39**	2447.55	7	85.33	925.09
6/25/08	**3319.52**	1862.08	5	56.09	832.75
7/24/08	**1070.59**	665.97	4	62.21	332.98
8/7/08	**4739.76**	1410.52	4	29.76	705.26
9/29/08	**1541.69**	1450.60	8	94.09	512.87
11/16/08	**1054.24**	213.96	4	20.29	106.98
12/16/08	**1059.17**	124.86	1	11.79	124.86
3/30/09	**483.12**	341.41	3	70.67	197.11
4/21/09	**249.81**	145.07	2	58.07	102.58
5/31/09	**248.60**	46.08	2	0.00	32.58
6/23/09	**190.07**	91.31	2	48.04	64.56
7/26/09	**293.86**	222.33	4	75.66	111.17
8/31/09	**66.07**	56.31	4	85.23	28.16

APPENDIX 4: MONTHLY MEAN MESOCOSM LEACHATE SULFATE CONTENT

Monthly mean mesocosm leachate Sulfate Content (ppm SO_4^{2-})
Ninigret Pond
Landscape: NFTD

Date	ppm SO_4^{2-}	σ		C*v*	SE
7/30/07	**1859.22**	424.00	7	22.81	160.26
8/13/07	**1817.99**	352.17	4	19.37	176.08
9/15/07	**2659.63**	990.69	8	37.25	350.26
4/29/08	**74.07**	122.83	6	165.84	50.15
6/25/08	**1.15**	2.58	5	223.61	1.15
7/24/08	**151.98**	132.91	3	87.45	76.74
8/7/08	**725.27**	971.32	3	133.92	560.79
9/29/08	**39.44**	37.12	6	94.12	15.15
11/16/08	**49.78**	46.35	4	93.10	23.17
12/16/08	**29.57**	37.66	4	127.36	18.83
3/30/09	**3.62**	0.00	1	0.00	0.00
4/21/09	**2.11**	2.49	4	117.80	1.24
5/31/09	**3.22**	5.57	3	0.00	3.22
6/23/09	**21.42**	24.97	4	116.59	12.49
7/26/09	**30.77**	23.51	4	76.41	11.76
8/31/09	**78.44**	82.55	4	105.24	41.28

Monthly mean mesocosm leachate Sulfate Content (ppm SO_4^{2-})
Ninigret Pond
Landscape: NWF

Date	ppm SO_4^{2-}	σ			
7/30/07	**1516.64**	522.30	14	34.44	139.59
8/13/07	**1353.81**	557.25	7	41.16	210.62
9/15/07	**526.73**	330.11	8	62.67	116.71
4/29/08	**25.25**	25.24	8	99.96	8.92
6/25/08	**86.57**	74.47	5	86.02	33.30
7/24/08	**484.80**	254.51	4	52.50	127.25
8/7/08	**378.03**	163.95	4	43.37	81.98
9/29/08	**119.04**	154.28	8	129.61	54.54
11/16/08	**101.07**	24.50	4	24.24	12.25
12/16/08	**11.77**	13.81	4	117.35	6.90
3/30/09	**19.31**	33.44	3	173.21	19.31
4/21/09	**23.53**	12.64	4	53.70	6.32
5/31/09	**18.40**	13.67	4	0.00	6.83
6/23/09	**38.62**	21.20	4	54.90	10.60
7/26/09	**10.56**	21.12	4	200.00	10.56
8/31/09	**71.60**	53.17	3	74.26	30.70

APPENDIX 4: MONTHLY MEAN MESOCOSM LEACHATE SULFATE CONTENT

Monthly mean mesocosm leachate Sulfate Content (ppm SO_4^{2-})
Ninigret Pond
Landscape: NLB

Date	ppm SO_4^{2-}	σ	n	C*v*	SE
7/30/07	**1133.29**	365.29	11	32.23	110.14
8/13/07	**777.70**	492.10	4	63.28	246.05
9/15/07	**1864.49**	398.52	7	21.37	150.63
4/29/08	**977.53**	915.84	8	93.69	323.80
6/25/08	**864.56**	515.81	5	59.66	230.68
7/24/08	**1079.25**	125.78	3	11.65	72.62
8/7/08	**1248.07**	367.60	4	29.45	183.80
9/29/08	**465.32**	389.52	8	83.71	137.72
11/16/08	**312.86**	123.52	4	39.48	61.76
12/16/08	**104.69**	57.09	4	54.54	28.55
3/30/09	**34.19**	26.34	3	77.03	15.21
4/21/09	**49.18**	11.96	4	24.32	5.98
5/31/09	**62.45**	13.42	4	0.00	6.71
6/23/09	**68.18**	26.85	4	39.38	13.42
7/26/09	**80.86**	10.84	4	13.41	5.42
8/31/09	**53.10**	22.73	4	42.80	11.36

Monthly mean mesocosm leachate Sulfate Content (ppm SO_4^{2-})
Ninigret Pond
Landscape: NMC

Date	ppm SO_4^{2-}	σ		C*v*	SE
7/30/07	**2104.00**	664.20	9	31.57	221.40
8/13/07	**2425.43**	710.26	4	29.28	355.13
9/15/07	**3748.45**	1171.57	8	31.25	414.21
4/29/08	**362.88**	729.98	8	201.17	258.09
6/25/08	**71.18**	146.67	6	206.06	59.88
7/24/08	**284.72**	259.80	3	91.25	149.99
8/7/08	**717.10**	197.10	4	27.49	98.55
9/29/08	**368.55**	475.41	7	129.00	179.69
11/16/08	**94.13**	21.14	3	22.46	12.21
12/16/08	**164.53**	257.27	3	156.37	148.53
3/30/09	**2.41**	3.19	3	132.29	1.84
4/21/09	**3.02**	0.70	4	23.09	0.35
5/31/09	**16.90**	4.35	3	0.00	2.51
6/23/09	**59.13**	26.88	3	45.45	15.52
7/26/09	**40.13**	12.32	4	30.71	6.16
8/31/09	**88.02**	60.31	3	68.52	34.82

APPENDIX 4: MONTHLY MEAN MESOCOSM LEACHATE SULFATE CONTENT

Monthly mean mesocosm leachate Sulfate Content (ppm SO_4^{2-})
Quonochontaug Pond
Landscape: QFTD

Date	ppm SO_4^{2-}	σ		C*v*	SE
7/30/07	**1371.67**	498.63	3	36.35	287.88
8/13/07	**1170.44**	247.71	5	21.16	110.78
9/15/07	**991.41**	837.73	8	84.50	296.18
4/29/08	**754.90**	1109.98	5	147.04	496.40
6/25/08	**93.79**	66.37	4	70.77	33.19
7/24/08	**80.80**	100.07	4	123.86	50.04
8/7/08	**763.27**	1311.68	4	171.85	655.84
9/29/08	**862.82**	1309.67	4	151.79	654.83
11/16/08	**128.32**	122.46	3	95.43	70.70
12/16/08	**27.76**	34.91	3	125.79	20.16
3/30/09	**12.07**	10.24	2	84.85	7.24
4/21/09	**7.54**	9.00	4	119.29	4.50
5/31/09	**35.30**	38.87	4	0.00	19.44
6/23/09	**81.16**	70.45	4	86.80	35.22
7/26/09	**16.59**	23.96	4	144.41	11.98
8/31/09	**275.15**	47.64	4	17.32	23.82

Monthly mean mesocosm leachate Sulfate Content (ppm SO_4^{2-})
Quonochontaug Pond
Landscape: QWF

Date	ppm SO_4^{2-}	σ		C*v*	SE
7/30/07	**1984.64**	410.69	8	20.69	145.20
8/13/07	**1645.57**	618.68	8	37.60	218.74
9/15/07	**761.96**	443.97	8	58.27	156.97
4/29/08	**405.92**	929.40	6	228.96	379.42
6/25/08	**46.17**	49.31	3	106.80	28.47
7/24/08	**169.29**	229.72	3	135.69	132.63
8/7/08	**275.10**	269.00	3	97.78	155.30
9/29/08	**666.60**	831.12	3	124.68	479.85
11/16/08	**22.12**	29.22	3	132.08	16.87
12/16/08	**6.64**	5.97	2	90.00	4.22
3/30/09	**0.60**	0.85	2	141.42	0.60
4/21/09	**4.83**	0.00	3	0.00	0.00
5/31/09	**2.01**	3.48	3	0.00	2.01
6/23/09	**12.87**	21.26	3	165.15	12.27
7/26/09	**12.07**	10.52	3	87.18	6.07
8/31/09	**131.54**	78.01	3	59.31	45.04

APPENDIX 4: MONTHLY MEAN MESOCOSM LEACHATE SULFATE CONTENT

Monthly mean mesocosm leachate Sulfate Content (ppm SO_4^{2-})
Quonochontaug Pond
Landscape: QLB

Date	ppm SO_4^{2-}	σ	n	C*v*	SE
7/30/07	**1393.47**	220.81	9	15.85	73.60
8/13/07	**905.15**	292.59	6	32.33	119.45
9/15/07	**1302.37**	856.71	5	65.78	383.13
4/29/08	**1459.20**	1843.10	6	126.31	752.44
6/25/08	**1201.61**	208.07	5	17.32	93.05
7/24/08	**1077.33**	178.10	3	16.53	102.83
8/7/08	**1540.96**	609.31	4	39.54	304.66
9/29/08	**1297.74**	682.19	4	52.57	341.10
11/16/08	**973.92**	213.48	4	21.92	106.74
12/16/08	**2545.19**	2081.31	2	81.77	1471.71
3/30/09	**951.87**	184.73	3	19.41	106.65
4/21/09	**887.30**	77.91	4	8.78	38.96
5/31/09	**821.65**	227.47	3	0.00	131.33
6/23/09	**790.15**	444.19	4	56.22	222.10
7/26/09	**579.26**	236.28	4	40.79	118.14
8/31/09	**328.25**	184.25	3	56.13	106.38

Monthly mean mesocosm leachate Sulfate Content (ppm SO_4^{2-})
Quonochontaug Pond
Landscape: QMC

Date	ppm SO_4^{2-}	σ		C*v*	SE
7/30/07	**1165.82**	126.40	7	10.84	47.78
8/13/07	**1081.18**	346.37	6	32.04	141.41
9/15/07	**1212.20**	874.77	6	72.16	357.12
4/29/08	**2247.00**	1993.54	6	88.72	813.86
6/25/08	**2757.29**	1395.01	4	50.59	697.51
7/24/08	**2045.96**	638.68	4	31.22	319.34
8/7/08	**2903.01**	747.93	4	25.76	373.96
9/29/08	**1910.33**	1195.07	7	62.56	451.70
11/16/08	**845.17**	232.81	4	27.55	116.41
12/16/08	**839.15**	933.86	4	111.29	466.93
3/30/09	**144.21**	147.54	4	102.31	73.77
4/21/09	**142.10**	127.11	4	89.45	63.55
5/31/09	**116.46**	105.94	4	0.00	52.97
6/23/09	**143.61**	73.57	4	51.23	36.79
7/26/09	**126.41**	38.22	4	30.23	19.11
8/31/09	**159.90**	63.37	4	39.63	31.69

APPENDIX 4: MONTHLY MEAN MESOCOSM LEACHATE SULFATE CONTENT

Monthly mean mesocosm leachate sulfate content
Mixed Mesocosms LB% to WF% by Volume
Ninigret Pond

Mixture	**5% LB**					**10% LB**				
Date	**ppm SO_4^{2-}**	**σ**	·	**C*v***	**SE**	**ppm SO_4^{2-}**	**σ**	·	**C*v***	**SE**
8/7/08	**3085.78**	949.57	3	30.77	548.24	**3485.93**	405.11	3	11.62	233.89
9/29/08	**3722.55**	0.00	1	0.00	0.00	**2721.22**	885.97	4	32.56	442.99
11/16/08	**709.88**	0.00	1	0.00	0.00	**857.05**	330.56	2	38.57	233.74
12/16/08	**450.14**	394.24	2	87.58	278.77	**778.39**	148.48	2	19.08	104.99
3/30/09	**64.56**	84.48	2	130.85	59.74	**150.25**	205.65	2	136.88	145.42
4/21/09	**115.25**	89.60	2	77.74	63.36	**133.95**	162.13	2	121.04	114.65
5/31/09	**219.03**	9.39	2	4.29	6.64	**338.51**	7.68	2	2.27	5.43
6/23/09	**499.01**	495.79	2	99.35	350.58	**405.48**	110.93	2	27.36	78.44
7/26/09	**289.63**	203.09	2	70.12	143.61	**289.63**	85.33	2	29.46	60.34
8/31/09	**988.37**	0.00	1	0.00	0.00	**480.91**	19.63	2	4.08	13.88

Mixture	**20% LB**					**40% LB**				
Date	**ppm SO_4^{2-}**	**σ**	·	**C*v***	**SE**	**ppm SO_4^{2-}**	**σ**	·	**C*v***	**SE**
8/7/08	**3823.55**	330.35	4	8.64	165.18	**3458.51**	614.82	4	17.78	307.41
9/29/08	**3405.13**	289.95	3	8.52	167.40	**2682.26**	1025.47	4	38.23	512.74
11/16/08	**2302.79**	375.45	2	16.30	265.48	**1157.17**	493.80	2	42.67	349.17
12/16/08	**1771.82**	0.00	1	0.00	0.00	**803.18**	586.32	2	73.00	414.59
3/30/09	**972.68**	459.10	2	47.20	324.63	**324.63**	170.67	2	52.57	120.68
4/21/09	**673.39**	360.11	2	53.48	254.63	**345.14**	332.80	2	96.42	235.33
5/31/09	**355.40**	502.62	2	141.42	355.40	**529.79**	418.13	2	78.93	295.67
6/23/09	**586.50**	167.25	2	28.52	118.27	**109.82**	155.31	2	141.42	109.82
7/26/09	**339.71**	166.40	2	48.98	117.66	**289.63**	238.93	2	82.50	168.95
8/31/09	**569.61**	0.00	1	0.00	0.00	**419.97**	37.55	2	8.94	26.55

APPENDIX 5: SOIL VIBRACORE LABORATORY DATA

Pedon ID and Horizon	Site ID	Horizon Depth (cm)	vcos (%)	cos (%)	ms (%)	fs (%)	vfs (%)	Totals: sand (%)	silt (%)	clay (%)	CF (%)	Texture
RI009-2008-008-NP												
C1	NWFS	0-21	20	0	0	53	0	73	27	0	0	lfs
Cg1	"	21-35	0	2	2	58	9	71	28	1	0	fsl
Cg2	"	35-58	1	1	4	55	5	65	34	1	0	fsl
Ab	"	58-68	1	2	4	39	28	74	24	3	0	lfs
Cg	"	68-75	0	0	3	23	3	30	70	0	0	sil
C/A	"	75-86	0	1	1	51	29	83	19	0	0	lfs
C'g	"	86-93	2	1	5	56	7	70	29	0	0	fsl
A'b	"	93-103	0	1	2	14	41	59	36	5	0	vfsl
CA1	"	103-127	3	34	4	31	26	93	2	5	0	fs
CA2	"	127-137	5	0	5	52	28	91	12	0	0	fs
2Ab	"	137-158	19	1	1	3	2	25	57	17	0	sil
2AC1	"	158-172	1	0	0	1	1	4	70	26	0	sil
2AC2	"	172-199	0	0	0	3	18	23	66	11	0	sil
2A'b	"	199-214	0	0	1	10	18	29	61	10	0	sil
RI009-2008-010-NP												
A	NWF	0-5	1	1	5	55	27	89	8	4	0	fs
CA1	"	5-13	0	1	9	61	23	95	3	2	0	fs
CA2	"	13-23	0	2	1	58	24	85	12	3	0	lfs
CA3	"	23-34	1	1	3	57	30	92	6	2	0	fs
Cg	"	34-43	0	1	3	72	20	96	4	0	0	fs
C/A	"	43-53	1	1	5	32	45	84	12	4	0	lfs
Ab	"	53-74	N/A	-	-	-	-	-	-	-	-	-
CA	"	74-103	0	1	27	37	13	79	21	0	0	lfs
A'b	"	103-150	0	0	0	24	49	74	26	0	0	lfs
AC	"	150-200	0	0	1	13	44	59	41	0	0	vfsl

APPENDIX 5: SOIL VIBRACORE LABORATORY DATA

Pedon ID and Horizon	Site ID	Horizon Depth (cm)	vcos (%)	cos (%)	ms (%)	fs (%)	vfs (%)	Totals: sand (%)	silt (%)	clay (%)	CF (%)	Texture
RI009-2008-009-NP												
A	NLB	0-24	2	1	1	6	13	23	58	18	0	sil
AC1	"	24-35	1	2	5	15	22	44	45	11	0	ls
AC2	"	35-48	8	12	14	23	20	76	19	4	4	ls
2Cg1	"	48-56	8	16	25	34	9	92	6	2	11	s
2Cg2	"	56-77	24	42	24	5	1	96	3	1	12	cos
RI009-2008-007-NP												
A1	NMC	0-5	15	22	13	9	3	63	29	9	10	cos
A2	"	5-19	13	19	16	12	4	64	27	9	6	cosl
CA	"	19-40	36	37	10	9	2	94	5	1	17	cos
Cg	"	40-50	29	15	6	12	5	67	22	11	36	cosl
2Oab	"	50-64	N/A	-	-	-	-	-	-	-	-	-
2Ab	"	64-79	2	9	20	20	10	62	33	4	0	sl
2AC1	"	79-100	4	10	21	21	11	66	32	3	10	sl
2AC2	"	100-130	7	14	23	19	10	72	26	2	19	sl

APPENDIX 5: SOIL VIBRACORE LABORATORY DATA

Pedon ID and Horizon	Site ID	Horizon Depth (cm)	vcos (%)	cos (%)	ms (%)	fs (%)	vfs (%)	Totals: sand (%)	silt (%)	clay (%)	CF (%)	Texture
RI009-2009-004-QP												
Cg1	QWFS	0-25	7	23	60	8	0	98	1	1	0	s
Cg2	"	25-36	2	8	58	31	0	99	0	1	0	s
Cg3	"	36-60	3	39	54	3	0	99	1	0	0	s
Cg4	"	60-76	0	4	64	29	1	98	1	1	0	s
Cg5	"	76-83	1	3	43	49	2	98	0	2	0	s
Cg6	"	83-93	5	25	58	12	0	98	0	2	0	s
Cg7	"	93-103	42	40	15	2	0	98	0	2	0	cos
CA	"	103-121	7	31	53	7	0	98	0	2	0	s
RI009-2008-013-QP												
Cg	QWF	0-6	N/A	-	-	-	-	-	-	-	-	-
AC	"	6-28	16	29	33	18	2	98	2	0	4	cos
Cg1	"	28-86	20	40	33	5	0	98	0	2	7	cos
Cg2	"	86-98	7	39	47	6	0	99	0	1	2	cos
Cg3	"	98-104	0	1	34	56	3	94	5	1	0	fs
CAb	"	104-114	0	0	17	72	7	96	4	0	0	fs
Ab	"	114-118	3	22	44	26	3	98	2	0	0	s

APPENDIX 5: SOIL VIBRACORE LABORATORY DATA

Pedon ID and Horizon	Site ID	Horizon Depth (cm)	vcos (%)	cos (%)	ms (%)	fs (%)	vfs (%)	Totals: sand (%)	silt (%)	clay (%)	CF (%)	Texture
RI009-2008-011-QP												
A	QLB	0-27	2	1	2	15	25	45	45	10	0	l
AC	"	27-52	0	1	2	6	13	22	61	17	0	sil
C	"	52-76	4	10	16	38	13	81	19	0	3	s
2Cg	"	76-100	1	4	6	10	17	40	58	2	8	sil
3C1	"	100-126	14	18	19	18	10	80	21	0	33	s
3C2	"	126-168	14	20	20	18	11	83	17	0	32	lcos
RI009-2008-012-QP												
Cg1	QSMB	0-13	4	7	35	43	4	92	7	1	0	s
Cg2	"	13-23	1	4	25	46	8	83	15	2	0	ls
Cg3	"	23-38	2	3	20	49	10	83	15	2	0	ls
2Cg4	"	38-48	2	1	5	11	2	21	74	5	0	sil
2Cg5	"	48-93	1	1	1	2	24	30	67	4	0	sil
3C	"	93-112	1	3	2	4	23	34	61	6	2	sil

APPENDIX 5: SOIL VIBRACORE LABORATORY DATA

Pedon ID and Horizon	Site ID	O.M. (%)	C (%)	$CaCO_3$ (%)	5:1 Conductivity dS m^{-1}	Incubation Ph (8 week)	pH Change
RI009-2008-008-NP							
C1	NWFS	1.24	0.62	0.50	1.24	7.24	-0.19
Cg1	"	0.87	0.44	0.50	1.35	7.53	-0.79
Cg2	"	4.44	2.22	3.27	3.08	7.99	-0.18
Ab	"	4.80	2.40	2.06	3.40	7.47	-0.34
Cg	"	1.28	0.64	1.01	1.84	7.82	-0.40
C/A	"	4.15	2.08	2.33	2.99	7.75	-0.35
C'g	"	0.87	0.43	0.67	2.49	8.07	-0.43
A'b	"	4.90	2.45	1.96	3.53	7.48	-0.64
CA1	"	5.97	2.98	3.72	2.39	7.98	-0.21
CA2	"	5.05	2.53	3.32	2.60	7.88	-0.35
2Ab	"	8.28	4.14	3.46	3.27	2.90	-4.84
2AC1	"	8.53	4.27	3.60	3.28	2.90	-5.10
2AC2	"	7.29	3.64	3.34	2.92	3.44	-4.80
2A'b	"	4.66	2.33	1.65	2.26	3.09	-4.98
RI009-2008-010-NP							
A	NWF	2.56	1.28	1.56	3.11	3.82	-2.52
CA1	"	1.35	0.68	0.53	2.30	2.65	-3.27
CA2	"	2.16	1.08	0.86	2.60	2.63	-2.48
CA3	"	1.98	0.99	1.10	2.73	2.75	-2.85
Cg	"	0.79	0.40	0.66	1.14	2.96	-3.37
C/A	"	2.51	1.26	2.15	3.60	7.26	-0.36
Ab	"	3.57	1.79	1.83	3.93	2.60	-4.79
CA	"	1.50	0.75	0.91	3.97	2.66	-4.80
A'b	"	2.02	1.01	1.17	3.51	2.69	-5.26
AC	"	3.23	1.62	2.00	4.53	2.61	-5.31
RI009-2008-009-NP							
A	NLB	10.62	5.31	4.28	4.46	3.21	-3.50
AC1	"	10.60	5.30	4.05	3.30	2.68	-3.57
AC2	"	1.38	0.69	0.72	2.30	2.78	-4.74
2Cg1	"	0.48	0.24	0.44	2.18	2.53	-5.20
2Cg2	"	0.35	0.18	0.34	1.59	2.66	-5.16
RI009-2008-007-NP							
A1	NMC	4.96	2.48	3.36	3.47	4.93	-2.64
A2	"	6.49	3.25	3.75	4.34	2.89	-4.75
CA	"	0.87	0.44	0.68	2.10	2.69	-5.15
Cg	"	5.79	2.89	6.90	2.46	7.00	-0.58
2Oab	"	18.74	9.37	5.88	7.46	6.23	-0.90
2Ab	"	4.47	2.24	1.02	3.24	5.52	-1.59
2AC1	"	3.03	1.51	0.78	2.86	5.13	-2.01
2AC2	"	2.18	1.09	0.63	2.67	4.96	-2.04

APPENDENDIX 5: SOIL VIBRACORE LABORATORY DATA

Pedon ID and Horizon	Site ID	O.M. (%)	C (%)	$CaCO_3$ (%)	5:1 Conductivity dS m^{-1}	Incubation pH (8 week)	pH Change
RI009-2009-004-QP							
Cg1	QWFS	0.23	0.12	0.26	0.51	N/A	N/A
Cg2	"	0.21	0.10	0.24	0.48	N/A	N/A
Cg3	"	0.24	0.12	0.20	0.29	N/A	N/A
Cg4	"	0.18	0.09	0.11	0.92	N/A	N/A
Cg5	"	0.34	0.17	0.41	1.39	N/A	N/A
Cg6	"	0.28	0.14	0.24	1.33	N/A	N/A
Cg7	"	0.27	0.13	0.17	0.66	N/A	N/A
CA	"	0.30	0.15	0.27	1.13	N/A	N/A
RI009-2008-013-QP							
Cg	QWF	0.58	0.29	0.63	1.47	5.07	-1.88
AC	"	0.32	0.16	0.52	1.21	8.07	0.10
Cg1	"	0.24	0.12	0.53	1.32	2.85	-4.92
Cg2	"	0.30	0.15	0.59	1.62	3.73	-3.95
Cg3	"	0.49	0.24	0.82	1.97	2.49	-5.32
CAb	"	0.71	0.36	0.89	1.97	2.67	-5.36
Ab	"	0.64	0.32	0.73	1.86	3.92	-3.83
RI009-2008-011-QP							
A	QLB	11.65	5.82	4.90	4.43	4.37	-2.53
AC	"	9.25	4.63	4.95	4.70	3.99	-3.05
C	"	1.76	0.88	0.80	1.57	6.86	-0.65
2Cg	"	1.55	0.78	0.99	1.35	4.20	-3.41
3C1	"	0.46	0.23	3.42	0.80	6.23	-2.07
3C2	"	0.38	0.19	0.22	0.94	8.16	-0.16
RI009-2008-012-QP							
Cg1	QSMB	0.61	0.30	0.27	1.39	7.04	-1.21
Cg2	"	0.73	0.36	0.46	1.27	4.25	-1.75
Cg3	"	0.46	0.23	0.30	1.05	6.44	-0.88
2Cg4	"	0.76	0.38	0.62	0.48	6.63	-0.51
2Cg5	"	1.22	0.61	0.92	0.05	6.65	-0.74
3C	"	N/A	N/A	N/A	0.04	5.91	-0.07

APPENDIX 6 SHELLFISH GROWTH DATA

2008 and 2009 summer mean oyster length (mm) and growth (mm/day) in Ninigret Pond

Landscape	7/22/2008	10/9/2008*	Growth (mm)	# Growing Days	mm/day	µm/day
NWFS	40 (8.5)†	50 (7.7)	10 (0.19)	79	0.12	120
NWF	37 (12.5)	48 (11.6)	11 (0.16)	85	0.13	130
NMC	36 (13.5)	47 (15.6)	11 (0.19)	85	0.13	130
NLB	34 (14.8)	42 (14.5)	8 (0.15)	79	0.10	100
Landscape	**6/25/2009**	**10/9/2009**	**Growth (mm)**	**# Growing Days**	**mm/day**	**µm/day**
NWFS	65 (1.04)	84 (7.6)	19 (0.18)	106	0.18	180
NWF	67 (1.16)	73 (8.1)	6 (0.19)	106	0.06	60
NMC	60 (14.1)	73 (8.4)	13 (0.18)	106	0.13	130
NLB	51 (13.1)	54 (9.5)	4 (0.12)	106	0.04	40

*NWF,NMC measured on 10/15/2008 n=90, all samples

† Mean (Standard Deviation)

2008 and 2009 Summer mean oyster length (mm) and growth (mm/day) in Quonochontaug Pond

Landscape	8/1/2008	10/2/2008	Growth (mm)	# Growing Days	mm/day	µm/day
QWFS	38 (9.4)†	52 (12.2)	14 (0.20)	69	0.203	203
QWF	35 (9.8)	55 (10.5)	20 (0.21)	69	0.290	290
QSMB	39 (9.2)	52 (12.1)	13 (0.21)	69	0.188	188
QLB	39 (9.8)	N/A	N/A	N/A	N/A	N/A
Landscape	**6/26/2009**	**10/2/2009**	**Growth (mm)**	**# Growing Days**	**mm/day**	**µm/day**
QWFS	65 (13.5)	82 (14.4)	17 (0.20)	98	0.173	173
QWF	65 (13.6)	82 (14.4)	17 (0.21)	98	0.173	173
QSMB	65 (13.0)	89 (15.2)	24 (0.20)	98	0.245	245
QLB	56 (12.5)	67 (15.5)	11 (0.20)	98	0.112	112

† Mean (Standard Deviation)

n=90, all samples

APPENDIX 6 SHELLFISH GROWTH DATA

Mean oyster growth among landscapes
7/22/2008-10/8/2009 (Ninigret Pond)
8/1/2008-10/2/2009 (Quonochontaug Pond)

Landscape	µm/day	σ	se	days
NWFS	98.6	38.6	4.1	443
NWF	81.9	40.2	4.2	443
NMC	85.4	38.8	4.1	443
NLB	46.0	28.1	3.0	443
QWFS	102.7	37.8	4.0	427
QWF	109.1	41.0	4.3	427
QSMB	100.1	44.5	4.7	427
QLB	65.5	41.2	4.3	427

Total live oysters and biovolume October 2009
Ninigret Pond
10/8/2009

Landscape	Total Live	Biovolume (L)
NWFS	96	11
NWF	324	23
NMC	347	22.5
NLB	208	5
Total	975	61.5

Total live oysters and biovolume October 2009
Quonochontaug Pond
10/2/2009

Landscape	Total Live	Biovolume (L)
QWFS	513	30
QWF	685	52
QSMB	513	35
QLB	396	16
Total	2107	133

APPENDIX 6 SHELLFISH GROWTH DATA

Quahog Sizes 10/2/2009 (Quonochontaug Pond); 10/8/2009 (Ninigret Pond)
Quahogs measured as hindge width

Landscape	Mean (mm)	σ	n	Biovolume (L)	#
Initial‡	9.1	0.7	90	4	2400
NWFS	22.1	3.4	73	2	730
NWF	16.8	3.3	30	0.25	32
NMC	18.1	2.9	89	1	115
NLB†	N/A	N/A	N/A	0	1
QWFS	17.6	2.9	90	1	109
QWF	19.1	2.6	90	2	126
QSMB	18.0	2.6	47	0.5	47
QLB*	15.9	3.0	90	2	243*

‡ 1/2 Liter at each plot ~300 quahogs
†Dead shells (All died?)
*Grown in a grow-out bag burried in LB

APPENDIX 7 Water Quality Data

Chlorophyll-a concentration

	2008				2009			
Landscape	**Mean**	**σ**	SE	n	Mean	σ	SE	n
NWFS	4.357	1.946	0.794	6	5.530	2.592	0.916	8
NWF	2.828	2.234	0.912	6	4.580	2.277	0.759	9
NMC	5.440	3.864	1.728	5	4.801	2.108	0.703	9
NLB	3.561	1.637	0.668	6	4.981	2.719	0.906	9
QWFS	5.085	1.757	0.786	5	4.856	2.049	0.774	7
QWF	4.396	1.902	0.851	5	4.054	1.653	0.625	7
QSMB	4.144	0.905	0.405	5	5.502	2.734	1.034	7
QLB	2.559	0.341	0.197	3	3.603	1.284	0.524	6

Chlorophyll-a concentration, pooled data (2008-2009)

Landscape	**Mean**	**σ**	SE	n
NWFS	5.028	2.332	0.623	14
NWF	3.879	2.353	0.607	15
NMC	5.029	2.726	0.728	14
NLB	4.413	2.388	0.616	15
QWFS	4.952	1.851	0.534	12
QWF	4.196	1.684	0.486	12
QSMB	4.936	2.206	0.637	12
QLB	3.290	1.174	0.371	10

APPENDIX 7 Water Quality Data

Ninigret Pond TSS mg/l

Date	NWFS	NWFS	NMC	NLB
8/5/08	35.67	43.67	68	87
8/14/08	42.5	25.8	34.17	33.33
8/26/08	42.67	26.33	25.5	40.5
9/18/08	53	17	24.83	25
5/21/09	26	22	24.33	20.67
6/2/09	-	21.83	24.17	26
7/29/09	22.33	29	30.5	25
8/11/09	26.83	37.17	23.67	26.83
9/2/09	2.83	123.67	3.83	2.33
9/16/09	23.67	21.17	16.83	22.17
10/9/09	25.17	28.67	29	32

Quonochontaug Pond TSS mg/l

Date	QWFS	QWF	QSMB	QLB
8/1/08	34	28.5	19	44.33
8/19/08	39.83	33.33	32.83	33.67
8/27/08	21	36	61	-
10/2/08	47	35.67	38.33	-
5/26/09	18.67	29.33	17	21.67
7/22/09	13	11	6	2.17
8/5/09	24	32.17	34.17	39
8/27/09	21.5	25.5	19.5	27.17
9/15/09	21.33	34.83	27.67	25
10/2/09	24	24	21.33	28.33

Total Suspened Solids Summary
Ninigret and Quonochontaug Ponds. 2008-2009

Landscape	Mean mg/l	σ	SE	n
NWFS	30.07	14.00	4.43	10.00
NWFS	36.03	30.04	9.06	11.00
NMC	27.71	15.55	4.69	11.00
NLB	30.98	20.87	6.29	11.00
QWFS	26.43	10.50	3.32	10.00
QWF	29.03	7.59	2.40	10.00
QSMB	27.68	15.13	4.78	10.00
QLB	27.67	12.74	4.50	8.00

APPENDIX 7 Water Quality Data

2008 Mean D.O. (mg/l) across landscapes

Landscape	D.O mg/l	σ	n
NWFS	6.63	1.73	4
NWF	7.46	1.18	4
NMC	7.04	1.41	4
NLB	7.47	1.67	4
QWFS	7.04	0.83	4
QWF	7.04	1.02	4
QSMB	6.59	0.48	4
QLB	7.17	0.91	4

2009 Mean D.O. (mg/l) across landscapes

Landscape	D.O. mg/l	σ	n
NWFS	6.75	0.86	5
NWF	6.80	1.37	6
NMC	6.38	0.61	6
NLB	6.53	0.78	6
QWFS	6.08	1.37	4
QWF	6.49	1.37	4
QSMB	6.31	1.23	4
QLB	6.32	0.75	4

Mean D.O. (mg/l) across landscapes

2008-2009 Landscape	Mean D.O. mg/l	σ	n
NWFS	6.69	1.22	9
NWF	7.07	1.27	10
NMC	6.64	0.99	10
NLB	6.91	1.22	10
QWFS	6.56	1.17	8
QWF	6.54	1.04	8
QSMB	6.74	0.74	8
QLB	6.79	0.90	8

APPENDIX 7 Water Quality Data

Mean Condcutivity Across Landscapes 2008-2009

Landacape	dS m^{-1}	σ	n
NWFS	37.32	4.22	10
NWF	39.01	3.54	10
NMC	39.04	3.69	11
NLB	38.55	4.03	11
QWFS	42.12	4.20	8
QWF	42.25	3.79	8
QSMB	41.50	5.12	8
QLB	40.96	4.31	8

Mean salinity across landscapes 2008-2009

Landacape	‰	σ	n
NWFS	28.09	0.76	6
NWF	28.76	0.88	7
NMC	29.50	1.32	7
NLB	28.93	0.95	7
QWFS	30.88	1.66	5
QWF	29.10	3.78	5
QSMB	29.14	4.02	5
QLB	31.46	1.83	5

APPENDIX 7 Water Quality Data

Mean pH across landscapes 2008-2009

Landscapes	pH	σ	n
NWFS	7.68	0.32	12
NWF	7.65	0.21	13
NMC	7.63	0.23	13
NLB	7.62	0.24	13
QWFS	7.57	0.29	11
QWF	7.63	0.26	11
QSMB	7.69	0.28	11
QLB	7.66	0.23	11

Mean water depth (m) across landscapes 2008-2009

Landscapes	Mean	σ	n
NWFS	0.96	0.16	6
NWF	1.04	0.09	6
NMC	1.00	0.18	6
NLB	1.00	0.11	7
QWFS	1.49	0.23	7
QWF	0.79	0.24	7
QSMB	0.99	0.26	7
QLB	3.19	0.21	8

APPENDIX 7 Water Quality Data

2008 Mean water temperature (C)
across landscapes during W.Q. Measurments

Landscapes	Mean	σ	n
NWFS	24.30	1.90	3
NWF	24.90	2.14	4
NMC	25.13	1.73	4
NLB	24.90	1.53	4
QWFS	23.20	1.02	4
QWF	23.20	0.65	4
QSMB	23.70	0.46	4
QLB	21.34	0.31	4

2009 Mean water temperature (C)
across landscapes during W.Q. Measurments

Landscapes	Mean	σ	n
NWFS	21.14	4.23	7
NWF	20.43	4.23	8
NMC	20.61	3.29	8
NLB	20.96	3.60	8
QWFS	21.40	2.68	6
QWF	21.72	2.65	6
QSMB	21.70	2.99	6
QLB	20.32	2.49	6

Mean water temperature (C) across landscapes
2008-2009

Landscapes	Mean	σ	n
NWFS	22.09	3.88	10
NWF	21.92	4.18	12
NMC	22.12	3.55	12
NLB	22.28	3.56	12
QWFS	22.12	2.28	10
QWF	22.31	2.18	10
QSMB	22.50	2.69	10
QLB	20.73	2.07	10

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