Sources of Nitrogen to the High Marsh/Upland Transition Zone of a Virginia Back-Barrier System

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Abstract

The results of several experimental studies demonstrate that nitrogen is the limiting nutrient in salt marsh systems. The two nitrogen species which can be readily utilized by the plant community are nitrate and ammonium. The inorganic nitrogen chemistry in the transition between upland and high marsh is poorly understood because of the numerous sources of nitrogen to this part of the marsh system, and the transformations of nitrogen from one form to another. The purpose of this study was to determine the significant sources of inorganic nitrogen to this boundary between terrestrial and marine environments in a pristine Virginia back-barrier marsh system, and to infer which transformations readily take place from the physical conditions present in each environment.

The sources of nitrogen to the high marsh include tidal flood waters, atmospheric inputs (both wet and dry), fresh groundwater discharges, fixation by bluegreen algae and bacteria, as well as fecal deposition by birds and mammals such as deer, fox, and raccoons. The most significant of these nitrogen sources identified in the literature are from tidal exchanges and groundwater inputs. However, in this study atmospheric inputs have also been realized as a significant source of nitrogen to the system under study. Nitrogen inputs by fecal deposition are considered insignificant in the literature, while fixation by algae and bacteria are significant, but not a primary

source. Therefore the sources identified and concentrated upon in this study include fresh groundwater inputs, tidal exchange, and atmospheric deposition.

This project was conducted on three separate back-barrier hummocks known as 'Parramore Pimples' within the Virginia Coast Reserve Long-Term Ecological Research (VCR LTER). The 'Parramore Pimples' are isolated, elevated land forms surrounded by salt marsh. The presence of a fresh water lens, coupled with the raised relief of the features allow each pimple to be characterized as a small upland ecosystem. The vegetation zonation around the features is typical of upland systems observed on the barrier islands of Virginia. The pimples therefore presented an ideal study site to investigate the upland/high marsh boundary conditions because they are independent hydrologic systems void of any direct anthropogenic nutrient inputs (other than atmospherically derived inputs).

Following extensive field and hydrologic investigations, a transect consisting of 9-10 porewater sippers extending from the pimple surface, through the brackish transition (shrub) zone, and out into the high marsh was established for each pimple. Porewater samples from each transect were collected and analyzed for ammonium (NH_4^+), nitrate (NO_3^-), pH and salinity from July-November, 1994. Laggonal waters from the tidal creeks behind the island were also analyzed. Wet deposition of atmospheric nitrate and ammonium has been measured on a weekly basis at the VCR-LTER site from March 1990 to the present.

The average concentrations of NO_3^- and NH_4^+ in the wet deposition exceeded the inorganic concentrations of porewater nitrogen measured along each of the three transects. During the summer months the average concentrations of NO_3^- and NH_4^+ were respectively 35.0 μmoles/l and 23 μmoles/l in the wet deposition. Through the summer of 1994, porewater NO_3^- concentrations were generally less than 3 μmoles/l, while NH_4^+ concentrations were usually less than 15 μmoles/liter. Following a large precipitation event (54.6 mm) on 5-August, 1994, significant increases in the porewater NO_3^- concentrations (3-12 times the background levels) were measured in the upland/high marsh transition zone. This increase in the nitrate concentration demonstrates the link between atmospheric deposition and available porewater nitrogen.

The results from this study indicate that the primary sources of nitrogen to this system are through atmospheric deposition and tidal exchange. Porewater NO_3^- and NH_4^+ concentrations along each transect are considerably lower than the concentrations in the wet deposition, indicating either rapid assimilation of the nitrogen into the system (plant uptake) or denitrification. The results suggest that denitrification is not significant in the fresh water, but does result in some losses of nitrate from the marsh. The inorganic nitrogen concentrations in the lagoonal waters are low, but the relatively frequent occurrence of tidal inundation maintains a significant supply of nitrogen to this region.

Acknowledgments

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Introduction

Background

Tidal salt marshes are among the most productive ecosystems in the world, producing as much as 2 kg C m^{-2} yr^{-1} (Pomeroy and Wiegert, 1981). Tidal salt marshes (Fig 1) are the vegetated regions (colonized by halophytes) between upland terrestrial environments and marine water bodies that are flooded cyclically by tidal waters. In the eastern United States salt marshes account for 40% of the area of coastal lagoonal basins (Hayden and Dolan, 1979). ~~A typical salt marsh hydrologic system is demonstrated in figure~~ 1. In and of themselves, these marshes are extremely important ecosystems, but perhaps of greater significance are the links between these systems and the larger systems to which they are connected: both the land and the sea. It is increasingly realized that the massive production which occurs in marsh systems form the basis for many estuarine foodwebs.

Every research project which fosters the knowledge base related to salt marshes helps develop a greater understanding of the actual links between salt marshes, uplands, and marine systems. Tidal salt marshes are inherently difficult to study because of the problem of variable controls which complicate quantitative analyses. Energy subsidies in the form of tidal oscillations serve as both importers as well as exporters of nutrients, organic matter, bacteria, phytoplankton, algae and macrofauna. Because of the complicated array of exchanges it is often difficult to include all the variables in a single study in order to develop a complete understanding of the links between salt marshes and other systems. A further complication arises when the realization that subtle differences in physical conditions (sediment character, tidal amplitude, quantity of upland water discharge, ect.) lead to the development of extremely different marshes which behave in entirely dissimilar ways. However, several studies have been completed which lead to a partial understanding of the significance tidal salt marsh systems have on the greater systems with which they are linked. With additional research efforts in several different marsh systems our comprehension of these links will be enhanced.

Perhaps of greatest significance are the links between the marsh and the sea. In a synthesis report on salt marsh ecosystems Weigert and Pomeroy (1981) suggest that "the most important link between the marsh and the sea are the trophic relationships of the macroconsumers in the water covering the marsh at high tide and residing in the creeks at low tide". Several lines of evidence from a number of sources were included in the development of this hypothesis. Carbon budgets developed for the Sapelo Island marshes resulted in an unexplained difference between measured production and measured losses (from respiration and tidal movement) of approximately 10% of the total budget. Weigert and Pomeroy believe that this discrepancy is due to a loss of carbon through microbial transformations which ultimately becomes secondary production of macroorganisms. This is coupled with other studies which demonstrate that tidal creeks and marshes serve as nurseries for a number of fish species, as well as full time habitats for many shellfish and other marine macroinvertebrates such as commercially important species of crabs and shrimp. For example, Gunter (1967) suggested that over 97% of the total commercial harvest of the states around the Gulf of Mexico is in some way dependent upon the estuaries and marshes of that region. It is, however, important to understand that many of the fundamental processes which occur in the marsh and ultimately lead to this production of economically important species are not clearly understood. The sources and transformations of inorganic nitrogen which support the production of carbon in these systems, particularly in the high marsh region, are not fully understood.

Nitrogen has long been recognized as the limiting nutrient in salt marsh systems (Valiela and Teal, 1974; Osgood, unpublished data). Several investigations have determined that phosphorous is not limiting in these systems. Phosphorous accumulates in marsh soils by sorbing to clay sediments or peat (Whitney, et al., 1981). Pomeroy et al. (1969) determined that there is enough available phosphorous in the upper meter of the salt marsh to support the marsh plants for several hundred years. Experimental studies involving the application of fertilizers in different marsh types have determined that phosphorus is not limiting in salt marsh systems (Valiela and Teal, 1974). Osgood (personal communication) conducted fertilizer experiments in Virginia back-barrier marsh systems and determined that these systems are also nitrogen limited. Applications of nitrogen increased production in these studies while phosphorous applications did not.

Nutrient inputs to the system follow a variety of pathways which include atmospheric deposition, removal from tidal (salt) waters during inundation, and groundwater discharge from upland sources. Small amounts of nitrogen may also be fixed by blue-green algae on the surface of the marsh, and by bacteria in the sediments

(Valiela and Teal, 1979). Nutrient exports results from tidal exchange (dissolved and solid materials) and denitrification. Several processes are involved in the movement and chemical transformations of nutrients within the marsh. Many of these nutrient processes have been clearly defined, and are understood in the context of nutrient cycling within the salt marsh system. However, several links in this system have not been fully investigated, and therefore present significant problems to developing an integrated understanding of nitrogen cycles in salt marshes. Specifically, the inorganic nitrogen chemistry (sources and transformations) in the high marsh/upland transition zone is poorly understood. Therefore, the purpose of this investigation was to determine the magnitude of inorganic nitrogen inputs from the individual sources, and to understand the nitrogen transformations which may be occurring in the high marsh/upland transition zone of a Virginia back barrier marsh system.

Significant nutrient inputs result from the discharge of upland waters into the high marsh (Valiela and Teal, 1979; Reay et al., 1992). The term 'high marsh' refers to tidal marsh areas adjacent to the upland (terrestrial region) which are flooded regularly during spring tide cycles, and occasionally during high neap tides. The chemical interactions which take place in this region are complex because two distinct water bodies interact in this zone: fresh upland groundwater and saline marsh groundwater. Fresh upland waters tend to have significant dissolved oxygen concentrations, and inorganic nitrogen in the form of nitrate. Saline marsh groundwater is usually depleted of oxygen, and the predominant inorganic nitrogen species present is ammonium. The relative concentrations of various nutrient species, as well as other significant chemical variables (such as pH, eH, and salinity) will affect the availability of these nutrients to the plants. For example, under certain conditions, denitrification reactions may be favored, and thereby reduce the available nitrogen to the plants. Several important transformations of nitrogen may occur in this region because of the mixing of these two chemically distinct water sources. The transformations which occur will determine if the nitrogen will be available to the plant community.

The high marsh region is arguably the most important sector of the marsh in terms of processing nutrients. It is the only region of the marsh where fresh groundwater discharges into the system. It is unclear whether or not the oxygenated, nitrate rich fresh water supplies significant quantities of available nitrogen to the marsh. The nitrate is either reduced to ammonium (nitrate reduction), and therefore available, or the conditions may favor denitrification reactions that yield nitrous gasses as end products, which may degas to the atmosphere. The nitrate may also be immobilized by plants. Equation 1 demonstrates the biochemical pathways which are believed to be involved in nitrate reduction and denitrification (Alexander, 1977). The question mark refers to an intermediate reaction which is not fully understood. The direction of the reaction (towards reduction or denitrification) will depend upon other physical and biological variables such as the pH and eH of the water, as well as the availability of denitrifying bacteria.

Equation 1:

$$2\,HNO_3 \xrightarrow[-2\,H_2O]{+\,4H} 2\,HNO_2 \begin{cases} \xrightarrow[-2\,H_2O]{+2\,H} 2\,NO \xrightarrow[-\,H_2O]{+\,2H} N_2O \xrightarrow[-H_2O]{+2H} N_2 \\ \rightarrow\ ?\ \rightarrow [2\,NH_2OH] \rightarrow 2\,NH_3 \end{cases}$$

The direction of this reaction has important implications for the ultimate fate of nitrogen discharged into the marsh, and subsequently to the ecology and groundwater chemistry of the marsh itself. Any changes in the availability of nitrogen and oxygen will affect the plant community in the high marsh. Certain high marsh species such as *Spartina patens* require an oxygenated rhizosphere in order to survive (Bertness, 1991). The balance between oxygen and nitrogen availability will determine which species are able to subsist in this zone.

Elevated groundwater nitrate levels have been documented in several agricultural regions within the Atlantic coastal plain. In a study conducted on the Chesapeake Bay side of the Eastern Shore of Virginia Reay et al., (1992) measured nitrate concentrations as high as 652 μmoles/l in the upland groundwater beneath an agricultural field. Groundwater nitrate concentrations beneath an adjacent forested tract ranged from 7-82 μmoles/l. Other studies on Virginia's eastern shore have measured nitrate concentrations below agricultural fields as high as 600-700 μmoles/l (Tapper, personal comm). Reay et al. also measured nearshore discharge rates (into the tidal creek) across the sediment-water interface of 0.02-3.69 l/m^2-hr, indicating significant exports of nitrate directly to the estuary. In an undisturbed (no anthropogenically derived sources of nitrogen) mainland marsh system in Massachusetts, Valiela and Teal (1979) report groundwater nitrate concentrations of 50 μmoles/l. The nitrate concentrations in the upland groundwater of Hog Island (a Virginia barrier island) are significantly lower than mainland concentrations. Day (personal communication) reported average nitrate concentrations of less than 5 micromoles/l along a transect which extends from the lagoon to the beach near the northern end of Hog Island. The majority of previous studies conducted have concentrated upon mainland marshes, many of which are surrounded by agricultural regions which contribute significant quantities of anthropogenicaly derived inorganic nitrogen to the adjacent marsh systems. Very few studies have focused upon understanding the sources and chemical transformations of inorganic nitrogen in pristine barrier island marsh systems.

The focus of this study was to determine the significant sources of inorganic nitrogen to the high marsh/upland fringe zone in a back barrier marsh system, and to understand the transformations of nitrogen based upon measured physical parameters. This zone receives significant inputs of nutrients from tidal flood waters, upland fresh water, and atmospheric deposition. Tidal waters flooding the marsh surface from the lagoon side of the island provide nutrients during spring tide cycles, when the entire marsh surface is inundated by salt water up to the fringes of the upland regions. A significant source of nutrients may come from the fresh groundwater which flows towards the marsh from the upland regions. As the fresh water approaches the high marsh/upland fringe, it is directed upwards because of the density differences between the fresh and salt water. The mixing of fresh and salt waters create a brackish transition zone between the fresh upland waters and the salt groundwater in the marsh. A salt water wedge extends beneath the upland and the transition zone, forcing the fresh water to upwell into the high marsh region (Falkland 1992). Within this mixing zone the dissolved solids from the two water sources (fresh and marine) must interact. The resultant chemical interactions are complex, and understanding them requires a determination of the magnitude of nitrogen inputs from each source, and an understanding of which reactions will be favored under particular conditions. In order to understand the nitrogen chemistry it was also necessary to characterize the hydrology and vegetation structure of the environment.

Objectives

The primary objectives of this study are to:

- Characterize the hydrology associated with the pimples.
- Characterize the vegetation structure associated with the pimples.
- Identify significant sources of inorganic nitrogen to the high marsh/upland transition.
- Determine the concentrations of inorganic nitrogen in each source.
- Understand the possible transformations of nitrogen in this zone based upon measured physical variables which affect the transformations.

Previous work

Much of the previous work related to the nutrient processes in tidal salt marsh systems has focused upon the nutrient exchanges between the marshes and the tidal creek waters (Chambers, 1990; Wolaver, 1981; Woodwell et al., 1979; Woodwell and Whitney, 1977; Valiela et al, 1978; Heinle and Flemer, 1976; Axelrad, 1974). The primary nutrient species examined in most of these investigations include total phosphorous (in the form of phosphate, dissolved organic phosphorous, and particulate phosphorous), as well as total nitrogen (in the form of ammonium, nitrite, nitrate, dissolved organic nitrogen, and particular nitrogen). However, the disparities between the results of these investigations indicate that it is, as yet, unclear whether tidal marsh systems are net importers or net exporters of total phosphorous and total nitrogen. Wolaver's (1981) results indicate that a marsh located near the lower Chesapeake Bay, Virginia (Carter's Creek marsh) was a net importer of total phosphorous and nitrogen. Axelrad (1974) studied two marshes in Virginia and determined that both marshes were net exporters of total nitrogen and that one marsh was a net importer of total phosphorous while the other was in balance with respect to total imports/exports of phosphorous. Woodwell et al. (1979) worked in a marsh near Flax Pond, NY, and realized a net export of total phosphorous from the system. Valiela et al. (1979) conducted their research in the Great Sippewissett Marsh, Massachusetts and report a net export of both total nitrogen and phosphorous.

Wolaver (1981) attributes these disparities to differences in location, as well as to problems associated with sampling procedures. He states that the sampling error may have resulted from inconsistencies in the sampling procedures, as well as from an incomplete knowledge of several nutrient transport mechanisms such as bed load, coarse size detrital export, and nutrient export due to biological activity. Storm surges may also contribute significant nutrient fluxes which cannot be accounted for. The previous studies determined the exchanges by measuring the total volume of water which flows through a tidal creek during the course of a tidal cycle and multiplying the nutrient concentrations with the total flow during an ebb or a flood tide. The problem with this approach is that it does not measure the exchanges which are related solely to the marsh, but measures the exchanges which occur in the whole system (marsh, mud flats, creeks). Wolaver attempted to reconcile several of the problems encountered by the previous researchers, and conducted the most complete study of total nutrient exchanges (through tidal inundation). Wolaver's research focused upon the exchanges which occur on the surface of the marsh, as opposed to the exchanges taking place in the whole system. His research indicates that the Carters Creek marsh was a net importer of total nitrogen (31.62 g m^{-2} yr^{-1}) and total phosphorous (10.92 g m^{-2} yr^{-1}).

Valiela and Teal (1979) published the first complete nitrogen budget of a marsh system by measuring all of the significant fluxes of nitrogen in and out of the

Great Sippewissit Marsh, Massachusetts over a two year period. The inputs they reported resulted from upland groundwater discharge, tidal inundation, precipitation, deposition by bird faeces, and fixation by blue green algae and bacteria. Outputs were measured through tidal water exchanges, denitrification, volatilization of ammonia, and shellfish harvesting. The most significant nitrogen fluxes occurred through the processes of groundwater input, tidal exchange, denitrification, and nitrogen fixation. The other mechanisms involved contributed less significant exchanges of nitrogen. The most important components of the nitrogen budget in the high marsh region involved groundwater inputs of nitrate, exchanges through the flooding tidal waters, and denitrification.

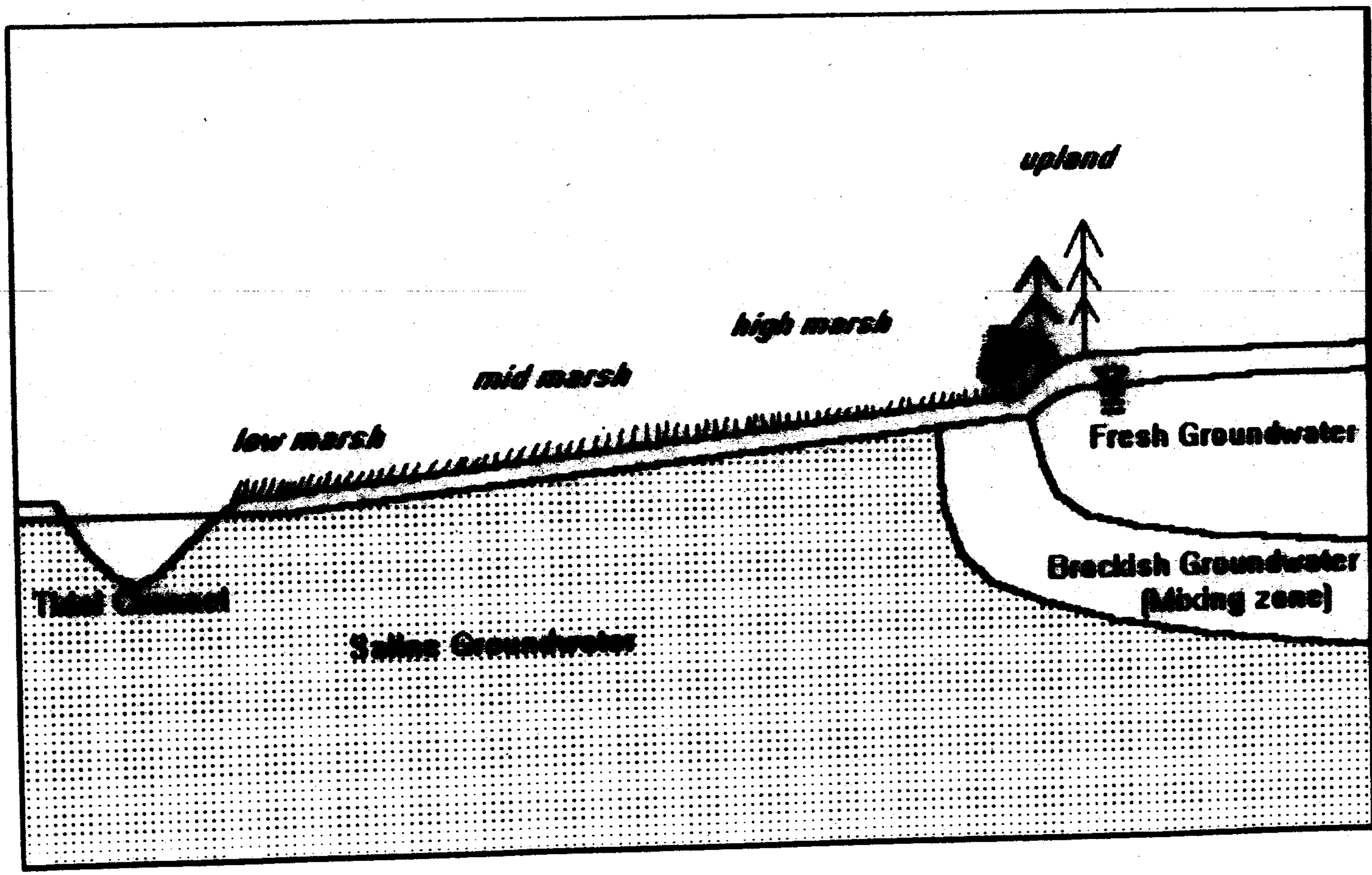
Valiela and Teal (1979) report a total input of 35,990 kg-N/yr, and a total export of 39,860 kg-N/yr from the marsh. Of the total inputs, 1% is attributed to precipitation, 17% is from fresh groundwater inputs, 9% from nitrogen fixation by blue green algae and bacteria, and 73% is derived from tidal water exchange. Nitrogen fixation was more significant in the low marsh than in the high marsh by a factor of 3-4. Tidal water exchange resulted in the export of 79% of the total nitrogen exports from the system while denitrification accounted for 17% of the losses. The remaining 4% of the losses are attributed to sedimentation (3%), volatilization of ammonia and shellfish harvesting (1%). The total imports subtracted from the total exports resulted in a net export of 3,870 kg-N/yr from the marsh.

The results reported by Valiela and Teal (1979), in conjunction with the research efforts discussed previously demonstrate that the most significant nutrient fluxes in the high marsh region are a result of upland groundwater discharge, tidal inundation, and denitrification. Nitrate rich upland waters discharge into the high marsh, while tidal waters contribute significant quantities of ammonium. Wolaver

(1981) demonstrated that the high marsh is more efficient in removing nitrogen from the tidal waters than the low marsh. However, the concentrations of ammonium in the waters which flood the high marsh tend to be lower than the waters which flood the low marsh because the low marsh plants have extracted some of the ammonium as the water floods the marsh surface. Denitrification is the primary mechanism responsible for nitrogen losses from the high marsh, particularly during the warm months of summer.

Other significant research includes work conducted by hydrologists. Harvey and Odum (1990) conducted hydrological investigations of salt marsh systems in Virginia. Their focus was on the role of tidal marshes on upland groundwater discharge to estuaries. Harvey and Odum concluded that groundwater discharged from an upland aquifer into a marsh system is retained longer in tidal marsh soils than in subtidal sediments in systems where the groundwater is discharged directly into the estuary. This result has important implications for the reactive dissolved solids entering the system from the upland groundwater. Longer soil contact time increases the possibility of nutrient immobilization by root water uptake, and also increases the possibility of nutrient transformations.

Figure 1: Schematic diagram demonstrating the groundwater hydrology of a typical salt marsh system



Site Description

The Study Site:

A study site located within the back barrier marshes of Parramore Island was selected for this research (figure 2). Parramore Island is located within the Virginia Coast Reserve (VCR), and is situated approximately twelve kilometers east of Virginia's Eastern Shore (figure 4). Parramore is one of a series of active barrier islands along the Delmarva Peninsula (conveniently named for the three states which share this peninsula: Delaware, Maryland and Virginia), which lies between the Atlantic Ocean and the Chesapeake Bay. The mouth of the Chesapeake Bay (approximately 30 km wide) separates the peninsula from the tidewater region of Virginia to the south. The climate of the region is humid-subtropical, with an average annual rainfall of 104 mm (Hayden, 1979). Monthly average temperatures range from 4.6 °C in January to 25.9 °C in July (data from Cheriton Virginia, located on the Eastern Shore of Virginia). The tides are semi-diurnal and have a range of approximately 1.0 meter.

The chain of barrier islands consists of several isolated islands separated from the peninsula by a lagoonal complex which is bounded by Assateague Island to the north, and Fisherman's Island 80 km to the south. Parramore Island lies approximately in the center of this island complex. The islands vary from 5 to 20 km long, and 0.3 to 2.0 km wide; Parramore is 11 km long and 2 km wide at its widest.

A typical transect extending across the lagoonal complex from the islands to the peninsula traverses a back-barrier marsh system into an open lagoon interspersed with lagoonal marshes in topographically high areas, across deep tidal creeks (up to 30 meters in depth), to fringing mainland marshes before extending up onto the mainland itself. The ratio of open lagoonal water to the area of the lagoon itself varies from .2 in the southern part of the lagoonal complex to .35 in the northern regions of the complex (Finkelstein and Ferland, 1987). The remainder of the area is covered by salt marshes or tidal flats.

A gradient in sediment size exists from the island marshes to the mainland marshes. The island marshes are dominated by sand size grains (up to 96%), while the mainland marshes are dominated by silt and clay size fractions (Robinson, 1994). This is a typical sequence resulting from the proximity of the various marshes to the source of the sediments. Back-barrier marsh systems receive most of their inorganic material directly from the beach during overwash events. The smaller size fractions can be held in suspension for longer periods of time in the less energetic waters of the lagoonal complex and are subsequently transported closer to the mainland.

An increase in sea level over the past several thousand years has resulted in the landward migration of the islands (Finkelstein and Ferland, 1987). Radiocarbon dating of lagoonal marsh peats indicate that these islands are at least 4,600 years old. Finkelstein and Ferland believe that Parramore Island was located approximately 5 km east of the present location 4,600 years ago, when sea level was about 6.60 meters below the present sea level. The islands literally roll over themselves as storms breach the dune line and transport beach sediment farther inland. The sediment is deposited upon the back-barrier marshes, constantly elevating or burying the high marsh region under washover fans. This active process is clearly visible on the southern portion of Parramore island. Relict marsh peat is exposed on the beach face, and behind the dune line several washover fans are active during storm events. Aerial photographs of this part of the island indicate that as much as 200 meters of the shoreward facing side of the island have eroded between 1949 and the present.

Scattered throughout the marshes on the lagoon side of Parramore Island are several hundred land forms known collectively as the "Parramore Pimples" (Cross, 1964). The Pimples are isolated land forms surrounded by salt marsh that tend to be round in shape, and range in size from approximately 10-250 meters in diameter. The pimple surfaces are elevated above the surrounding marsh by 1-3 meters. The features which are at least 30 meters in diameter are able to support an assemblage of terrestrial vegetation species because a shallow fresh water lens has developed beneath the surface. This lens constitutes a body of fresh water, recharged by precipitation, that rests on top of the denser, saline groundwater below. The presence of the fresh water coupled with the raised relief of the features allow each pimple to be characterized as a small upland ecosystem. The vegetation zonation around the features is typical of upland systems observed on the barrier islands of Virginia. The pimples therefore present an ideal study site to investigate the upland/high marsh boundary conditions because they are independent hydrologic systems void of any direct anthropogenic nutrient inputs. This is crucial in obtaining information leading to the understanding of natural processes occurring in this zone. Studying isolated systems also reduces the possibility of error resulting from the inherent problems associated with defining all of the variables within a more open system such as a dune ridge.

The upland systems represented by the pimples have developed distinct vegetation patterns. A typical pimple has a sandy, barren interior surface with a few grasses present, as well as an occasional Prickly Pear cactus. Outward from the barren areas the surface has been colonized by various terrestrial grass species. Eastern Red

Cedar trees (*Juniperus virginiana*) dominate along the relatively steep edges of the features. Several shrub species extend along the transition from upland to high-marsh, including *Iva frutescens*, and *Baccharis halimifolia*. Some of the pimples also support *Myrica pensylvanica* which will only grow along the edges of the features because it can not tolerate salinities above 3ppt (Schneider, 1984).

Within the salt marsh surrounding the pimples the halophytes also display distinct vegetation patterns. Immediately below the pimple edge *Spartina patens* is intermixed within the shrub zone; at lower elevations *S. patens* tends to dominate, forming a ring around the pimple that is clearly visible from the air. It has been demonstrated that *S. patens* thrives in this zone because it requires the oxic conditions that are generally associated with the high marsh (Bertness, 1991). Unlike *Spartina alterniflora, S. patens* is not capable of oxygenating its rhyzosphere in anoxic soils. Around many of the pimples the *S. patens* ring grades into a shallow trough which extends partially or completely around the feature. Within this trough a wide assemblage of species tend to coexist: *Salicornia bigelovii*, *Salicornia virginica*, *Distichlis spicata*, *Limonium caroliniaum*, short form *Spartina alterniflora,* and *Spartina patens*. Further outward from the pimples the topography tends to become more random, with isolated, small hummocks (1 - 25 meters in diameter), as well as minor depressions scattered within the landscape. Various plant species tend to dominate within the individual conditions. Within the depressions *Salicornia spp.* usually dominates because it is capable of surviving in high salinity zones. During summer months the salinities tend to increase within the depressions because of the concentrating effects of evaporation. The small, elevated hummocks resemble pimples, and have similar zonation patterns on a smaller scale. A few isolated shrubs may be present, while *Spartina patens* dominates below the shrubline. It is likely that the plant zonation is a result of physical conditions (a combination of salinity, DO concentrations, nutrient availability, tidal inundation periods) maintained by hydrological processes.

This study was conducted in association with a larger experimental project which is examining the effects of climatic change on the vegetation species present on and around the pimples. The coordination of these two separate projects at one site facilitated each project through the possibility of sharing data. Three pimples were chosen for this study (figure 3). These three pimples are approximately equal in size (30-40 meters in diameter), in order to avoid problems associated with scale. These three pimples also exhibit similar vegetation zonation patterns, although the number of individuals of a given species may vary considerably. For example, Pimple 3 has a nearly unbroken ring of *J. virginiana*, while Pimples 1 and 2 have only several individuals of this species scattered around the feature.

Pimple 1 is the highest feature topographically, reaching 2.0 meters above msl at its highest point. Pimple 2 has a maximum elevation of 1.8 meters above msl, while Pimple 3's highest point is at 1.5 meters above msl. The low elevations of these features result in occasional submergence by sea water during extreme storm events and astronomically high tides. Between January-October, 1994, six tides higher than 1.5 meters above msl were recorded at the Hog Island tide station (4 km south of the study site). Five of these tides were between 1.51 and 1.57 m above msl, and the sixth event was recorded at 2.03 meters. Therefore, the first five would have flooded Pimple 3, while the last event would have flooded all three pimples. Evidence of washover includes wrack deposits on the upper surfaces of these pimples. Pimples 1 and 2 are situated approximately 200 meters from the beach face, while Pimple 3 is set slightly farther back at 250 meters from the beach face. The tidal creek which supplies flood water to the marshes around the pimples is located between 200-300 meters west of the pimples. The larger, more elevated pimples to the north are less susceptible to washover events and therefore display a wider assemblage of woody vegetation such as Black Cherry (*Prunus serotina*), Loblolly pine (*Pinus taeda*), and *Myrica pensylvanica*.

Figure 2: Map of Parramore Island. The study site is located within the red box and is illustrated in greater detail in figure 3.

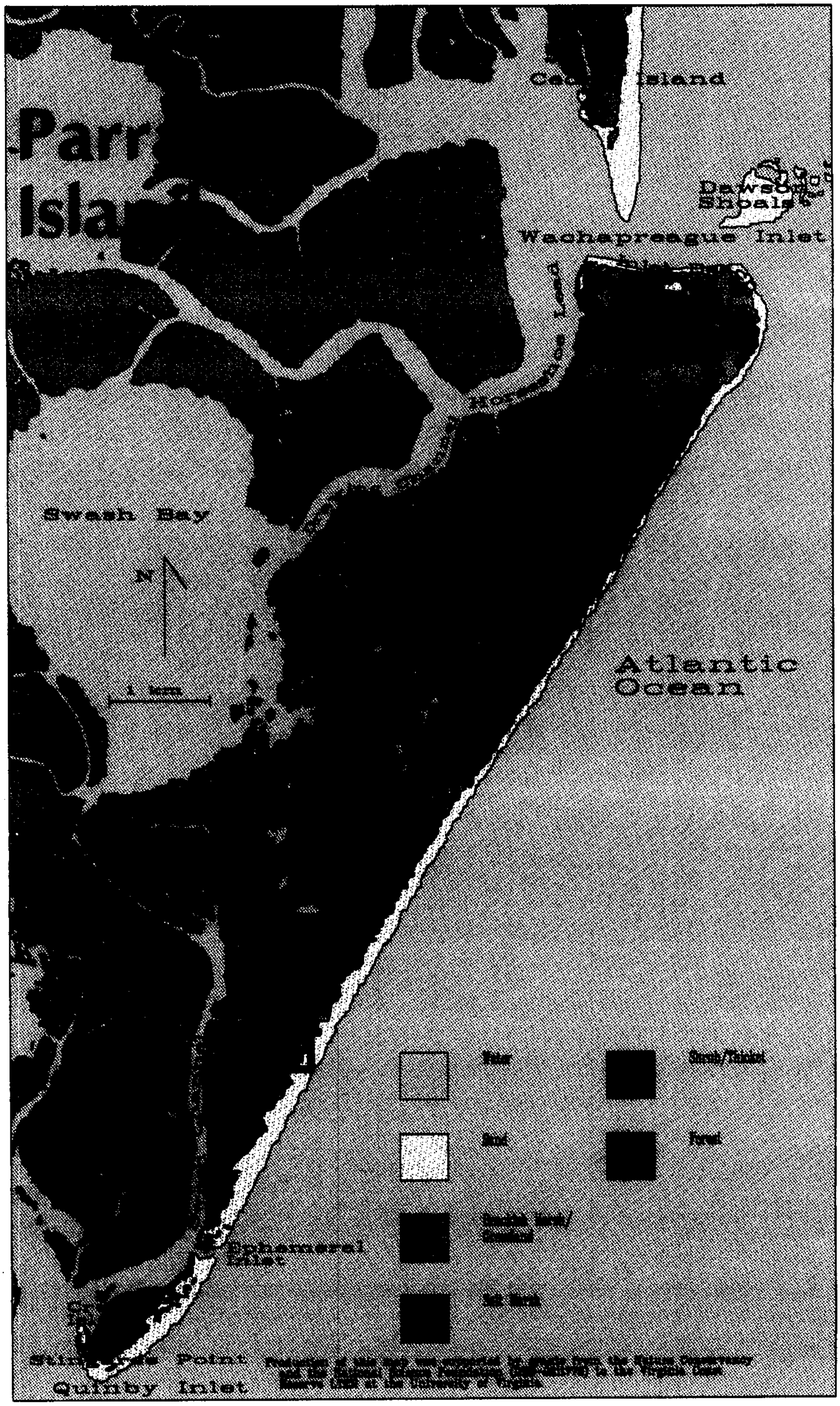


Figure 3: The study site. Porewater samples were collected along each transect.

The Study Site (South Parramore Island)

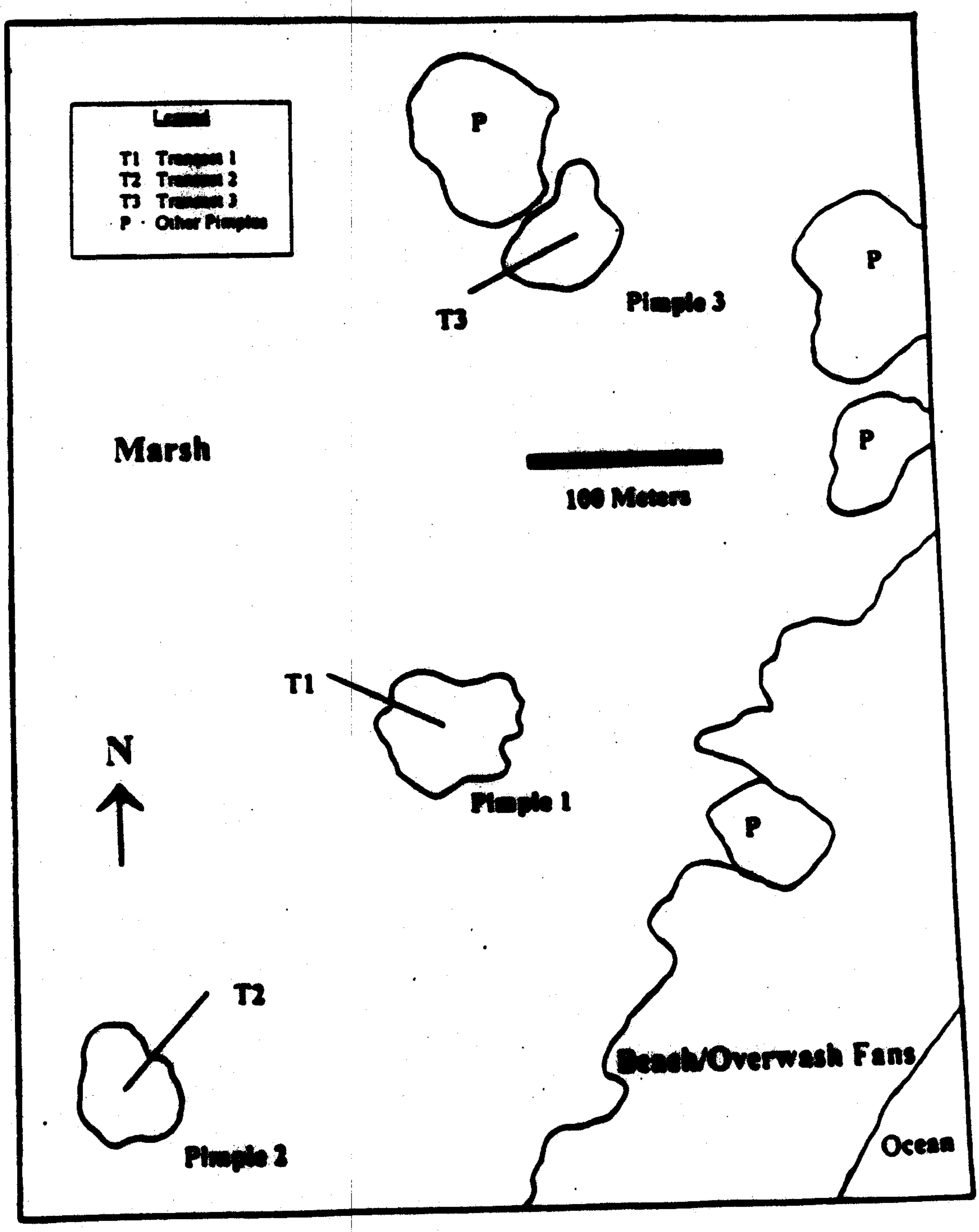
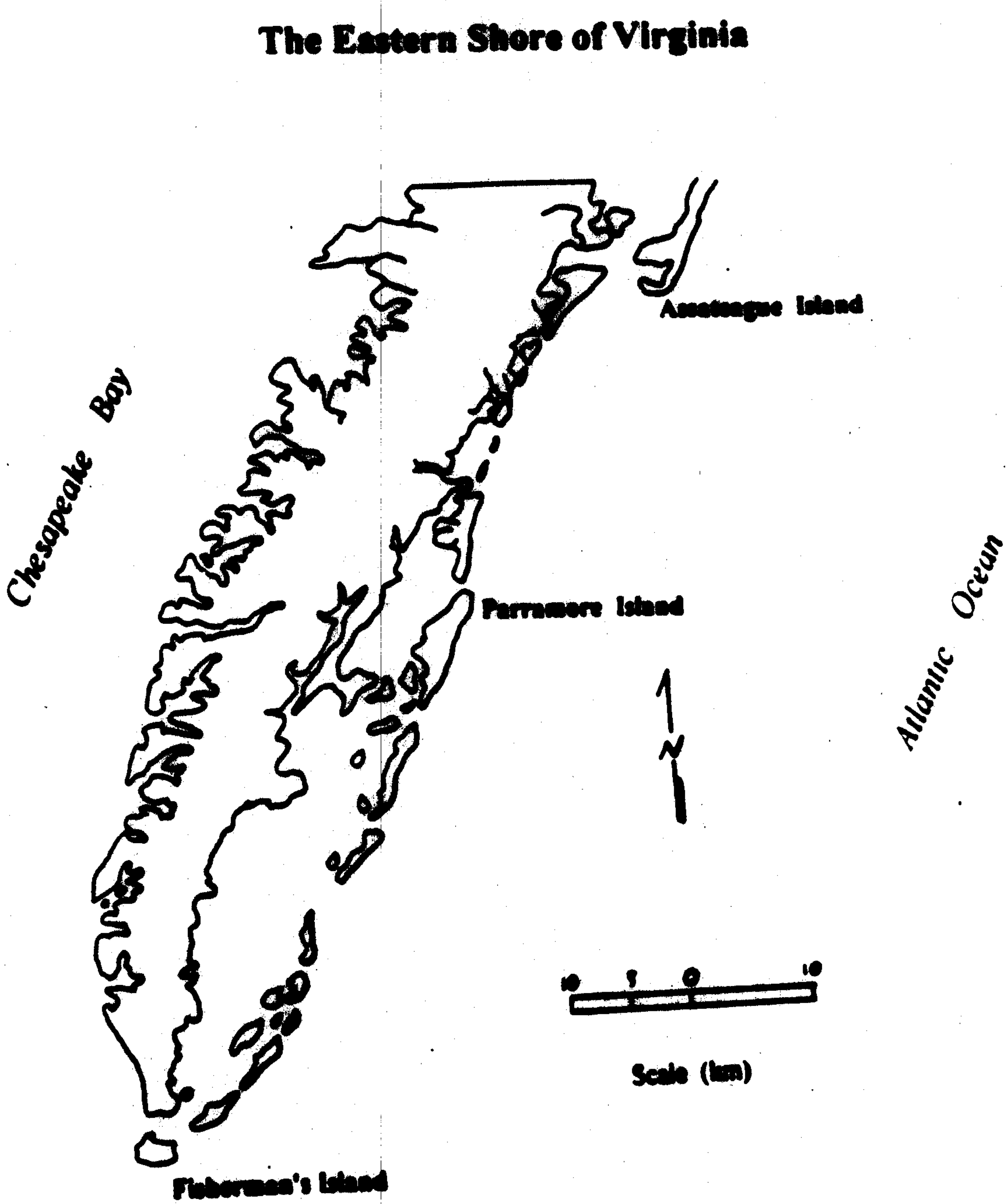


Figure 4: The Eastern Shore of Virginia. The study was conducted on Parramore Island.



Methodology

Hydrology

Several nests of monitoring wells were installed in order to determine the extent of the small fresh water lenses beneath each pimple. These wells were installed during summer, 1993 and monitored over the study period in order to understand the effects of short term climatic variables on the size of the lens and the brackish transition zone. Three nests of three wells each were installed on Pimple 1 and Pimple 3, and one nest of three wells was installed on Pimple 2. A high nest was placed near the center of each feature; on Pimples 1 and 3 a middle nest was installed within the grass zone between the edge and the center, and a low nest was placed on the edge of these pimples (figure 5). For each nest of wells, a shallow well was installed near the boundary between the fresh water and the transition zone. The second well was driven to the approximate center of the transition zone (approximately 15 ppt), and the deep well was located at the boundary between the transition zone and the saline marsh groundwater (about 27 ppt). During well installation salinity profiles were constructed by extracting and testing water samples every 50 cm. Salinity was tested in the field using a refractometer accurate to 1 ppt. Water samples have been extracted and tested for salinity on a monthly basis (as weather and tides permitted) in order to monitor the lens and the transition zone.

The wells consist of an iron point welded onto a section of half inch diameter galvanized pipe with a series of holes drilled in the lower 10 cm. A 500 micron screen was wrapped around this section of the pipe in order to exclude sediments during well installation. The well point flanged out approximately 1 cm beyond the diameter of the pipe in order to protect the screened area during installation. The wells were installed by driving the well point into the substrate with a manual driver. Each pipe section was threaded, allowing as many sections to be driven in as was necessary to reach the appropriate depth.

A monitoring well on the center of Pimple 1 was installed at a depth of approximately 1.5 meters. A solar panel attached above the well powered a data logger which continually monitored the water table height, and also recorded precipitation totals from a collector installed on the surface of the pimple. The water table level was measured by a pressure transducer in the well.

Two sediment cores were extracted using a vibra-coring device. The first core was extracted from the center of Pimple 1. The second core was extracted from the high marsh approximately two meters out from the nutrient transect. Each sample was split and half of each core was archived at the Bucknell University geology department. A grain size analysis was performed on the cores using standard US sieves. Subsamples from the pimple core were analyzed every foot, while subsamples from the marsh core were analyzed every two feet. Deeper cores were unsuccessfully attempted because the nearly pure sand collapsed upon extraction.

Nitrogen Chemistry

In order to understand the nitrogen chemistry in the high marsh/upland transition zone it was necessary to determine which sources contributed significant quantities of nitrogen, as well as determine the concentrations of porewater inorganic nitrogen in this zone. The sources which were investigated included flood waters, fresh groundwater (lens water), and precipitation. Inorganic nitrogen concentrations were measured for each pimple along the gradient from fresh to salt water (from upland to high marsh) on a monthly basis for five months beginning in July, 1994.

Porewater samples were extracted from sippers which were constructed following the guidelines established by Osgood (1992). The sippers allowed the extraction of pore waters without contaminating the samples with oxygen from the atmosphere, which could result in the oxidation of ammonium towards nitrite or nitrate. The sippers were constructed of 1.5 inch diameter pvc pipe. A 40 micron 'frit' was glued to the bottom using 100% silicon sealant. A 1/8 inch diameter length of Tygon™ tubing was glued near the inner bottom of the pipe and extended to the top of the pipe. The Tygon™ was then attached to a rubber stopper at the top of the pipe. Two valves were attached to each stopper, one connecting to the Tygon™ while the other opened directly to the pipe interior. The samples were collected by flushing the 'old water' (water which had been sitting in the tube) out of the pipe with nitrogen gas. This was accomplished by opening both valves and injecting nitrogen gas through the valve which opened directly into the tube. The increased pressure forced the old water up through the Tygon™ and out of the sipper. A sample was subsequently collected by drawing new porewater through the valve attached to the Tygon™ with a syringe. The samples were immediately placed on ice for transport to the laboratory where they were filtered prior to the nutrient analysis

Several sippers were installed along three transects (one on each pimple); each transect extended from the surface of the pimple, through the brackish shrub zone, and out into the high marsh. The transects will be referred to as T1, T2, and T3 for Pimples 1, 2, and 3 respectively. Ten porewater sippers were installed along T1 and T2, while nine sippers were installed along T3. The sippers were installed to a depth immediately below the root zone.

Ammonium concentrations were determined using a standard two-reagent colorimetry technique based upon the formation of the blue color of indophenol by phenol and hypochlorite in the presence of ammonia. Nitrate concentrations were determined by the nitrate reduction technique developed by Jones (1984) which involves shaking with cadmium as opposed to the traditional use of cadmium columns to reduce the nitrate. Jones developed this technique because of the need for an accurate method of measuring low nitrate concentrations. Huxley and Wisel (1974) determined that none of the previously available techniques could be considered precise for measuring low concentrations of nitrate. This procedure actually measures the combined concentrations of nitrate plus nitrite, however it was experimentally determined that the nitrite concentrations in this environment are less than 1% (usually about 0.01%) of the nitrate concentrations (Osgood, personal communication). Therefore the concentrations measured are reported as nitrate. Sample salinity was measured using a refractometer accurate to 1 ppt, and pH was determined using a standard pH probe.

A wet only automatic sampler has been collecting weekly precipitation samples from a station established by Galloway and Keene on northern Hog island. Samples have been collected on a monthly basis from March 1990 to the present. Samples are collected and preserved by VCR-LTER staff and subsequently sent to a laboratory for chemical analysis. The collection station is located approximately 4 kilometers south of the pimples study site. These samples are analyzed for several constituents including nitrate and ammonium. Stability studies indicate that less than 10% of the inorganic nitrogen (primarily ammonium) is lost from these samples between collection and analysis due to inadequate preservation against microbial degradation (Keene, personal communication). Therefore Keene suggests that the measured concentrations should be viewed as minimum estimates of inorganic nitrogen.

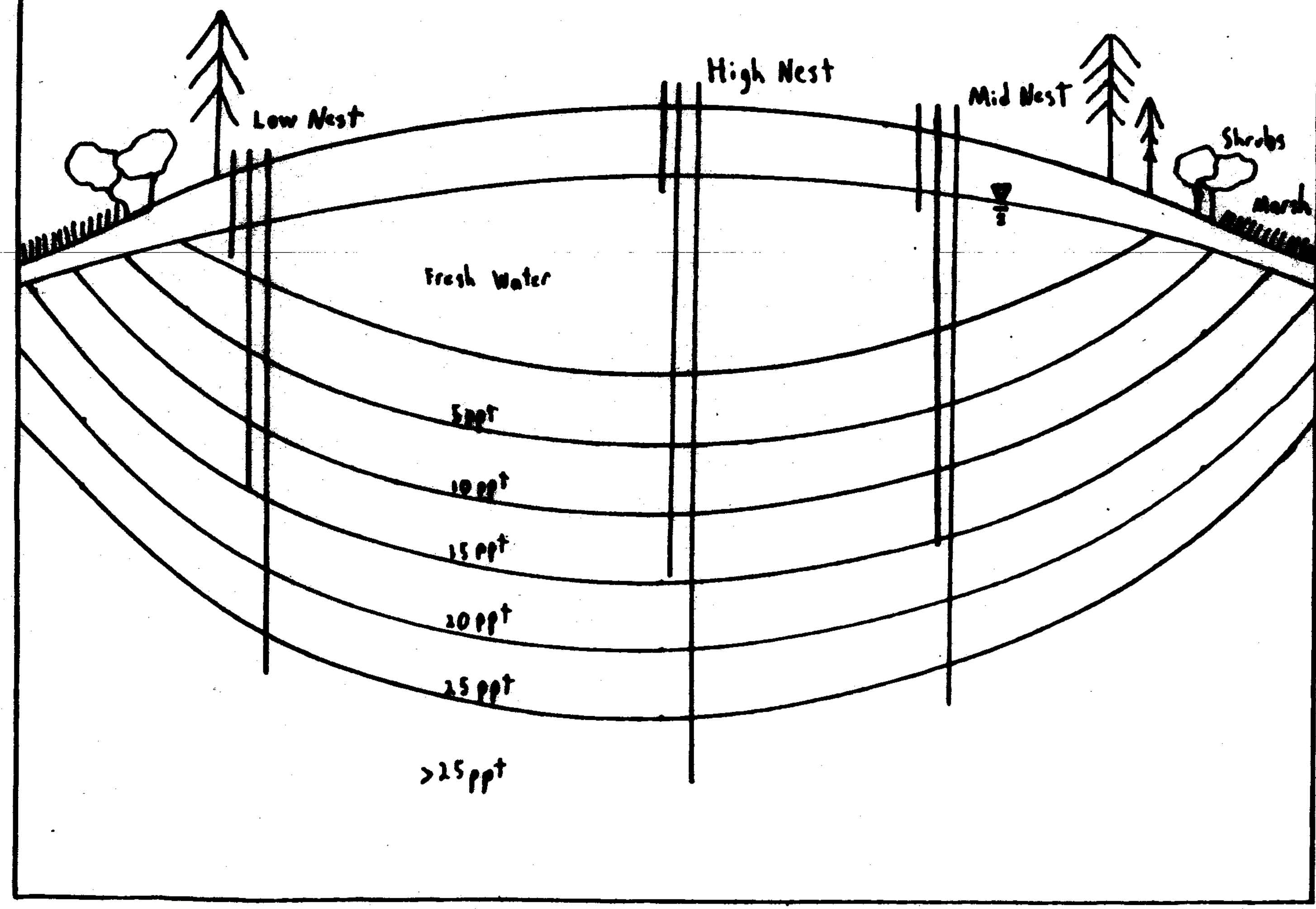
Tidal flood waters were sampled from the small tidal creek which supplies water to the study marshes on several visits to the island. This creek is connected to the Swash (figure ?). Additional data were also available from the water quality project which has sampled lagoonal waters from an area inside Quinby Inlet (Christian and Blum, 1994). Quinby Inlet is located approximately 2 km south of the Pimple study site, and is directly connected to the site via the Swash Channel. The water quality study measured ammonium and nitrate concentrations on a monthly basis.

Tidal and GPS Data

The VCR-LTER monitors a tide station inside the lagoon adjacent to the north end of Hog Island. This data is recorded and retrieved from a data logger attached to a water level recorder. The tide station has been surveyed in to a nearby GPS monument.

Topographic surveys of the study site were conducted during the summer of 1993. The sippers along each transect were surveyed during the summer of 1994 and referenced to a GPS monument which was installed on the surface of Pimple 1. All surveys were conducted using laser surveying equipment (Pentax III Repeat Theodolite). The area was surveyed intensively in order to establish the topography of each feature and the surrounding marsh. Noted for each point surveyed was the vegetation present in order to develop vegetation maps overlain on the topography. This data was employed for selecting appropriate sites for establishing the three transects. Combining the tidal data with the site survey it was possible to determine which sippers were flooded during crucial times when it was necessary to determine if that region of the marsh was flooded. It was also possible to use this data to determine how often certain regions of the marsh and transition zone were flooded.

Figure 5: Three nests of three wells were installed on the pimples in order to develop salinity profiles and monitor the lens.



Results

Hydrological Investigations

Salinity profiles developed from the monitoring well data indicate that the fresh water lens under the pimples consists of a shallow body of fresh water (< 1ppt salinity) surrounded by a brackish transition zone. Continuous monitoring of the lens indicates that the fresh water lens and the transition zone expand and contract seasonally. The lens expands and contracts both vertically and horizontally. The thickness of the fresh water lens varies between 1-2 meters, depending upon the season and short term climatic conditions. Figure 6 displays a two dimensional salinity profile of Pimple 1 in August, 1993. These data were collected following an extended dry period, and the lens had contracted significantly since spring, 1993, when the fresh water lens extended to the edges of the feature. The lens expanded again to this former size during the 1994-1995 winter.

Following a perigean tide (24-May, 1994) which flooded the edges of the pimples, samples were collected from the salinity monitoring wells on 26-May, 1994. The salinities which were measured in the three wells of the low nest of Pimple 3 were 26, 14, and 23 ppt at depths of 0.75, 1.5, and 3.0 meters respectively. This nest is located on the lower edge of the pimple, directly beneath several red cedar trees. Slightly more than a month later, on 6-July, 1994 the salinities in the same three wells were 0, 12, and 25 ppt. The high perigean tide had flooded the edges of the pimple; the salt water infiltrated into the soil and mixed with the fresh water in the surface of the lens. However, it took less than a month for this water to flow out into the marsh and be replaced with fresh water.

Figure 7 displays a graph of the water table height and precipitation (measured continuously) for July - September, 1993. Evident in this graph are several variables which affect the water table elevation. Two high and two low spikes daily represent the tidal oscillations. Daily drawdown due to evapotranspiration (ET) is also evident as a daily drop in the water table coincident with daytime conditions. The spring and neap tide cycles are evident in this graph as a pseudo-cyclic pattern on a bimonthly time scale. The immediate response of the water table to precipitation inputs is demonstrated by the increase in the water table elevation following precipitation events. However, the magnitude of the water table increase is much greater than the volume of precipitation inputs. For example, on day 258 an event deposited approximately 2.25 cm of precipitation onto the pimple, yet the water table rose by about 30 cm! Given a porosity of about 0.4, a recharge of 1.0 would raise the water table following this event by 5.6 cm. However, other variables will also affect the water table elevation. Vacher (1978) also observed a similar phenomenon in Bermuda. He attributed the majority of the increase in the water table not to the direct recharge of the lens, but rather to a coincident drop in the atmospheric pressure with the storm event.

Grain Size Analysis

The purpose of extracting a core from the pimple and one from the marsh was to determine if the sediment was significantly different in these environments. Similar sediment characteristics would indicate that the hydraulic conductivities and the permeabilities of the mediums are also similar. Tables 1 and 2 display the results of the grain size analysis performed on the sediment from the two vibra-cores. These data demonstrate that the sediment consists of a minimum of 99% sand in all samples analyzed. This is slightly higher than the values reported by Robinson (1994) from marshes located on Crescent Island (96% sand) and south Hog Island (95% sand) (figure 2). Several cores were extracted from an overwash fan located approximately 200 m south of Pimple 2 in a separate project conducted by Craig Kochel. The sediment in this region was consistent with the sediment from the two cores extracted from the Pimple study site. Kochel believes that the sediment is characteristic of an inlet fill (personal comm.).

Porewater Analysis

Porewater samples were collected and analyzed from the sippers along the three transects on six visits to the study site between July and November, 1995. Table 3 displays the elevation, along with the location and vegetation associated with each of the sippers. Each sample was analyzed for nitrate (NO_3^-), ammonium (NH_4^+), salinity, and pH. A single factor analysis of variance (ANOVA) was performed on the data collected for each variable in order to determine if significant differences existed in the means of all the data from each pimple. The purpose of this was to determine if any of the pimples may be significantly different from the others in any single variable studied. Significant differences would indicate that different processes are responsible for developing the porewater chemistry of each pimple, and would need to be identified. Most of the pimples were sampled on each date, but occasionally time did not permit a complete sampling from each pimple. It was often necessary to leave the island early because boat access was limited by shallow channels which were navigable only during high water. Frequent storms were also a culprit; the study site offered no shelter or protection from thunder storms which would often shorten the sampling trip.

Ammonium:

The ammonium concentrations of the samples collected during the course of this study are displayed in table 4. While the concentrations display considerable variation spatially and temporally, a single factor test for analysis of variance (ANOVA) between the three populations (pimples 1, 2, and 3) was performed in order to determine if a significant difference between the means of each population existed at the 5% level. The mean NH_4^+ concentrations for each pimple transect over the course of the study period were 6.6, 10.6, and 8.0 micromoles/l for pimples 1, 2, and 3 respectively. The calculated F value of 1.77 was less than the critical F value of 3.06; therefore the means of the populations are not considered significantly different from one another (table 5).

While the porewater ammonium concentrations are generally low, occasional short lived surges in the concentrations were measured in a few of the sippers. For example, on 26-July, 1994 the concentrations in sippers 4 and 6 of T1 were 68.7 and 55.3 micromoles/l respectively These were the highest concentrations measured during the study period. Although these concentrations are extremely high for this marsh, the average concentrations measured in Georgia (Sapelo Island) were between 30-70 micromoles/l (Whitney, et al, 1981). A number of possibilities may be responsible for the high values which were measured. Both of these sippers are located in the transition zone where large quantities of wrack accumulate. Localized conditions may have been conducive to support large populations of bacteria which can mineralize organic nitrogen. However, the ammonia which was produced was rapidly assimilated into the system (plant uptake) because the concentrations had dropped to values below the background level by the next sampling visit on 10-August, 1994. The most significant results pertaining to ammonium in this study are the low mean concentrations. The concentrations are significantly lower than the values reported in the literature.

Nitrate:

The porewater nitrate concentrations which were measured from the three pimples are listed in table 6. A single factor ANOVA was run on this data as well in order to determine if significant differences among the means of the three populations existed. The mean NO_3^- concentrations for the three pimple transects were 0.9, 0.9, and 2.4 micromoles/l for pimples 1, 2, and 3 respectively. These values are consistent with the concentrations measured by Osgood (personal comm.) in similar Virginia back-barrier marshes. Once again, a calculated F score which is lower than the critical

F score indicates that no significant difference exists in the mean NO_3^- concentrations between the three populations (table 5).

Salinity:

The salinity of each sample collected was measured in parts per thousand (ppt). Table 7 displays the results of these measurements. While an ANOVA performed on this data may not be helpful in understanding the salinity changes across any individual transect, it can provide valuable information which can be used to determine if the mean salinities of each transect are significantly different from the other transects. The mean salinities of the transects were 10.9, 12.0, and 9.4 ppt for pimples 1, 2, and 3 respectively. A calculated F score of 1.18 is lower than the critical F score of 3.06 (table 5). This indicates that there is no significant difference between the mean salinities of each transect.

pH:

The pH of each sample collected is displayed in table 8. An ANOVA was run on this data as well in order to determine if significant differences exist between the mean pH values calculated for each transect. The mean pH values calculated for each transect of pimples 1, 2, and 3 were 7.2, 7.4, and 7.1 respectively. The results of the ANOVA indicate that a significant difference does exist between the mean pH values of each pimple. The calculated F score of 4.84 was higher than the critical F score of

3.06 (table 5). However, the pH probe which was used is only accurate to 0.1 pH units. Therefore the differences in the mean pH between the three pimples is not considered significant.

Precipitation Chemistry

Table 9 displays the average monthly nitrate and ammonium concentrations (from the Hog Island collection station) which were measured during the period from March 1990 through February 1994 (Galloway and Keene, unpublished data). These concentrations are approximately an order of magnitude higher than the concentrations measured in remote regions of the world (Keene, personal comm.). The average annual wet deposition of inorganic nitrogen (nitrate + ammonium) in this region is 33 millimoles/m^2-year. The primary source of nitrate is from fossil fuel combustion in the form of nitric acid (HNO_3). Keene also suggests that the dry deposition rate of nitrate (not measured) is greatly enhanced in coastal zones and may actually equal or exceed the inorganic nitrogen inputs from wet deposition. When polluted continental air high in nitric acid mixes with marine air masses, HNO_3 is quickly scavenged by super-micron, alkaline sea-salt aerosols and subsequently deposited to the surface. Therefore, the actual atmospheric inorganic nitrogen inputs to the system are probably twice the reported values in the wet deposition alone.

The yearly average nitrate concentration of the wet deposition is 24 micromoles/l. The actual concentrations of nitrate in any given event varied considerably from less than 1 to 76 micromoles/l during the three years which the samples were collected. The variance can be attributed to the source of the air mass delivering the precipitation. Continental air masses have higher concentrations of nitrate than marine air masses. Average nitrate concentrations are slightly higher during the summer months, but due to the great degree of variance in individual events there is no significant difference between the monthly average concentrations.

The average annual ammonium concentration in the wet precipitation during this period (March 1990 through February 1994) was 11.9 micromoles/l. While a large degree of variability in the ammonium concentrations between events is evident (from less than 1 micromole/l to 49 micromoles/l), significant seasonal differences in the concentrations exist. The increased ammonium concentrations in the summer months can be attributed to the volatilization of ammonia from mainland fertilizer applications during the spring (Keene, personal communication).

Tidal Flood Waters

The nitrate concentrations of the creek water behind the island ranged from 0 to 1 micromole/l, while the ammonium concentrations ranged from 1 to 8 micromoles/l. These values are consistent with the inorganic nitrogen concentrations measured by Christian and Blum (1994) inside Quinby Inlet, 2 km south of the study site. The concentrations which were measured inside Quinby Inlet ranged from 0 to 7 micromoles/l for ammonium, and 0 to 7 micromoles/l for nitrate as well. The nitrate concentrations were generally below 3 micromoles/l, but occasional spikes to 7 micromoles/l were attributed to surges of oxygenated ocean water entering the inlet.

Figure 6: Graph of water table height and precipitation for Pimple 1. Water table height is the distance above a continuously recording pressure transducer located within the phreatic zone near the center of Pimple 1.

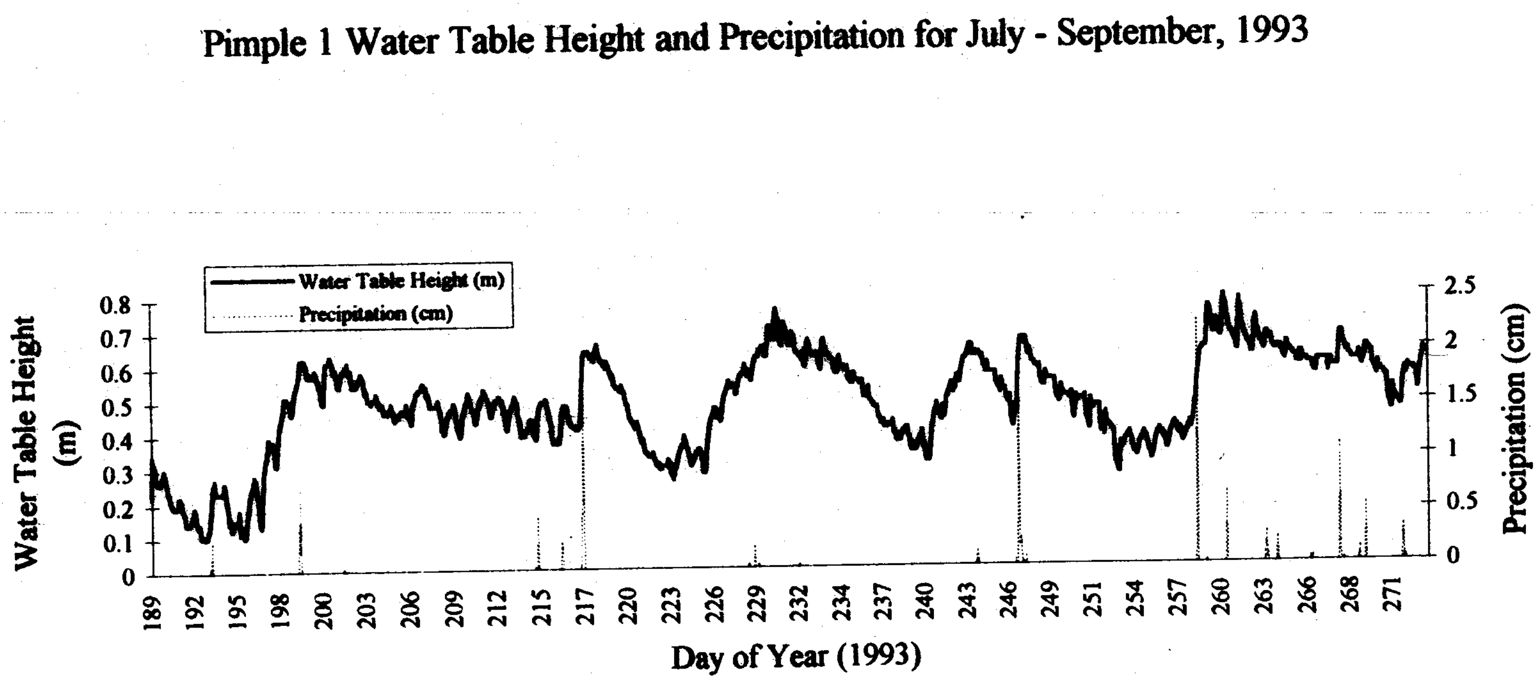


Figure 7: Two dimensional salinity profile of Pimple 1 in August, 1993. Following a dry summer the fresh water lens had contracted significantly from the spring, 1993.

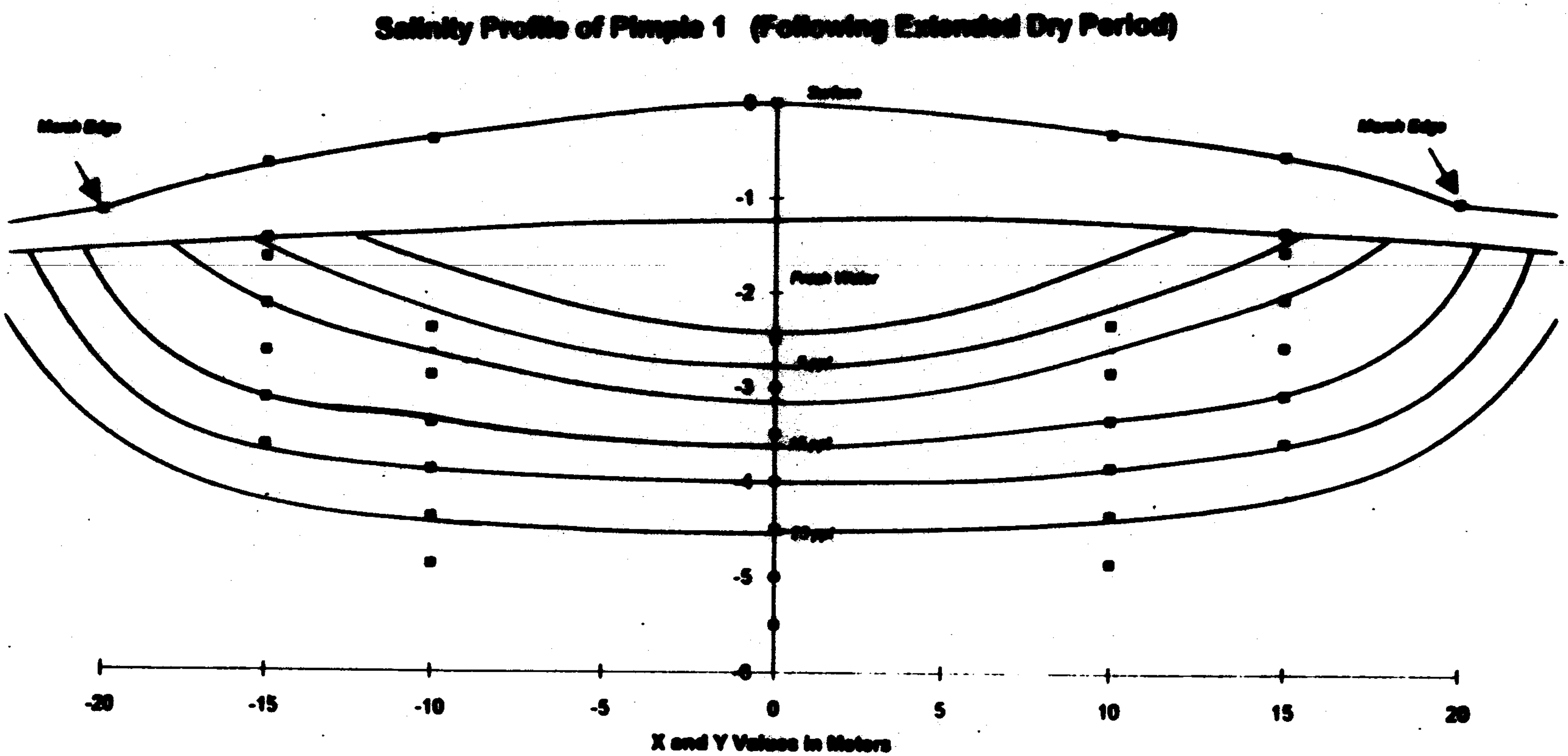


Table 1: Grain size analysis for core extracted from pimple 1

Sieve # (US Standard)	mm opening	wt%	cumulative %
For the surface			
25	0.71	0.94%	0.94%
40	0.425	4.14%	5.08%
60	0.25	17.25%	22.33%
80	0.177	39.78%	62.11%
120	0.125	20.35%	82.46%
230	0.063	17.28%	99.74%
pan	0	0.25%	99.99%
For 1' down			
25	0.71	0.10%	0.10%
40	0.425	0.13%	0.23%
60	0.25	9.67%	9.90%
80	0.177	52.22%	62.12%
120	0.125	28.18%	90.30%
230	0.063	9.64%	99.94%
pan	0	0.06%	100.00%
For 2' down			
25	0.71	0.05%	0.05%
40	0.425	0.03%	0.08%
60	0.25	6.40%	6.48%
80	0.177	45.13%	51.61%
120	0.125	38.48%	90.09%
230	0.063	9.86%	99.95%
pan	0	0.05%	100.00%

Sieve # (US Standard)	mm opening	wt%	cumulative %
For 3' down			
25	0.71	0.00%	0.00%
40	0.425	0.01%	0.01%
60	0.25	5.17%	5.18%
80	0.177	42.66%	47.84%
120	0.125	39.79%	87.63%
230	0.063	12.29%	99.92%
pan	0	0.07%	99.99%
For 4' down			
25	0.71	0.00%	0.00%
40	0.425	0.01%	0.01%
60	0.25	5.99%	6.00%
80	0.177	39.31%	45.31%
120	0.125	31.22%	76.53%
230	0.063	23.32%	99.85%
pan	0	0.14%	99.99%
For 5' down			
25	0.71	0.00%	0.00%
40	0.425	0.01%	0.01%
60	0.25	6.99%	7.00%
80	0.177	38.14%	45.14%
120	0.125	42.99%	88.13%
230	0.063	11.86%	99.99%
pan	0	0.01%	100.00%

Table 2: Grain size analysis for core extracted from high marsh

Sieve # (US Standard)	mm opening	wt%	cumulative %
For 1' down			
25	0.71	0.73	0.73
40	0.425	0.3	1.03
60	0.25	15.85	16.88
80	0.177	39.58	56.46
120	0.125	26.61	83.07
230	0.063	16.84	99.91
pan	0	0.1	100.01
For 3' down			
25	0.71	0.51	0.51
40	0.425	2.2	2.71
60	0.25	20.09	22.80
80	0.177	39.83	62.63
120	0.125	25.75	88.38
230	0.063	11.52	99.90
pan	0	0.1	100.00
For 5' down			
25	0.71	0.05	0.05
40	0.425	0.68	0.73
60	0.25	20.8	21.53
80	0.177	56.06	77.59
120	0.125	14.87	92.46
230	0.063	7.44	99.90
pan	0	0.1	100.00
For 7' down			
25	0.71	0.12	0.12
40	0.425	0.4	0.52
60	0.25	53.1	53.62
80	0.177	16.39	70.01
120	0.125	16.39	86.40
230	0.063	13.32	99.72
pan	0	0.29	100.01

Table 3: Vegetation and Elevation Associated with Sipper Transects

Transect 1:

Sipper number	Location/Vegetation	Elevation (m above msl)
1	pimple center: barren/sparse grasses	1.83
2	pimple: under cedar, in grasses	1.54
3	pimple edge: under cedar, in grasses	1.04
4	upper transition zone: *B. halimifolia*	0.80
5	middle transition zone, small depression: *S. alterniflora*	0.71
6	middle transition zone: *I. frutescens, S. patens*	0.78
7	lower/outer transition zone: *I. frutescens, S. patens, S. alterniflora*	0.75
8	high marsh: *S. alterniflora, D. spicata*	0.66
9	high marsh: *D. spicata, Salicornia spp., S. alterniflora, S. patens*	0.61
10	high marsh: *S. alterniflora, Salicornia spp., D. spicata*	0.59

Transect 2:

Sipper number	Location/Vegetation	Elevation (m above msl)
1	pimple center: barren	1.69
2	pimple: grasses	1.37
3	pimple edge/upper transition zone: *B. halimifolia*	0.97
4	middle transition zone: *B. halimifolia*	0.79
5	lower/outer transition zone: *I. frutescens, S. alterniflora*	0.59
6	high marsh: *D. spicata, S. alterniflora, S. patens*	0.71
7	high marsh: *D. spicata, S. alterniflora,*	0.64
8	high marsh: *D. spicata*	0.61
9	high marsh: *D. spicata, S. alterniflora, Salicornia spp.*	0.52
10	high marsh: *D. spicata, S. alterniflora, Salicornia spp., L. caroliniaum*	0.53

Transect 3:

Sipper number	Location/Vegetation	Elevation (m above msl)
1	pimple center: barren	1.42
2	pimple: under *M. pensylvanica*, grasses	1.33
3	pimple edge/upper transition zone: under *M. pensylvanica, B. halimifolia*	0.98
4	middle transition zone: *B. halimifolia*	0.87
5	middle transition zone: *B. halimifolia, I. frutescens*	0.82
6	lower/outer transition zone: *B. halimifolia, I. frutescens, S. patens*	0.83
7	high marsh: *S. patens*	0.71
8	high marsh: *D. spicata, S. patens, I. frutescens* (dead)	0.78
9	high marsh: *S. patens, D. spicata*	0.71

Table 4: Porewater ammonium concentrations (micromoles/liter) measured from the three sipper transects.

Pimple 1:

Sipper Number	*13-Jul*	*26-Jul*	*10-Aug*	*1-Sep*	*20-Sep*	*8-Nov*	*average*	*std dev*
1	4.5	3.2	0.1	na	5.6	1.9	3.1	2.1
2	1.4	0.7	0.0	na	5.0	1.9	1.8	1.9
3	2.8	6.0	1.1	na	5.2	10.5	5.1	3.6
4	4.8	68.7	1.0	na	2.9	2.6	16.0	29.5
5	2.7	19.8	0.0	na	4.8	1.1	5.7	8.1
6	3.5	55.3	0.0	na	5.4	1.2	13.1	23.7
7	4.7	7.8	2.0	na	2.9	9.7	5.4	3.3
8	5.0	5.7	17.6	na	3.2	2.2	6.7	6.2
9	13.5	7.5	0.0	na	3.2	3.2	5.5	5.2
10	2.1	6.1	2.2	na	5.6	3.4	3.9	1.9

Pimple 2:

1	14.4	14.3	39.2	na	11.0	2.3	16.2	13.7
2	16.3	5.3	2.0	na	16.1	1.3	8.2	7.4
3	24.8	3.6	1.1	na	3.7	3.3	7.3	9.8
4	26.6	1.5	3.8	na	4.8	8.9	9.1	10.2
5	26.8	11.2	10.0	na	3.2	3.8	11.0	9.6
6	21.9	6.8	0.7	na	2.0	3.4	7.0	8.7
7	14.6	19.9	10.7	na	3.0	3.0	10.2	7.4
8	19.9	9.2	7.3	na	4.1	2.9	8.7	6.8
9	12.2	2.0	22.0	na	3.7	4.9	8.9	8.3
10	36.0	35.7	12.9	na	9.8	2.3	19.3	15.5

Pimple 3

1	29.9	na	0.9	9.6	3.2	2.8	9.3	12.0
2	11.0	na	0.0	4.7	2.2	7.9	5.1	4.4
3	14.7	na	4.0	20.1	2.0	4.7	9.1	7.9
4	54.4	na	0.2	2.9	3.0	6.5	13.4	23.0
5	8.5	na	0.0	2.7	3.8	6.2	4.2	3.3
6	16.5	na	6.5	6.5	3.7	5.0	7.6	5.1
7	12.8	na	2.6	9.1	3.2	4.4	6.4	4.4
8	30.0	na	1.6	10.1	3.6	2.1	9.5	12.0
9	15.3	na	3.4	12.3	4.0	1.9	7.4	6.0

Table 5: ANOVA results from comparing the precipitation chemistry from the three transects at the 5% level of significance.

Ammonium:

Source of Variation					
	Sum of Squares	*Degrees of Freedom*	*Mean Square*	*F*	*F crit*
Between Groups	406.9	2	203.5	1.77	3.06
Within Groups	16360.6	142	115.2		

Nitrate:

Source of Variation					
	Sum of Squares	*Degrees of Freedom*	*Mean Square*	*F*	*F crit*
Between Groups	5.7	2	2.9	1.22	3.06
Within Groups	331.0	142	2.3		

Salinity:

Source of Variation					
	Sum of Squares	*Degrees of Freedom*	*Mean Square*	*F*	*F crit*
Between Groups	154.3	2	77.2	1.18	3.06
Within Groups	9235.6	141	65.52		

pH:

Source of Variation					
	Sum of Squares	*Degrees of Freedom*	*Mean Square*	*F*	*F crit*
Between Groups	1.7	2	0.9	4.84	3.06
Within Groups	25.1	141	0.2		

Table 6: Porewater nitrate concentrations (micromoles/liter) measured from the three sipper transects.

Pimple 1:

Sipper Number	*13-Jul*	*26-Jul*	*10-Aug*	*1-Sep*	*20-Sep*	*8-Nov*	*average*	*std dev*
1	0.1	0.8	0.5	na	0.7	0.2	0.5	0.3
2	0.5	1.2	0.9	na	5.7	0.5	1.8	2.2
3	0.0	0.8	0.2	na	0.2	0.3	0.3	0.3
4	0.0	0.8	2.6	na	0.2	0.0	0.7	1.1
5	0.0	0.9	0.5	na	0.4	0.4	0.4	0.3
6	0.0	0.4	0.3	na	0.3	0.2	0.3	0.2
7	0.0	0.2	0.4	na	0.7	0.3	0.3	0.3
8	0.0	0.4	0.3	na	0.0	0.0	0.1	0.2
9	0.0	0.0	0.0	na	0.0	0.1	0.0	0.0
10	0.0	0.4	0.1	na	0.1	0.1	0.1	0.1

Pimple 2:

1	2.1	2.7	0.7	na	1.7	0.3	1.5	1.0
2	0.4	3.2	0.7	na	0.5	0.1	1.0	1.2
3	0.0	0.9	0.6	na	0.3	0.1	0.4	0.4
4	0.0	0.6	0.6	na	0.4	0.1	0.4	0.3
5	0.0	0.0	4.9	na	0.4	0.2	1.1	2.2
6	0.0	0.1	0.6	na	0.1	0.1	0.2	0.2
7	0.0	0.8	0.1	na	0.0	0.1	0.2	0.3
8	0.0	0.4	0.1	na	0.0	0.1	0.1	0.2
9	0.0	0.0	0.0	na	0.4	0.2	0.1	0.2
10	0.0	1.1	0.1	na	0.3	0.1	0.3	0.4

Pimple 3

1	4.2	na	0.3	10.0	0.3	0.1	3.0	4.3
2	0.0	na	0.0	0.1	1.8	0.3	0.4	0.8
3	0.2	na	0.2	0.2	0.3	0.1	0.2	0.1
4	0.0	na	0.0	0.2	0.2	0.1	0.1	0.1
5	0.0	na	3.0	0.5	0.2	0.0	0.7	1.3
6	0.0	na	11.9	0.2	0.3	0.2	2.5	5.2
7	0.0	na	4.0	0.2	0.2	0.0	0.9	1.7
8	0.0	na	0.0	0.4	0.5	0.0	0.2	0.2
9	0.0	na	0.3	0.3	0.2	0.1	0.2	0.1

Table 7: Porewater salinity measured from the three sipper transects

Pimple 1:

Sipper Number	*13-Jul*	*26-Jul*	*10-Aug*	*1-Sep*	*20-Sep*	*8-Nov*	*average*	*std dev*
1	0	0	7	na	2	0	1.8	3.0
2	0	0	1	na	2	0	0.6	0.9
3	1	1	2	na	6	2	2.4	2.1
4	8	8	8	na	10	8	8.4	0.9
5	7	9	7	na	16	16	11.0	4.6
6	12	8	13	na	18	16	13.4	3.8
7	15	18	20	na	22	20	19.0	2.6
8	11	15	17	na	22	15	16.0	4.0
9	16	12	14	na	28	8	15.6	7.5
10	19	20	22	na	25	19	21.0	2.5

Pimple 2:

1	0	0	0	na	na	0	0.0	0.0
2	0	0	1	na	0	0	0.2	0.4
3	1	1	1	na	1	1	1.0	0.0
4	10	8	5	na	6	7	7.2	1.9
5	17	10	12	na	10	15	12.8	3.1
6	17	18	18	na	14	16	16.6	1.7
7	22	20	23	na	16	18	19.8	2.9
8	12	10	15	na	20	23	16.0	5.4
9	21	12	24	na	19	17	18.6	4.5
10	25	25	28	na	26	22	25.2	2.2

Pimple 3

1	0	na	0	0	1	0	0.2	0.4
2	0	na	0	0	2	2	0.8	1.1
3	3	na	1	4	6	4	3.6	1.8
4	7	na	6	6	7	8	6.8	0.8
5	7	na	10	11	10	10	9.6	1.5
6	8	na	12	9	15	15	11.8	3.3
7	12	na	8	15	15	18	13.6	3.8
8	21	na	13	16	24	16	18.0	4.4
9	22	na	14	22	22	22	20.4	3.6

Table 8: Porewater pH measured from the three sipper transects

Pimple 1:

Sipper Number	*13-Jul*	*26-Jul*	*10-Aug*	*1-Sep*	*20-Sep*	*8-Nov*	*average*	*std dev*
1	7.0	7.0	7.1	na	6.7	6.5	6.9	0.3
2	6.9	7.0	7.0	na	6.6	7.2	6.9	0.2
3	7.0	7.1	7.0	na	6.9	7.0	7.0	0.1
4	7.7	7.6	7.5	na	6.8	7.4	7.4	0.4
5	7.5	7.5	7.4	na	6.8	7.3	7.3	0.3
6	7.4	7.3	7.5	na	6.9	7.3	7.3	0.2
7	7.6	7.6	7.3	na	6.9	7.2	7.3	0.3
8	7.7	7.5	7.2	na	6.9	7.2	7.3	0.3
9	7.7	7.6	7.6	na	7.0	7.5	7.4	0.3
10	7.9	7.6	7.7	na	7.1	7.4	7.5	0.3

Pimple 2:

1	7.4	8.0	7.7	na	na	7.1	7.6	0.4
2	7.3	7.6	7.1	na	6.8	7.0	7.2	0.3
3	7.2	7.4	7.4	na	6.9	7.3	7.2	0.2
4	7.7	7.6	7.5	na	6.8	7.4	7.4	0.3
5	7.7	7.7	7.6	na	7.2	7.4	7.5	0.2
6	7.5	7.2	7.3	na	7.2	7.3	7.3	0.2
7	7.5	7.5	7.5	na	7.2	7.2	7.4	0.1
8	7.6	7.6	7.4	na	7.2	7.1	7.4	0.3
9	7.6	7.3	7.5	na	7.1	7.4	7.4	0.2
10	7.7	7.7	7.7	na	7.2	7.0	7.4	0.3

Pimple 3

1	6.6	na	6.8	6.1	6.4	6.3	6.4	0.3
2	5.0	na	6.6	6.3	6.3	6.0	6.1	0.6
3	6.8	na	6.9	7.0	6.5	6.9	6.8	0.2
4	7.3	na	7.2	7.1	6.7	7.6	7.2	0.3
5	7.6	na	7.6	7.6	6.9	7.7	7.5	0.3
6	7.5	na	7.6	7.4	7.1	7.6	7.4	0.2
7	7.8	na	7.6	7.3	7.2	7.7	7.5	0.2
8	7.9	na	7.4	7.5	6.9	7.5	7.5	0.4
9	8.0	na	7.6	7.7	7.3	7.6	7.6	0.2

Table 9: Monthly average ammonium and nitrate concentrations (micromoles/l) in the wet deposition from the Hog Island collection station during the period from March, 1990 to February, 1994.

Ammonium	
Month	*Concentration*
Jan	2.0
Feb	8.4
Mar	8.9
Apr	17.6
May	21.1
Jun	21.3
July	26.8
Aug	10.8
Sep	8.5
Oct	7.5
Nov	5.7
Dec	4.8

Nitrate	
Month	*Concentration*
Jan	19.2
Feb	19.1
Mar	24.1
Apr	25.5
May	30.3
Jun	35.4
July	39.2
Aug	30.0
Sep	17.8
Oct	16.0
Nov	14.3
Dec	11.3

Discussion

Hydrology

The terrestrial community associated with each pimple is inherently unstable because of the hydrology (fresh water availability). The thin fresh water lens expands and contracts with the seasons, as well as with short term climatic changes such as droughts (See Appendix A for a detailed analysis of the development and stability of fresh water lenses). Complete submergence of these features by sea-water during extreme storm events affects the fresh water supply as well. Evidence from the terrestrial community suggests that modern sea level rise of approximately 1.5 mm/year (Finkelstein and Ferland, 1987) appears to be affecting the fresh water reserves. Smaller pimples (< 20 m in diameter) in the same area as the three under investigation have several dead trees and shrubs on the features. The surfaces of these pimples no longer support terrestrial plant species; several halophytes such as *Iva frutescens* and *Spartina patens* now dominate. The trees on these smaller pimples (*Juniperus virginiana*) appear to be of a common age class, indicating a stage of colonization, followed later by stage of mortality. It is difficult to determine the age of individuals of this particular tree specie because it is an evergreen which adds false rings during warm winter periods. However, the dead trees are relatively consistent in size with a dbh of approximately 10 cm, and a height of 3-4 m.

Porewater samples collected from the smaller pimples varied from 5-15 ppt through the spring and summer, 1993. Fresh water was never detected in these features, and therefore pimples of this size can no longer support terrestrial vegetation species. The trees apparently colonized the pimples at a time when sea level was slightly lower. The fact that these trees appear to be of a similar age class indicates that conditions were optimal for the germination of the seeds, and the maintenance of the trees. Following a period of initial stable growth the trees were overcome by a loss of the fresh water reserves of the pimples. Either a severe drought, the relative rise in sea level, or a combination of the two caused the fresh water lens to become brackish and result in tree mortality. The eventual replacement of terrestrial plant species with halophytes, as well as the maintenance of a brackish lens indicates that a relative sea level rise is responsible for the permanence of this change.

The three pimples included in this study also are affected by adverse conditions related to the hydrology. Several of the trees on the lower edge of the three study pimples show signs of salt stress or mortality. In figure 8 the average salinities measured between July-November, 1994, and the surface elevation of each sipper are graphed in order to display the relationship between elevation and salinity in this environment. The lower edge of the pimples (approximately 1 meter above msl on all three pimples) is the point of transition between fresh and brackish water. Figure 9 displays the relationship between salinity and surface elevation around the three pimples in the form of a linear regression analysis. The Y intercept of 0.98m represents the surface elevation beneath which the transition from fresh to brackish groundwater exists. However, the actual point of transition varies with the seasons and other physical factors. This region actually becomes brackish following dry spells during the summer, and after occasional submergence by extreme high tides and storm surges.

Figure 10 displays the cumulative grain size distributions for the two cores. As is evident in this figure, the grain size distributions are extremely similar for each core. The exception is the slight deviation in the distribution from the 7 foot sample in the high marsh. However, the flow paths in this type of environment are predominantly horizontal.. Therefore, the slight change in the grain size distribution at this depth is inconsequential. It is interesting to note the coarsening-upward trend of the sediment in both cores. This is a result of the proximity of the location to the source material. As the southern end of Parramore island erodes away, the beach and dunes (sand source) come closer to the point where the cores were extracted.

Inorganic Nitrogen Chemistry

The results from this study indicate that background porewater inorganic nitrogen concentrations in the back-barrier system investigated are extremely low. The groundwater inorganic nitrogen concentrations along each transect were consistently low throughout the study period in both the fresh and the saline waters. The average NH_4^+ concentration of all samples collected was 8.4 micromoles/l while the average NO_3^- concentrations were less than 1 micromole/l. Because of the low concentrations any source of nitrogen would be significant, although the principle sources at this site appear to be from precipitation and from flood waters. Fresh upland groundwaters are often a significant source of nitrate to high marsh systems (Valiela and Teal, 1979), but in this study the upland waters were generally depleted of inorganic nitrogen and therefore cannot provide significant inputs to the high marsh. The pimples are also very small catchments which do not retain enough water to supply significant quantities of nitrogen to the high marsh even if the inorganic nitrogen concentrations of the fresh water were higher.

The relatively high concentrations of inorganic nitrogen in the precipitation are significant in this system because the concentrations of inorganic nitrogen in the porewater are extremely low. Valiela and Teal (1979) also measured inorganic nitrogen inputs through precipitation but determined that less than 1% of the total nitrogen inputs to their system were through precipitation. However, in their study the total inputs through groundwater greatly exceeded the groundwater contributions in this study. The marsh which they investigated, the Great Sippewissett Marsh in Massachusetts, is a mainland marsh and therefore the fresh groundwater volumes which flow into the marsh are considerably higher than would occur in a back-barrier marsh system where fresh groundwater is limited. Mainland fresh groundwater tends to have higher natural background inorganic nitrogen concentrations then barrier island fresh groundwater. This difference occurs because mainland soils are older and have developed larger pools of inorganic nitrogen. Well developed older soils have a distinct organic horizon which releases nitrogen as the organic matter decomposes. The porewater nitrate concentrations measured by Day (personal communication) on Hog island were less than 5 micromoles/l. The concentrations which Valiela and Teal measured in the groundwater averaged 50 micromoles/l, and they do not believe that the groundwater had been contaminated from anthropogenic sources of nitrogen. The only probable anthropogenic source listed was from septic tanks upstream, and they claim that there is little evidence of any increase in nitrogenous concentrations from leaching. The average concentrations of nitrate measured in the fresh groundwater of the pimples was 1 micromole/l.

Nitrate is an extremely soluble anion in nearly any aqueous compound. It is therefore highly mobile and is not readily retained by soil colloids. This may partially explain the low nitrate concentrations measured in this study. The three graphs in figure 11 display the nitrate concentrations measured from each transect throughout the study period. Nitrate inputs to the system are extremely low, and because of the mobile nature of nitrate, and the extreme degree of movement of the waters it can quickly come into contact with plant roots and be assimilated by the plant material. A second mechanism of nitrate removal from groundwater occurs in recharge areas where hydrologic flowpaths are directed downwards, as in some regions of the high marsh where the nitrate may quickly be transported into deeper groundwater where anoxic conditions prevail. In this situation the nitrate would most likely denitrify to NO_2 and wouldn't be measured by the analytical techniques of this study.

The sources of nitrate to the system are limited. In the fresh upland waters of the pimples, the only significant source of nitrate is from precipitation. A second source of nitrate exists for the high marsh region, and at times for the transition zone. Flood waters occasionally have significant nitrate concentrations. While the lagoonal waters generally have very low nitrate concentrations, occasional surges of oxygenated ocean-water enter the lagoon during storm events. The oxygen rich ocean water may elevate the lagoonal nitrate concentrations to 7 micromoles/l (Christian and Blum, 1994). However, these surges of nitrate rich waters are short lived, and infrequent. Between July 1992 and February 1994 the lagoonal nitrate concentrations from Quinby Inlet exceeded 4 micromoles/l on only one sampling visit (December 1992: 7 micromoles/l). The concentration which was measured in November 1992 was close to 0 micromoles/l, while in January 1993 the concentration was 3 micromoles/l.

None of the three pimples have significant numbers of nitrogen fixing species present. Pimple 3 does have a few small individuals of the nitrogen fixing *Myrica pensylvanica* scattered around the edge, but these few plants are considered insignificant to the total nitrogen supply. One of the sippers along T3 was installed directly below the largest of the myrica shrubs on the pimple; the inorganic nitrogen concentrations measured from this sipper were not significantly different from the sippers on the other transects which were in the same zone (pimple edge). Several of the pimples which exist farther north on the island have continuous rings of myrica. It is likely that the myrica does contribute significant quantities of nitrogen on these pimples, although this has not been investigated.

Nitrate derived from the decomposition of plant material is not considered a significant source, either. The dry conditions present on the pimple surfaces are not conducive to rapid decay of organic matter. A thin organic horizon does exist under the trees around the pimple edge, but this horizon is extremely thin (1-2 inches) and has slowly developed over the period that the pimples have existed. Therefore the only significant sources of nitrate to the upland fresh water can be from precipitation.

Given the large concentrations of nitrate in the wet deposition, it is believed that this is the most significant source of nitrate to the system. Figure 12 displays the average monthly concentrations of nitrate in the wet deposition from March, 1990 through February of 1994. Precipitation derived nitrate is immediately available to the upland regions, as well as to the marsh and transition zone when these regions are not flooded by tidal water.

Figure 13 displays the porewater nitrate concentrations from samples collected from each transect on August 10, 1994. This was the only sampling visit which followed a significant precipitation event. On 5-August, 1994 a convective system deposited 54.6 mm of rain at the Hog Island meteorological station, 4 km south of the study site. The increase in the porewater nitrate concentrations measured in the sippers located in the upland/high marsh transition (shrub) zone is believed to have resulted from this precipitation event. The upland/high marsh transition zone has developed a spongy organic layer from partially decomposed wrack which is approximately 5-10 cm thick. This layer can absorb and hold rain water for significant periods of time.

Elevated nitrate concentrations were not measured in the fresh water of the pimple, or in the high marsh. On the barren pimple surface the rainwater infiltrates the surface extremely rapidly and is quickly diluted by the large volume of fresh water within the lens. The nitrate in the lens is also immediately available to the trees and shrubs which grow around the features. These plants have extensive root systems which extend laterally into the center of the pimple at or below the water table elevation. Therefore most of the nitrate which infiltrates into the system comes into contact with the roots and is immobilized by the plants. Elevated nitrate concentrations were not measured in the high marsh sippers because the precipitation event coincided with high tide, at a time when the high marsh was flooded. The bulk of the precipitation fell between 16:00 and 19:00 EST. High tide (spring tide) at 18:48 EST reached a height of 0.84 meters above MSL at the Hog Island tide gauge (figure 14). As a result, the rain water which fell on the flooded marsh surface was immediately diluted by sea-water, and no increase in the porewater nitrate in the high marsh occurred. The elevated levels of nitrate in the shrub zone had diminished to the normal background levels by the next sampling visit on September 1, 1994.

Another possible source of nitrate is through nitrification. Nitrification is the process of ammonium oxidation to nitrite, and subsequently to nitrate. This process will only take place under alkaline, oxidized conditions (Alexander, 1971). Tidal marsh groundwater tends to be depleted in oxygen, while upland waters are usually oxic. The eH, or redox potential is a measure of the potential for redox reactions to occur. It is therefore an indirect measure of the approximate DO concentration of the water. However, it does not directly translate into a specific DO concentration because other factors will also affect the redox potential. Figure 15 displays the eH readings along T1 on July 26, 1994. High eH values reflect oxic conditions, while low eH values depict reduced conditions. The high values in the first 3 sippers represent the oxic conditions associated with the fresh upland water. Immediately below the pimple edge the conditions become more reduced, and the eH drops consistently through the shrub zone. The pattern is broken in sippers 9 and 10, where the eH rises slightly. These sippers are located in a lower area where vegetation is sparse, allowing the soils to dry out considerably during the summer neap tide cycles, when the high marsh does not get flooded. As the sandy soils dry out the water in the pore spaces will be replaced by atmospheric gasses: the most significant being oxygen. Figure 16 displays the average pH values measured for the three transects during the coarse of this study. Combining these variables, it is evident that the only region which supports conditions favorable for nitrification would be in the regions of the high marsh which have a high redox potential, as well as a high pH. However, the nitrate concentrations in these regions were not higher than in the areas which do not support conditions favorable for nitrification. Other studies have demonstrated that nitrification is inhibited by the Cl^- present in saline soils (McClung and Frankenburger, 1985). Therefore, the results suggest that nitrification is not a significant component of the nitrogen cycle in this environment.

Denitrification is the reduction of nitrate to nitrite, and subsequently to N_2 by denitrifying bacteria. This process results in a loss of nitrogen from the system to the atmosphere. The conditions necessary for bacteria to denitrify are a lack of O_2, a source of nitrate, and an energy supply (usually an organic substrate) (Alexander, 1971). Substantial quantities of nitrate are deposited on the marsh surface through precipitation, and occasionally flood waters are sufficiently oxygenated to supply significant quantities of nitrate to the marsh. The porewater nitrate concentrations are significantly lower than those measured in precipitation, indicating a loss which could only occur through denitrification, leaching, or immobilization by plants. It is likely that a combination of these three processes are responsible for the loss of nitrate. Any nitrate which leaches into deep groundwater is probably lost through denitrification in the reduced deep marsh sediments. The reduced conditions present in some regions of the high marsh can support denitrifying bacteria, however the oxidized conditions which prevail in the fresh upland waters do not support denitrifiers. Denitrifying enzymes are induced by the absence of oxygen (Wiebe et al, 1981). Therefore, the low nitrate concentrations in the fresh water indicate that this nutrient is efficiently immobilized by the plant community, and not lost through denitrification. However, in the high marsh, significant losses of nitrate through denitrification are possible.

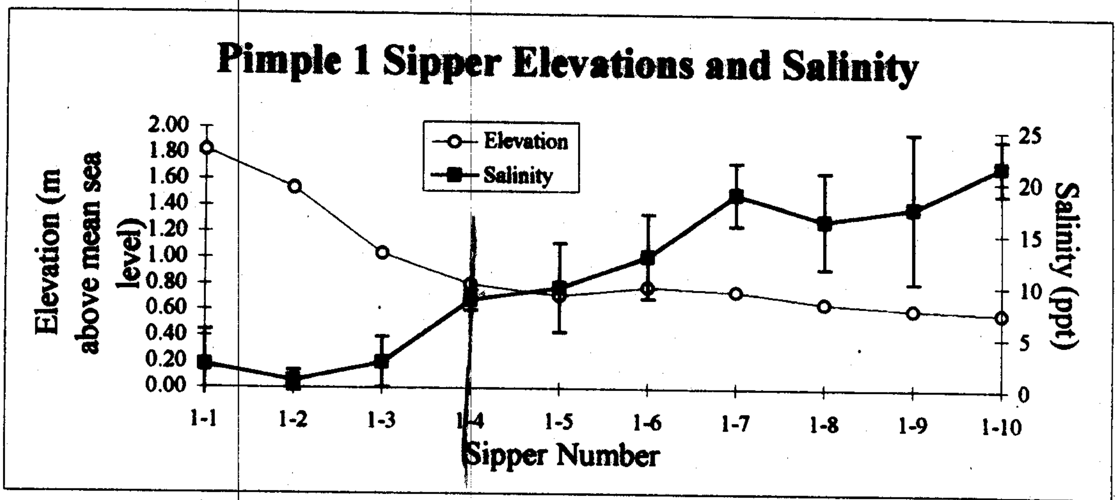
The significant sources of ammonium to this region are precipitation (figure 12) and flood waters. Figure 17 shows the porewater ammonium concentrations along each transect from July through November, 1994 (average concentration of all samples collected: 8.4 micromoles/l). These values are considerably lower than the values reported from mainland marshes, but consistent with the values measured in other back-barrier high marsh systems (Osgood, personal communication). Porewater ammonium concentrations measured in the high marsh region of the Brownsville Marsh (a mainland marsh located on the Eastern Shore of Virginia) were approximately 40 micromoles/l during the summer of 1994 (Tapper, personal comm.). In a Georgia marsh, porewater ammonium concentrations average 30-70 micromoles/l in both the high and low marsh (Whitney et al., 1981).

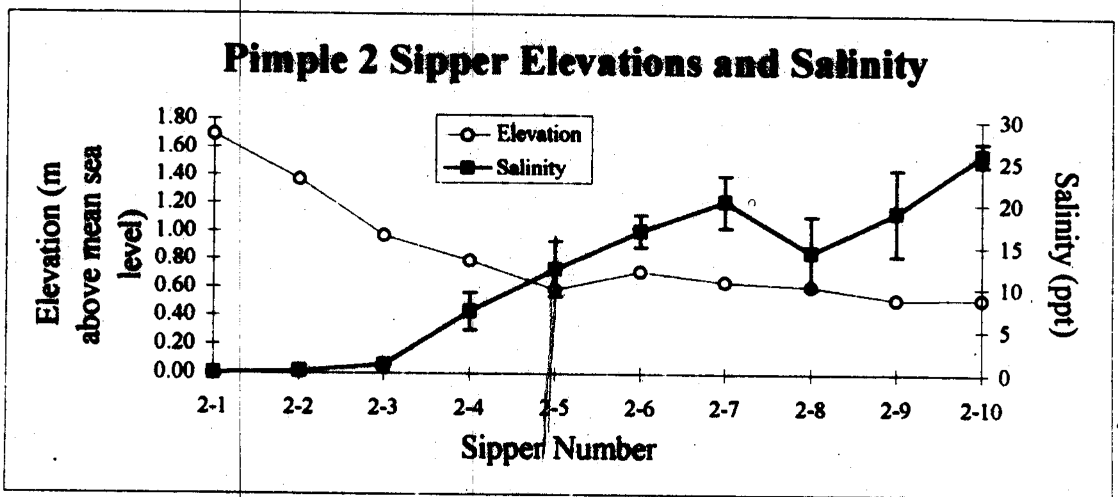
Lagoonal ammonium concentrations vary seasonally, with the highest concentrations (4-7 micromoles/l) occurring during the summer months (Blum and Christian, 1994). These high concentrations coincide with increased water temperatures, and subsequently with increased bacterial activity. The lowest concentrations (< 2 micromoles/l) were measured during the winter and spring months when bacterial activity had diminished due to the cold water. Therefore, the largest inputs of ammonium to the high marsh (and transition zone) through tidal inputs occur when this region of the marsh is flooded during the summer months. This result is significant because the summer months are when the demand for nitrogen is greatest for plant growth. Based on 515 tidal cycles at the Hog Island tide gauge between 1-January and 12-October, 1994, 436 high tides (85 % of all high tides) reached a level of 0.60 meters or higher. This level is approximately coincident with the elevation of sipper 9 in T1 and sipper 8 in T2. Tides of 1 m or more were recorded on 149 tides. The border between the transition (shrub zone) region and the upland occurs at approximately 1 meter in elevation for each pimple indicating that the transition zone is flooded during 29 % of all high tides. Therefore this region also receives the most significant inputs of ammonium during the summer when lagoonal ammonium concentrations are highest. The transition region also receives greater quantities of precipitation derived inorganic nitrogen (both ammonium and nitrate) than the high marsh because the transition zone is flooded less frequently.

Ammonium is the most significant inorganic nitrogen specie in salt marsh systems. Nitrate and ammonium are both important in that plants can utilize either as a nitrogen source. However, ammonium concentrations are consistently higher than nitrate concentrations in salt marsh systems. Therefore ammonium is more available than nitrate. Unlike nitrate it is not highly mobile, and is therefore readily retained in the system. It is not mobile because it tends to form complexes which bind to soil surfaces where it can serve as a storage pool of nitrogen for the community. As the complexes break down, nitrogen is made available to the plant community. As discussed earlier, the reducing conditions present in the marsh do not support significant nitrification; therefore ammonium cannot oxidize to nitrate, and subsequently be lost through denitrification. As a result, ammonium can only be lost through the export of organic and mineral forms through tidal exchange. Nitrate is obviously an important source of nitrogen to the marsh community as well, but this nitrogen specie must be utilized immediately by the community or it will be lost through denitrification, or to deeper groundwater out of reach of the plant community.

In the fresh waters of the pimple, nitrate is more important to the plant community than ammonium. The oxidized conditions do not support losses through denitrification, and the principle source of inorganic nitrogen to the fresh water is precipitation. Nitrate concentrations in the rain water are higher than ammonium. The fresh water lens is a thin lens (1-2 meters thick) which is perched on the saline marsh groundwater. Therefore the fresh water is essentially trapped and may prevent the nitrate from leaching into deeper groundwater. The trees and shrubs which occupy the pimples can therefore readily assimilate the nitrate.

Figure 8: Elevation (above msl) and average salinity (from July-November, 1994) of each sipper along the three transects





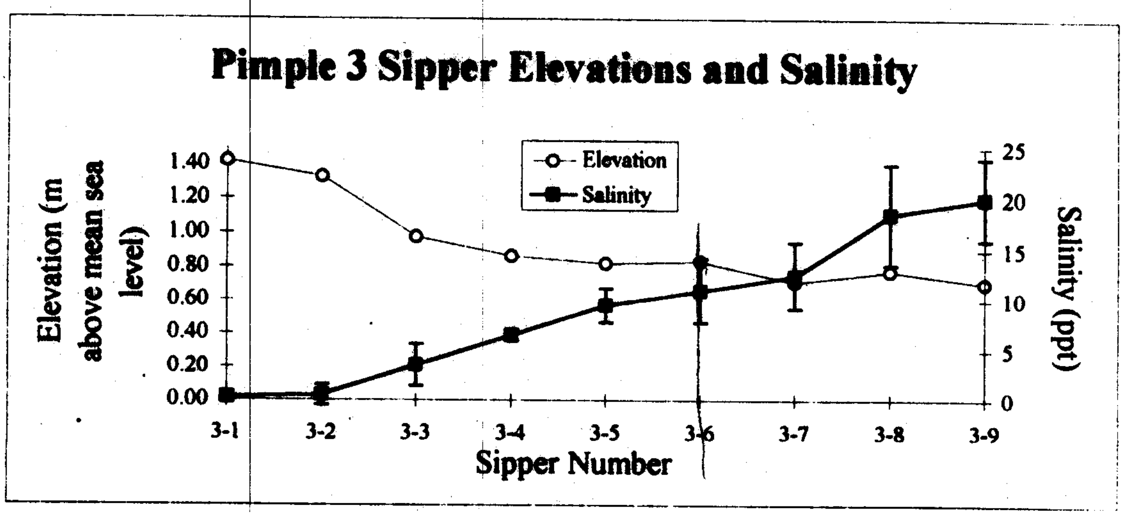


Figure 9: The relationship between salinity and elevation from the high marsh and transition zone around the three pimples. Salinity values reflect the mean salinity from July-November, 1994.

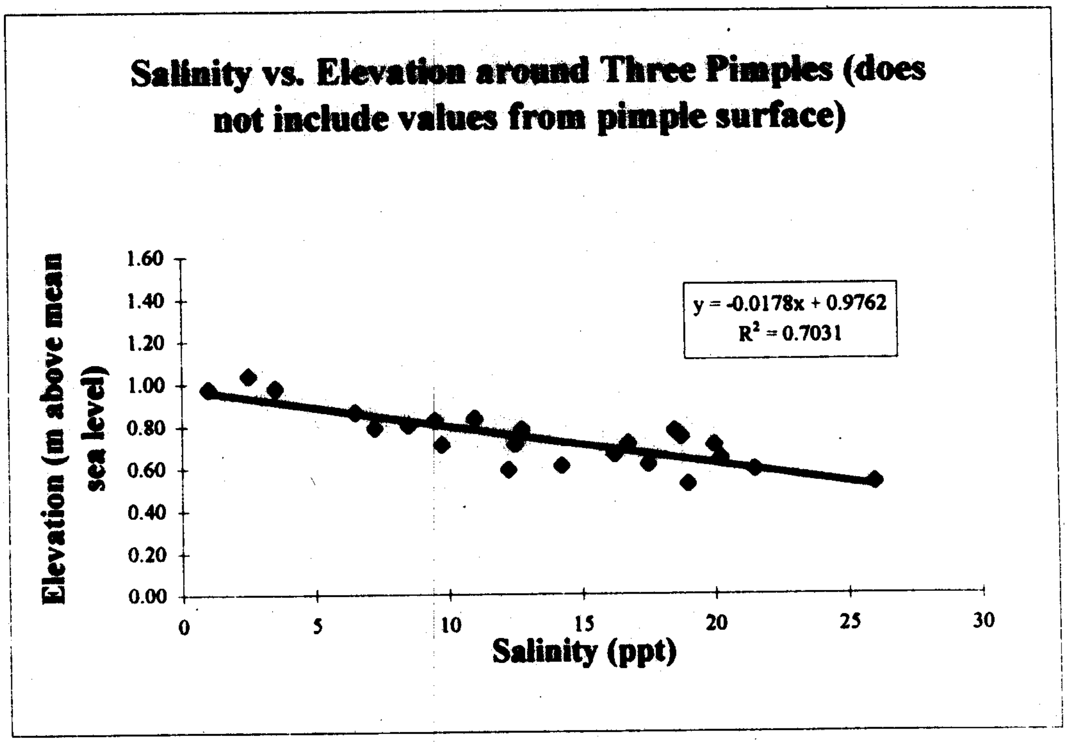
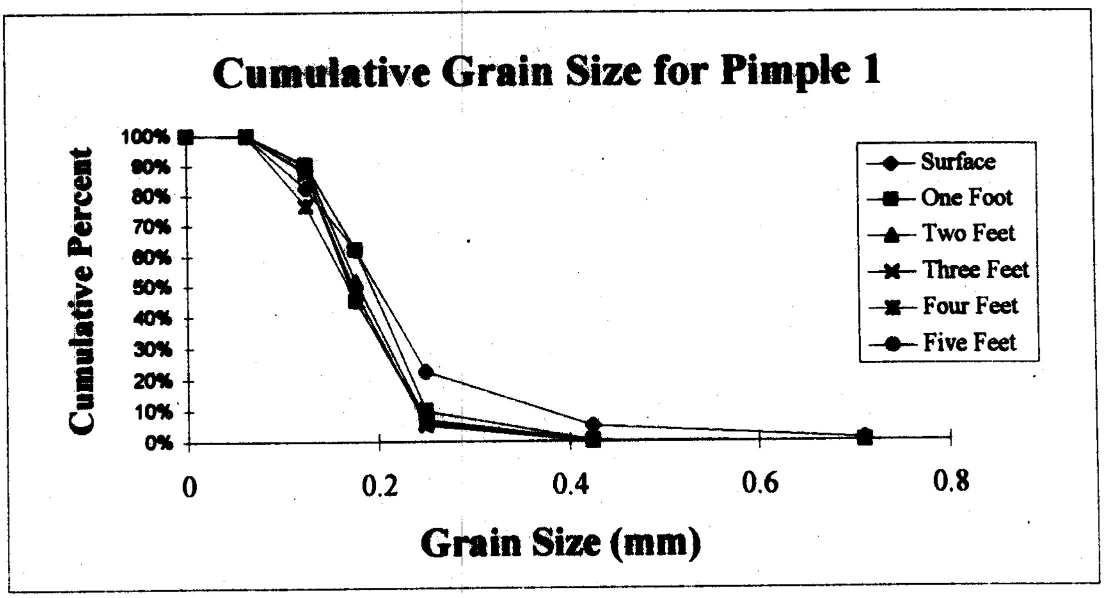


Figure 10: Cumulative grain size for Pimple 1 and the high marsh (from the end of transect 1). The cores were obtained using a vibra-coring machine.



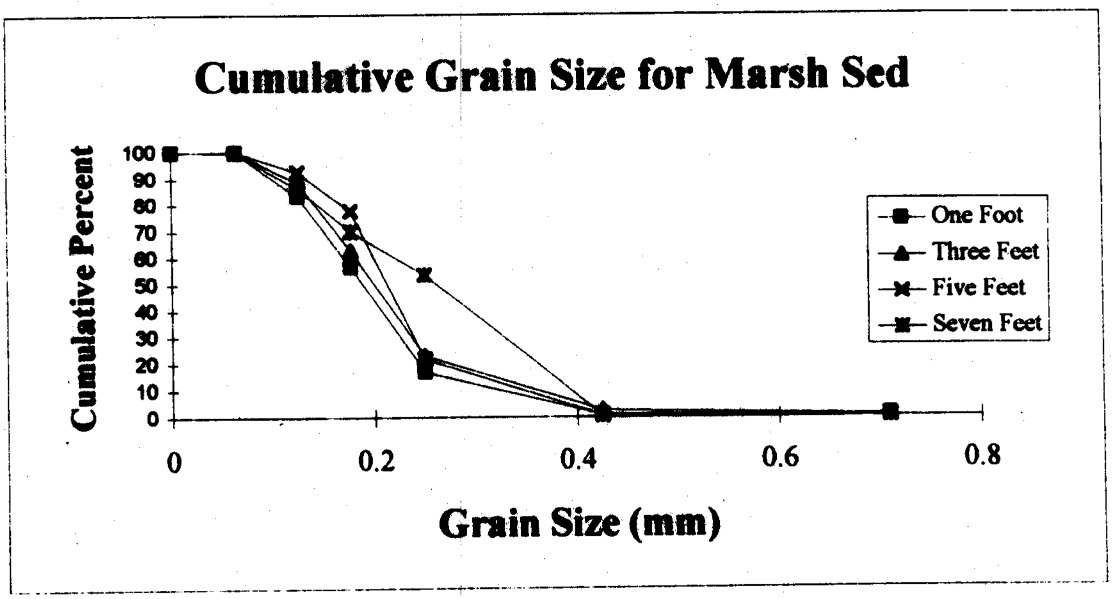


Figure 11: Porewater nitrate concentrations measured along each transect.

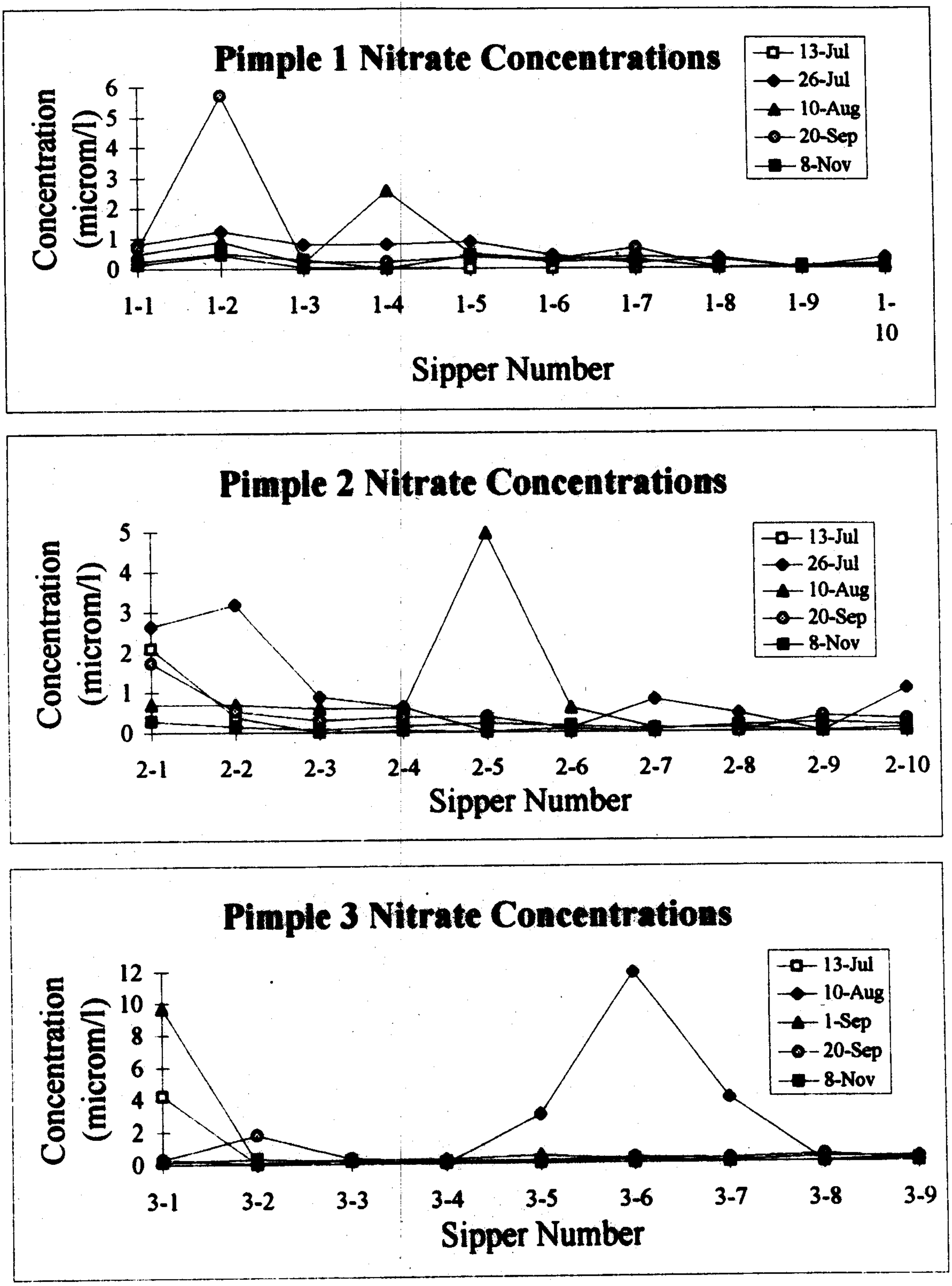
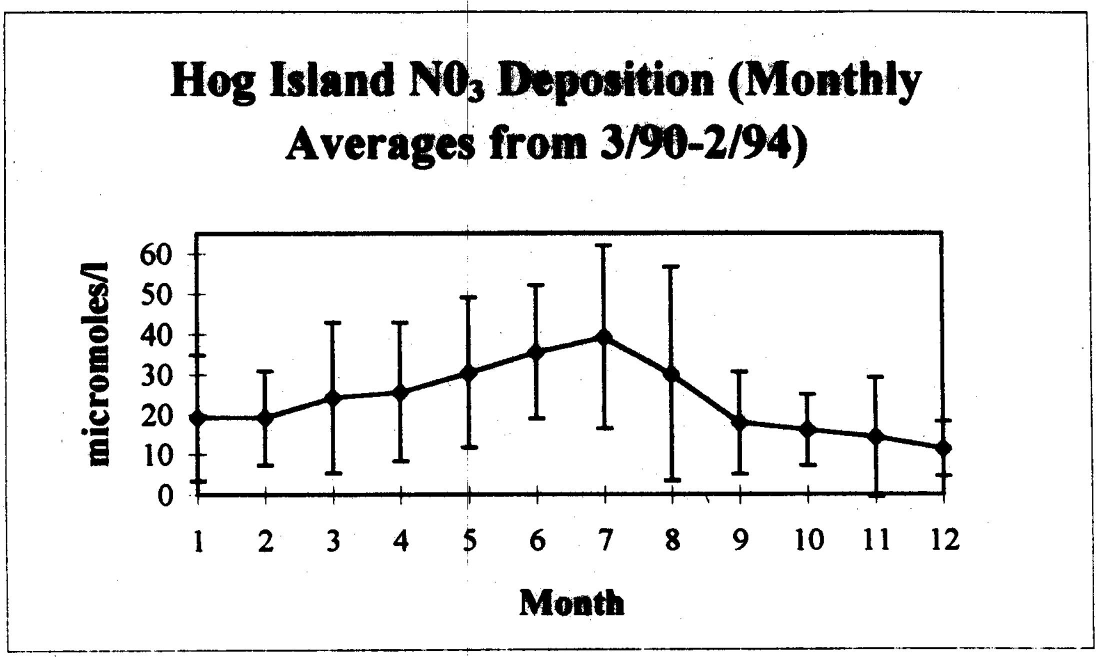


Figure 12: Average monthly inorganic nitrogen concentrations (nitrate and ammonium) in the wet deposition from samples collected from north Hog Island between March, 1990 and February, 1994.



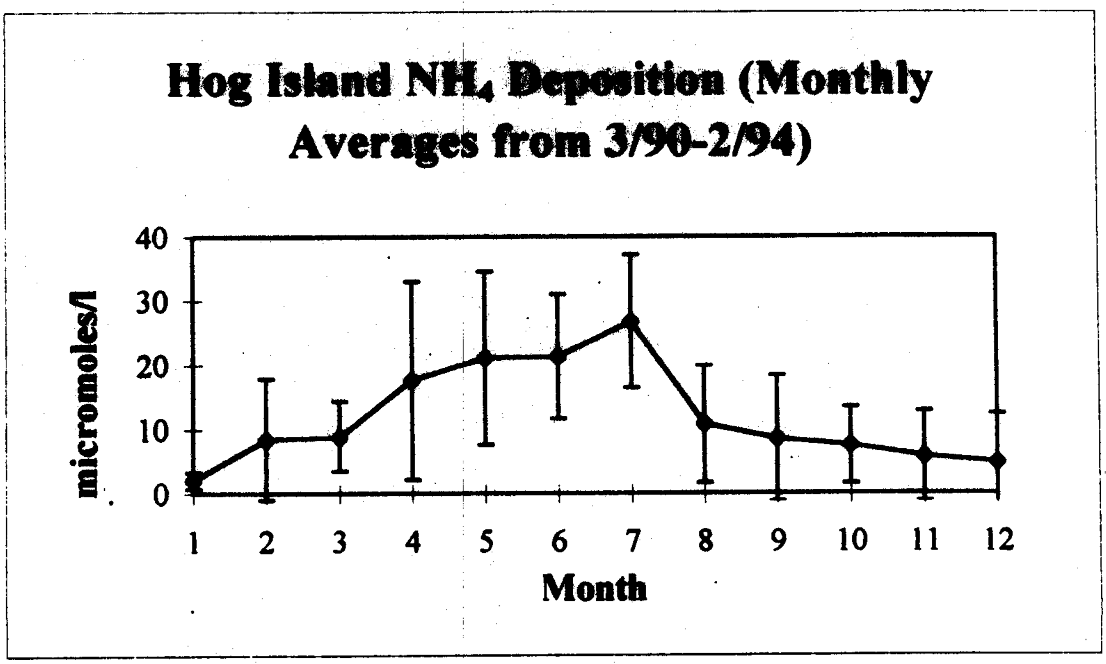
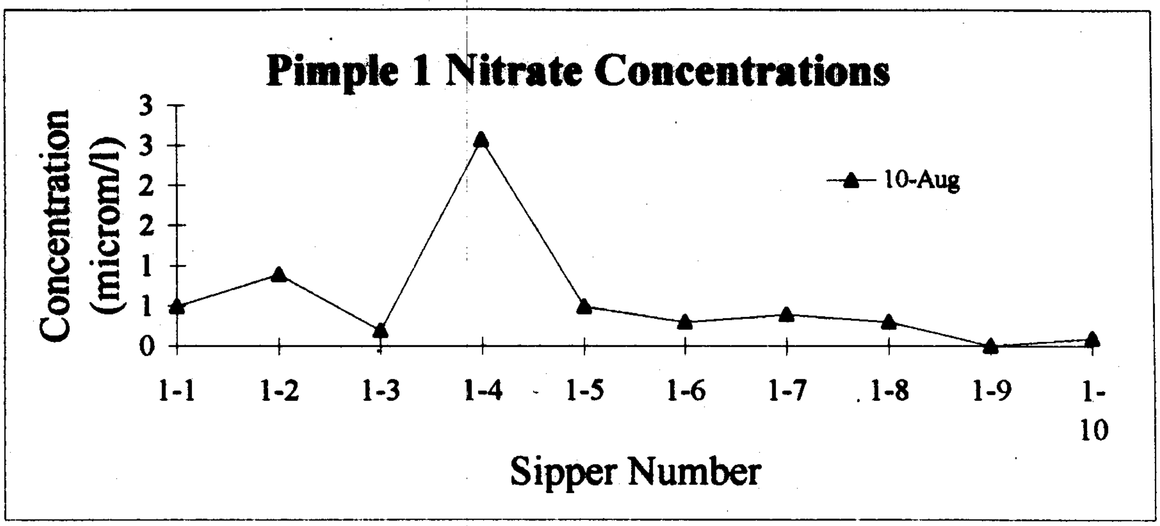
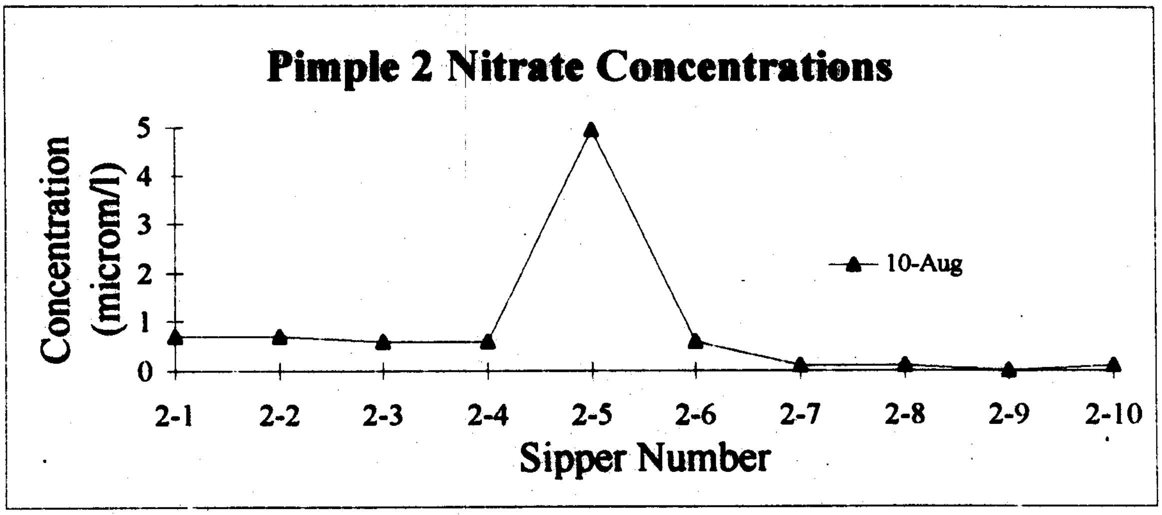


Figure 13: Porewater nitrate concentrations measured along each transect on 10-Aug, 1994.





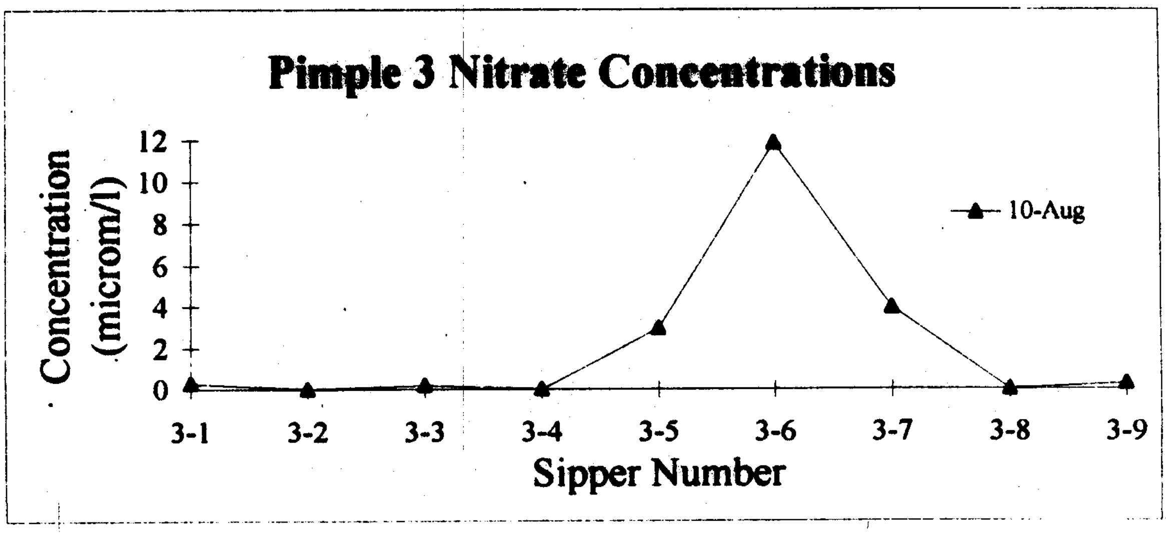


Figure 14: Hourly precipitation and tidal heights measured on north Hog Island, 5-August, 1994

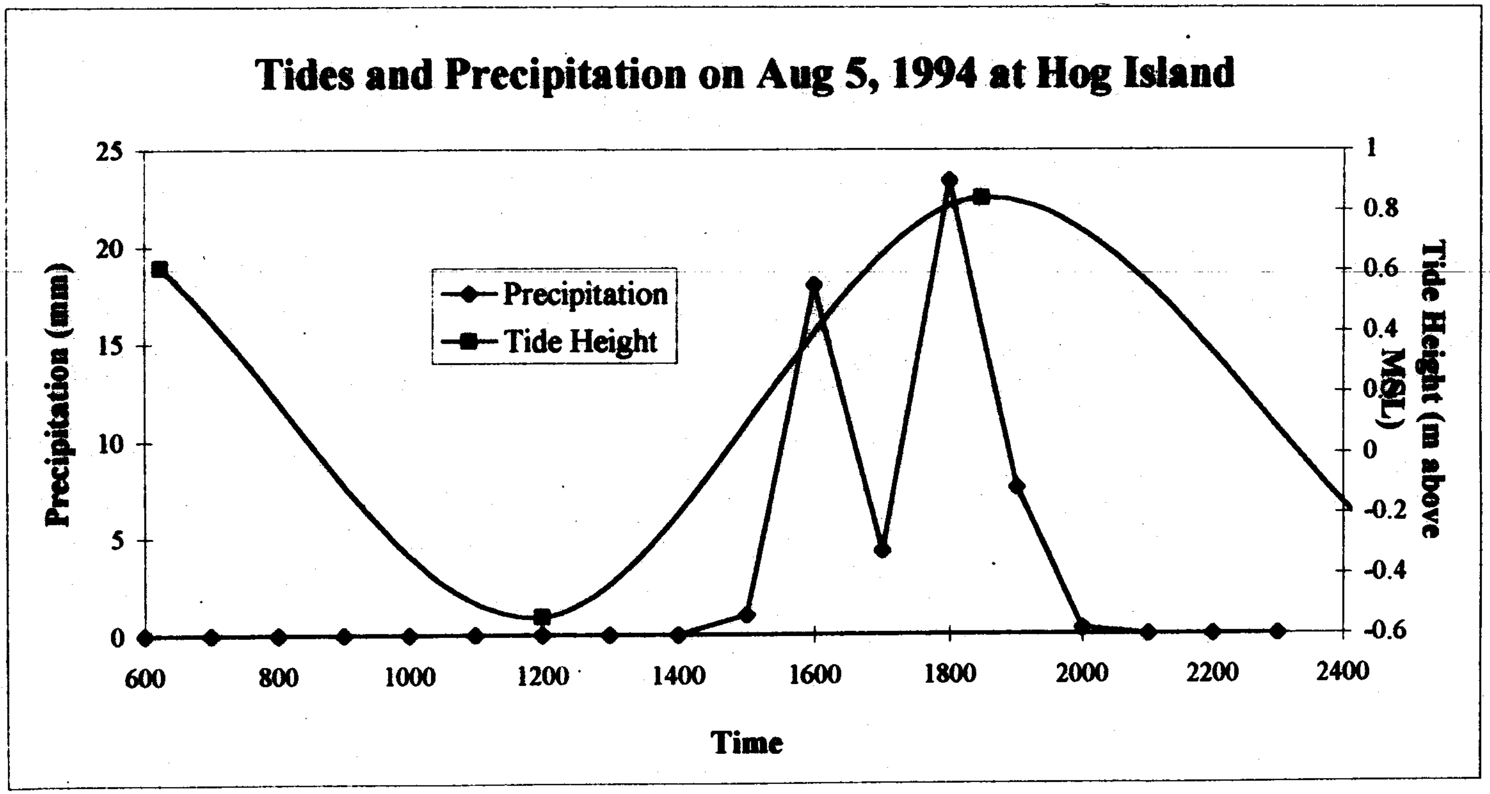


Figure 15: Pimple 1 eH measured on 26-July, 1994 along Transect 1

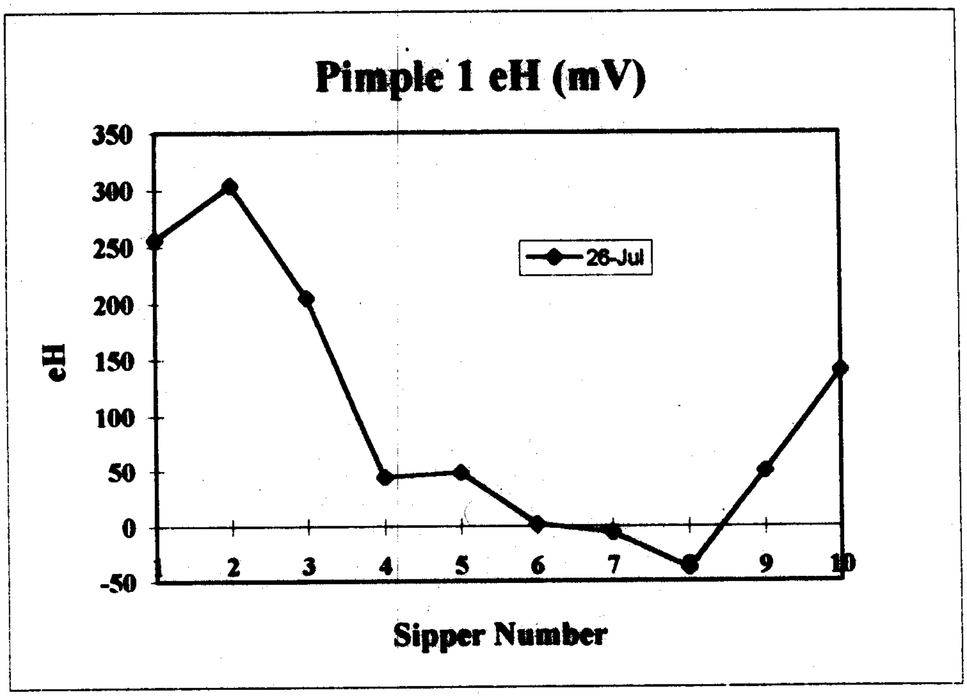
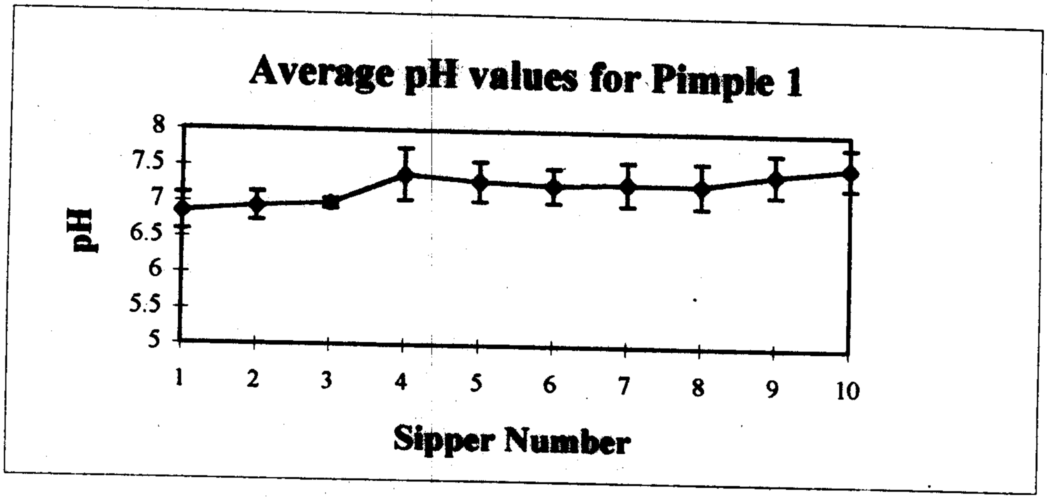
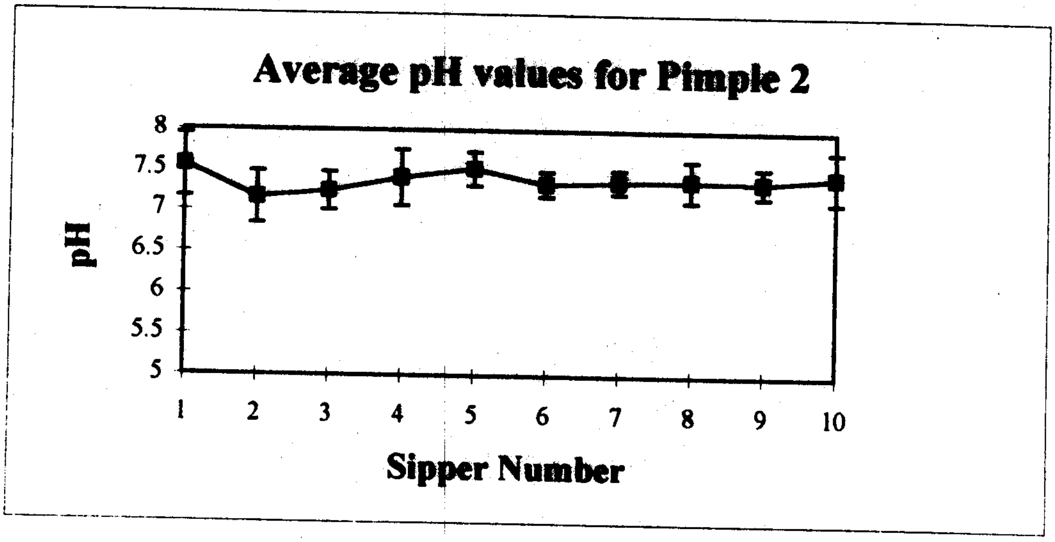


Figure 16: Average porewater pH measured from each sipper transect from July-November, 1994





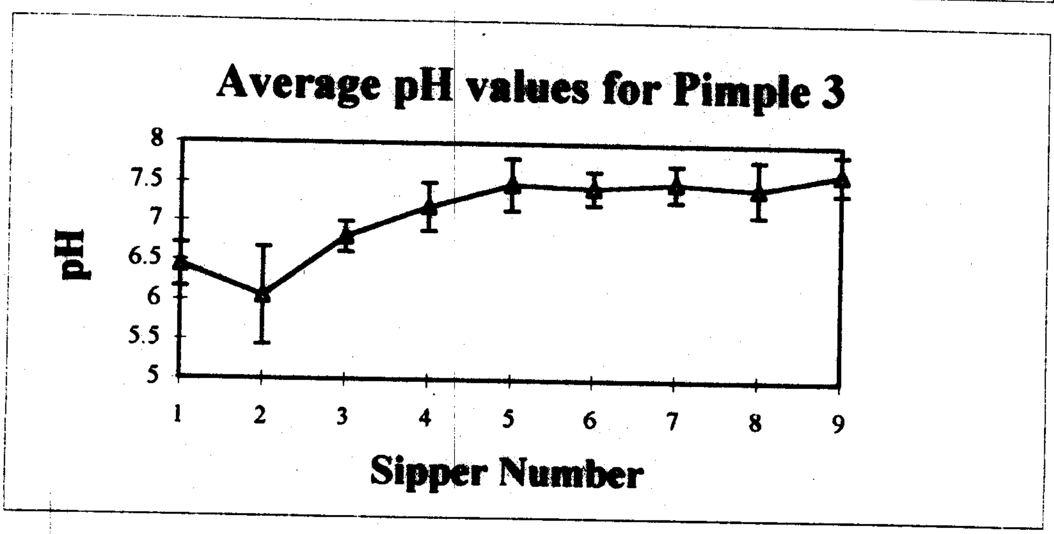
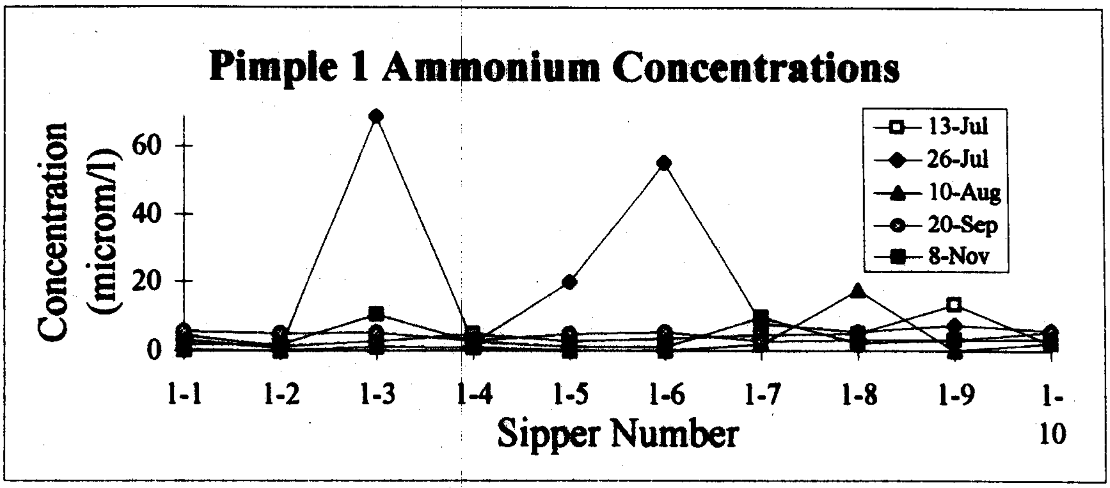
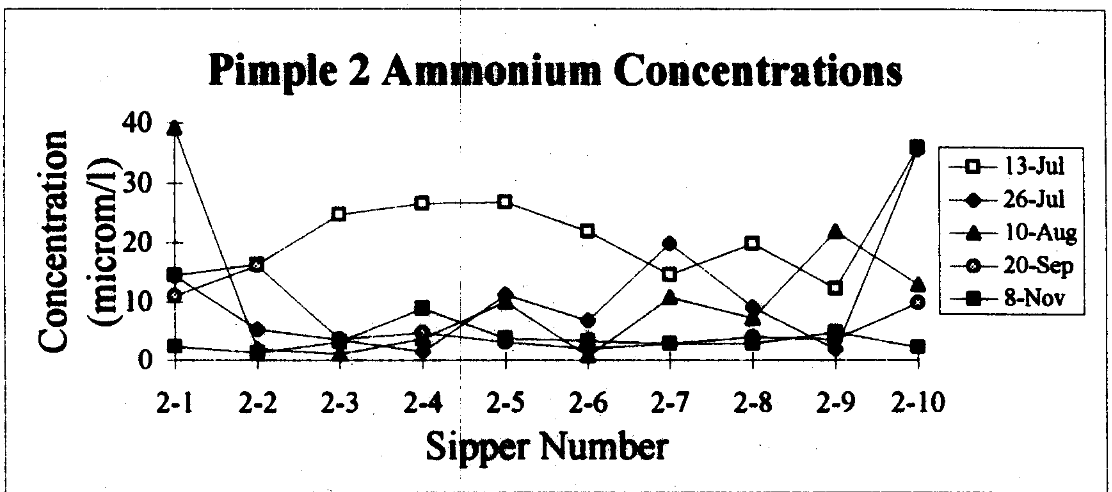
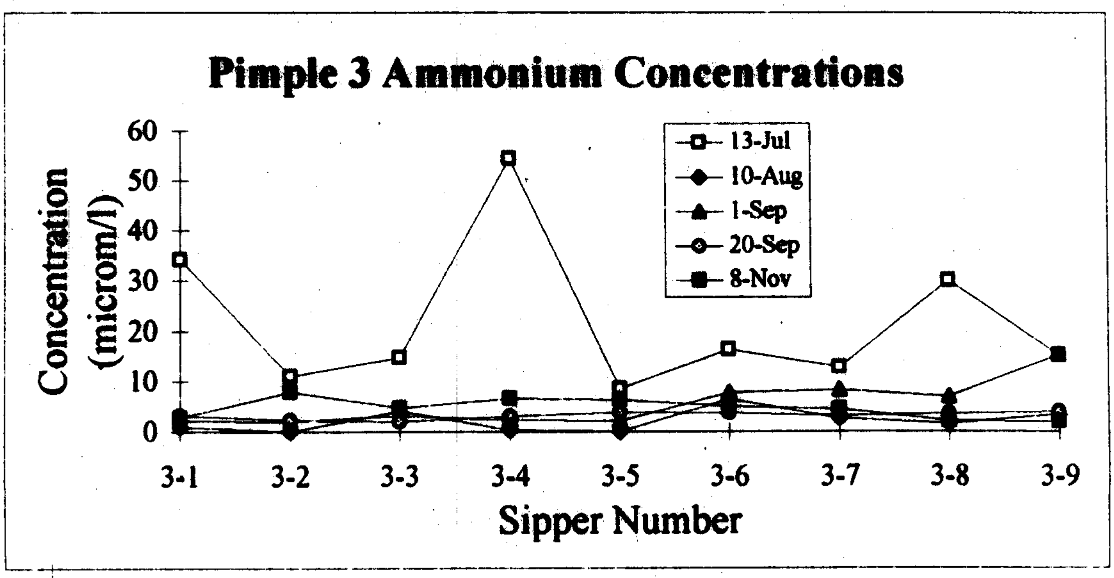


Figure 17: Porewater ammonium concentrations measured along each sipper transect.







Conclusions

Salt marsh communities are inherently limited by nitrogen (Valiela and Teal, 1979). The concentrations of inorganic nitrogen which were measured in the high marsh/upland region in this study were extremely low, making the plant community very sensitive to any significant inputs of nitrogen. The major sources of inorganic nitrogen to this region are from precipitation and tidal flood waters. This result contrasts with other studies which determined that precipitation does not contribute quantities of nitrogen which are proportionately significant due to the large inputs from fresh groundwater. The current study is unique in that it examines sources of inorganic nitrogen to a back-barrier marsh system. Most of the studies to date have focused upon mainland marsh systems. The volume of upland groundwater discharge to a back-barrier marsh system is inherently limited by the small scale of the recharge area. Also, the concentrations of inorganic nitrogen in the upland water of barrier islands are significantly lower than the concentrations of mainland groundwater. Therefore, the results from this study are applicable to undisturbed back-barrier marsh systems behind small upland systems which have limited fresh water reserves. Examples of these include low-relief barrier islands which have narrow dune systems, as opposed to the islands which are more elevated and have developed extensive fresh water lenses.

The inorganic nitrogen inputs to this region are quickly assimilated into the system. Nitrate inputs to the fresh upland waters are rapidly immobilized through plant uptake. The source of the fresh water is precipitation, yet the nitrate concentrations in the fresh water are on average 24 times less than the nitrate concentrations in the precipitation. The oxidized conditions present in the fresh water do not support denitrifiers, or the reduction of nitrate to ammonium. The thin, perched fresh water lens does not support flow paths which would carry the nitrate into deeper groundwater. Therefore the nitrate must be efficiently assimilated into the plant material. The nitrate which is deposited on the marsh surface through precipitation is either assimilated by the marsh plants, or a portion of it may be lost through denitrification. Conditions present in some areas of the marsh do support denitrifying bacteria.

Significant ammonium inputs also result from tidal flood waters and precipitation. The highest ammonium concentrations in both the flood waters and the precipitation occur in the summer months. This is important for the marsh community because it during these months (the growing season) that the nitrogen is in demand. Ammonium is also quickly assimilated into the system, either through plant uptake or through the immobilization of this nutrient by bacteria which form complexes on soil surfaces. These complexes make this inorganic form of nitrogen unavailable to the plant community, but will build up a pool of nitrogen which may be available in the future when conditions may support the release of available nitrogen from these complexes.

Future Research

The questions which arise from this study indicate the need for additional research in this area in order to fully understand the role of many factors on the nitrogen cycle in the high marsh/upland region. Particular attention should be focused upon developing analytical techniques which can directly measure the rates of various reactions (nitrogen transformations) in the transition zone where the two chemically distinct groundwaters mix. This study makes inferences to which reactions are favored based upon the physical conditions present. However, there exists a need to quantitatively develop a nitrogen budget for this region. Also, how does the volume of fresh water affect the availability of inorganic nitrogen species in this region? How does it affect the bacterial communities which drive the transformations which determine whether or not the nitrogen will be available? Comparisons should be made between undisturbed systems and systems heavily polluted with nitrogen from agricultural practices. These comparisons should include studies which examine the differences in the microbial community in order to understand whether or not the bacteria are able to balance the system through processes which may either retain or degas the nitrogen which enters the system. However, in order to make such a comparison, advances in techniques used to measure several variables must also be improved.

Isotopic studies must be developed which can accurately measure the transformations of individual nitrogen species to both organic and inorganic forms.

Presently the techniques of following the nitrogen through various transformations are not available. Therefore, at present, only inferences regarding these transformations can be derived from studying the physical conditions present and relating the processes to known transformations which occur under particular conditions. These are difficult processes to measure, but it is likely that advances in isotopic research will substantially increase our understanding of these systems through the development of techniques which will allow us to follow the transformations by measuring the ratios of ^{14}N to ^{15}N which result from individual processes.

Appendix A

A Review of the Factors Which Affect the Development and Stability of Ghyben-Herzberg Lenses: with a particular Emphasis on Scale

Introduction:

Ghijben-Herzberg (fresh water) lenses are groundwater bodies which have developed beneath marine islands which support conditions favorable for their development. A fresh water lens constitutes a body of fresh water which effectively floats on top of denser, saline groundwater (Freeze and Cherry, 1979). The recharge into the lens occurs via infiltration of precipitation. Fresh water losses occur through evapotranspiration (ET) and groundwater discharge into adjacent marine water bodies (either open water bodies such as an estuary, or into saline groundwater). There are four primary factors which effect the development, stability, and extent of the fresh water lens. (Vacher, 1988; Cant and Weech, 1986). These include the size and geometry of the recharge area, the hydrogeology, the volume of precipitation inputs, and the rate of groundwater losses from the system through groundwater discharge and ET.

Island hydrologists have primarily been interested in understanding the formation and stability of these groundwater reserves because the islands' inhabitants often rely on the groundwater for a majority of their water needs. As populations increase on many of these islands it has become necessary to quantify the volumes of available groundwater, as well as determine recharge rates in order to develop appropriate planning policies which will assure a continuous supply of potable water (Chidley, 1977; Falkland, 1991). It is for this reason that island hydrologic systems have been extensively studied, and the processes which control the supply and flow of water in these systems have been researched at several scales under varying geologic and climatic conditions. These studies include numerous field investigations, as well as the development of computer models which simulate flow and predict water availability based on the physical characteristics of an island (and calibrated for a particular climate). However, because the primary reasoning behind their work has been to assure water supplies for human needs, hydrologic systems which are of the scale that are too small to provide adequate water resources for humans have received little attention.

Fresh water lenses which are of this scale (variable in size, but generally less than 1/2 kilometer in width) may not be large enough to warrant investigations into the development of their water resources for human needs, but they may provide fresh water for an assemblage of terrestrial vegetation species. Excellent examples of small scale fresh water lenses have developed beneath the Parramore Pimples which were associated with this study. In other instances, long narrow lenses have been documented in dune systems on the Dutch coast (Dachler, 1936). It is conceivable that the fresh water reserves may sustain a terrestrial biome, which in turn sustains the stability of the features themselves. It has been demonstrated that in dune systems the vegetation stabilizes the landforms (Ranwell, 1972). Small, isolated systems such as the Pimples can provide opportunities to study processes which are inherently difficult to quantify because of the problems associated with identifying all of the variables which influence systems of a much larger scale.

The purpose of this appendix is to review the factors which affect the development, shape, and stability of fresh water lenses, and furthermore, to relate these processes to lenses of a much smaller scale. In particular, comparisons will be made with the lenses which have been identified beneath the Parramore Pimples.

Special attention will be relegated to the processes which are inherently more relevant in terms of maintaining these lenses, because of their small scale. These include mixing of fresh and salt/brackish waters due to tidal oscillations and diffusion, and the effects of disturbances (drought, possible overwash events in the case of a very small lens).

Hydologic Theory:

Fresh water lenses are often refereed to as Ghijben-Herzberg lenses because the first quantitative observations of the depth to the interface between fresh and salt waters were conducted independently by Badon Ghijben (1889) in Holland and Herzberg (1901) in Northern Germany. They both developed a hydrostatic approach to calculating the depth to the interface (a sharp, well defined interface) based upon the equilibrium of two stationary immiscible fluids of different densities. On any point on the interface the water pressure (water depth times the specific weight of the water) must be the same on both sides (adapted from Falkland, 1991). Because these two pressures must be equal, the fresh water pressure at point A is $(z + h_f)\rho_f$ and is equal to the salt water pressure ($z\rho_s$) at point A'. Thus:

$$(z + h_f)\,\rho_f = z\,\rho_s$$

and: $$z = (\rho_f/(\rho_s - \rho_f))\,h_f = \alpha\,h_f$$

where:

h_f = fresh water head (elevation of fresh water table above mean local sea level)

z = depth of the interface below local mean sea level

ρ_f = density of fresh water (1000 kg/m^3)

ρ_s = density of salt water (average value of 1025 kg/m^3, but can vary spatially between 1020 and 1030 kg/m^3.

α = specific weight (density) ratio = $\rho_f/(\rho_s - \rho_f)$.

This formula is know as the Ghijben-Herzberg formula. The average value of α is 40. In other words, the depth to the salt/fresh interface (below mean local sea level) beneath a fresh water lens should be equal to 40 times the height of the fresh water head.

This solution, however, is a theoretical solution which requires the statement of two assumptions which do not exist in the real world. These include the assumption that salt and fresh waters are immiscible (resulting in a sharp interface), and that the fluids are static. In reality, salt and fresh waters are miscible, and therefore a zone of mixing (due to tidal oscillations and diffusion) develops a brackish transition zone which consists of a salinity gradient from the fresh water to the salt water. The salinity gradient has been observed to follow an error function distribution symmetric about the midline of the transition zone (Cooper, 1959; Kohout, 1960). This is also consistent with the distribution determined by theoretical models of dispersion caused by tides (Carrier, 1959; Bear and Todd, 1960). The width of the transition zone is a function of the size of the fresh water lens, the magnitude of the tidal oscillations and the permeability of the porous medium. Vacher (1978a) observed an areal variation in the transition zone thickness under Bermuda that corresponded to the amplitude of short-period water table fluctuations generated by two forces: astronomical tides and changes in atmospheric pressure. The width of the transition zone diminished inland as the effects of astronomical tides became less influential.

A Review of Factors Which Influence Lens Dynamics:

There exist four primary factors which affect the development and stability of fresh water lenses. These include the hydrogeology, the size and geometry of the recharge area, the volume of recharge, and the volume of water lost to groundwater discharge. The volume of recharge is a function of precipitation inputs, and the volume of water lost from the system to ET. These factors can be described as independent processes, but do not operate independently from one another. For example, if an island consists of impermeable, exposed bedrock, then it is obvious that a lens will not form regardless of the volume of precipitation which is deposited upon the island.

Hydrogeology:

Given sufficient precipitation inputs the hydrogeology is likely the most important factor which will affect the development of a fresh water lens. The primary hydrogeologic variable which will affect lens development is the permeability of the medium. The permeability of the medium will not only determine the size of the lens, but will also affect the width of the transition zone. Heterogeneities in the permeability (vertically as well as horizontally) will affect the shape of the lens, as well as the groundwater flow lines. This has been demonstrated in numerous field studies (Vacher, 1978a; Cant and Weech, 1986, Ayers and Vacher, 1986; Anthony et al., 1989), as well through analytical modeling exercises (Vacher, 1988; Underwood et al., 1992; Chidley and Lloyd, 1977).

Vacher (1978a) conducted a study in Bermuda which focused upon understanding the affects of changes in permeability on lens dynamics and geometry.

A hydrologic cross section of the island indicates the presence of two surficial geologic formations (the Paget and the Belmont). These two formations are the most relevant hydrogeologically because they constitute the upper saturated zone of more than 80% of the island. The contact between the two occurs near the center of the island, and is approximately vertical. The younger, less permeable Paget formation (about 125,000 years old) consists primarily of a loosely cemented calcarenite of eolian origin. The Belmont formation consists of eolian calcarenites as well, but is the oldest formation on the island. The dissolution of much of this unit through time has resulted in the development of a hydraulic conductivity which is an order of magnitude higher than the hydraulic conductivity of the Paget formation.

Vacher mapped the freshwater lens and the transition zone along a cross section of the island where the northern half of the cross section consisted of the Paget formation, and the southern end consisted of the Belmont formation. He then overlapped a curve of the fit of the Ghyben-Herzberg-Dupuit model to this cross section in order to determine the relative 'goodness of fit' of the model to reality. The interface was taken to be along the curve representing a salinity equal to 50% that of sea water.

Vacher's results indicate that in the less permeable Paget formation the interface (at the deepest point) was at approximately 17 meters below sea level. In the Belmont formation the interface was at a depth of about 10 meters. Perhaps of greater significance was the difference in the width of the transition zone. Within the Paget formation the thickness of the transition zone (vertical distance between 1% and 50% sea water) remained fairly consistent throughout the formation at about 2 meters. The thickness was slightly higher near the coast. In the more permeable Belmont formation the transition zone thickness varied from 4 meters at the center of the island to 10 meters near the islands edge. Along approximately 1/4 of the island's southern extent (in the Belmont formation) the transition zone extends to the surface of the water table, resulting in unpotable water in this region. A fit of the Ghyben-Herzberg-Dupuit model along this cross section indicated a very good fit within the Paget formation (within 4% of the observed values), and a reasonably good fit in the Belmont formation (within 8% of the observed values). However, the model did not have the capacity to evaluate the thickness of the transition zone.

The differences in thickness of the transition zones were taken to be a result of the varying effects of astronomical tides and atmospheric pressure changes on the fluctuations in the water table. The amplitude of the water table fluctuations decrease inland due to the progressive dampening of the tidal influences. This dampening is not only a function of the distance inland, but also of the hydraulic conductivity of the medium. The dampening of water table waves generated by tides varies inversely with the hydraulic conductivity. Therefore, the water table fluctuations in the Belmont formation are greater than the fluctuations in the Paget. The end result is increased mixing of waters beneath the Belmont which develops a thicker transition zone.

In a Dupuit-Ghyben-Herzberg analysis of strip-islands, Vacher (1988) examined the influence of horizontal heterogeneities in hydraulic conductivity on fresh water lenses. His analysis suggested that a high permeability basement material will compress the "root" of the lens, thereby decreasing the water table height. A lens perched on an impermeable basement would have a higher water table than would otherwise occur, but the total volume of fresh water would be less.

Scale and Geometry of the Recharge Area:

The size as well as the geometry of the recharge area has been demonstrated to affect the development of fresh water lenses. In a study conducted by Cant and Weech (1986) in the Bahamas, they examined the relationships between island size and the volume of fresh water within the lenses of 21 islands ranging in size from 777 hectares to 326,338 hectares. Figure 1 displays a plot of log volume versus log land area. A linear regression analysis resulted in an r^2 value of 0.80 for water volume versus land area. It is evident that the larger the recharge area is, the greater the capacity to store water becomes. However, deviations from the best line fit result from varying geologic and climatic conditions.

The geometry of an island has a significant impact upon the lens configuration, and subsequently the volume of fresh water as well. Cant and Weech state that many of the long, thin islands in the Bahamas are only able to develop brackish lenses. The tidal oscillations are significant enough across the width of the island that mixing occurs throughout the groundwater, resulting in brackish lenses.

Recharge and Discharge:

Estimating recharge in island systems can be difficult. Recharge is defined as the ratio of precipitation which becomes groundwater to total precipitation. The losses occur through evapotranspiration. Unlike a catchment, a single outlet does not exist where the volume of discharge can be determined from a stream. Recharge in a catchment can be approximated by measuring the stream discharge over a specified time scale (assuming no groundwater losses or changes in storage). On small islands the discharge occurs through groundwater losses which are difficult to quantify. However several techniques have been developed which can be used to estimate the recharge in island situations. Vacher and Ayers (1980) present a review of several techniques and also proposed a new technique which they believe is simple, accurate, and cost efficient.

One of the techniques they review involves a Penman- and Thornwaite-type water budget. However, they believe that this approach generally produces results which are considered too low. A second technique involved the analysis of water-table hydrographs following recharge events. This technique was also largely discounted because the temporal changes in water table fluctuations are strongly influenced by several non-tidal variables which introduced too much noise. A third technique involved examining hydrogeologic evidence using computer simulation to interpret the size and configuration of the lens, and the behavior of the water table both under natural conditions and in the vicinity of major water extraction sites. They believe that this method produced reasonable values for recharge. By employing this technique they determined that the recharge in Bermuda was approximately equal to 0.25. However, this evaluation was time consuming and expensive. Therefore they suggested an alternative method.

The method they developed involved using chloride as a tracer in the groundwater to estimate recharge. They suggest that chloride can be utilized as a conservative tracer which is concentrated in the groundwater from ET. The idea they propose is based upon the assumption that the ratio of the chloride concentrations measured within the fresh groundwater in the lens to the chloride concentration in precipitation should be equal to the recharge rate. In order to minimize the possibility of sea-spray contamination and other possible chloride sources they suggest that the lowest chloride concentrations measured should be used from "the freshest part of the lens" for this analysis. They determined that the average chloride concentration of the precipitation in Bermuda is about 15 ppm. The lowest chloride concentration measured in the lens was 60 ppm. Therefore the average recharge rate was estimated at 0.25. Average annual rainfall in Bermuda is 147 cm/yr, therefore the recharge rate would be 37 cm/yr. The 0.25 value was consistent with the 0.25 value determined using the hydrogeologic approach.

Measuring discharge from freshwater lenses can be difficult. However, if a reasonable value for the recharge is obtained, the discharge should equal the recharge (assuming no change in storage). A change in storage would be evident if the average annual water table level changes, or if a change in the position of the interface between salt and fresh waters is observed.

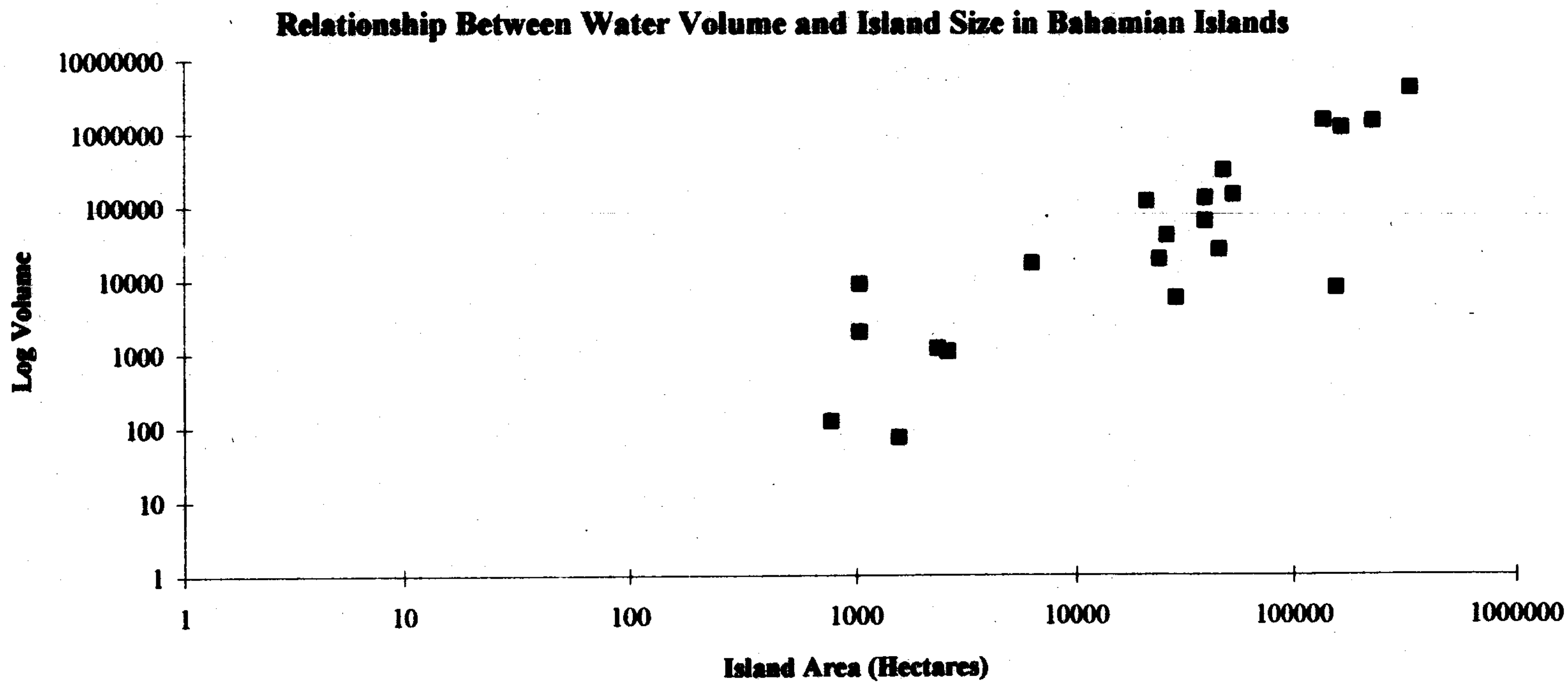
Small Scale Lens Dynamics:

Fresh water lenses which are extremely small (< 0.5 km in width) have not been studied to a significant degree. The most likely explanation for this is that these water bodies are not large enough be directly utilized for human needs. However, these lenses may support islands of terrestrial plant species which depend upon the fresh water reserves. In many cases the water table is close enough to the ground surface that the plants extend their roots into the phreatic zone. These small biomes are dependent upon the fresh water, and therefore are subject to severe stress or mortality if the fresh water reserves are not maintained.

The fresh water lenses of the Parramore Pimples are excellent examples of small scale lens systems. The hydrological investigations conducted on these features indicate that the small fresh water lenses behave similarly to larger lens systems. The same variables which control the development and stability of island-scale lenses also support the Pimples' lenses. Interestingly, the width of the brackish transition zone beneath the Pimple lenses is similar in width to the transition zones reported for much larger islands. The consistency of the sediment within the pimples has resulted in the development of symmetrical lenses. The seasonal expansion and contraction of the lens (volume of available fresh water) is a function of the evapotranspiration rates, the rate of discharge to the marsh, and the volume of inputs through precipitation.

However, the smaller lenses are inherently more unstable in the sense that the volume of fresh water is small enough that the effects of drought conditions may cause the fresh water reserves to be completely lost due to ET and mixing with saline groundwater. This is obviously consequential for any biome that may be directly dependent upon the fresh water reserves. Therefore, the principle effect of scale on fresh water lenses is in the stability of the lens, and subsequently of the vegetation dependent upon the fresh water reserves. Consequently, the stability of the features supporting small scale lenses may also be affected because a loss of the vegetation which stabilizes the features can result in erosion from wind and overwash.

Figure 18: Plot of log volume of fresh water lens versus log land area of Bahamian islands (from Cant and Weech, 1986)



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