Armoring the Coast: The Effects of Bulkheads on Salt Marsh Habitats

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Abstract

Shoreline hardening structures, such as bulkheads, are becoming an increasingly popular method of mitigating shoreline erosion. However, few studies have examined the ecological impacts of such structures. Salt marshes are highly productive ecosystems that act as a medium of exchange between marine and terrestrial environments. Bulkheads are thought to disrupt the natural processes associated with salt marshes. Our project was a two-pronged effort 1) we synthesized currently available literature and information regarding the presence and roles of shoreline hardening structures found in estuarine and sound-side locations of eastern NC, and 2) we conducted a field study that examined differences between bulkheaded and natural marshes at four sites located along Bogue Sound, North Carolina. An observational survey quantified the presence or absence of marsh in front of bulkheads. Greater than half of the bulkheads surveyed had marsh; indicating that marshes can coexist with properly cited bulkheads along Bogue Sound. Relative marsh health was experimentally determined by the presence and quantity of *Spartina spp.*, chlorophyll *a* concentration, and sediment organic matter. Results indicate that bulkheads had no immediately apparent deleterious influence on salt marsh health. However, we also noted extremely high variability among sites for all metrics that we examined, thereby reducing our ability to note significant impacts from bulkheads. Furthermore, when results were broken down by site, we had small sample sizes also limiting our power to assess differences between bulkheaded and natural marsh areas. Even though our results imply that bulkheads may not have dramatic deleterious effects on natural marsh systems, it is clear that further research is needed to confirm our findings.

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I. An Interdisciplinary Approach to Understanding Shoreline Hardening Structures

Introduction

Eastern North Carolina is a gently sloping coastal plain drainage basin containing many brackish lagoons, sounds, and salt marshes. These coastal estuaries are a natural by-product of flooded river valleys and coastal plains due to rising sea level. North Carolina has 2.2 million acres of estuarine waters and hosts the second largest estuary in the country, the Albemarle-Pamlico Estuarine System. These shorelines provide valuable natural aesthetic value to coastal communities, and they can be used for many recreation activities. As well, estuarine waters can act as a nursery habitat for marine organisms. Shoreline marshes help to improve water quality by acting as a buffer for stormwater runoff that can rapidly introduce sediments, pollutants, and pathogens into the estuary (Mallin 2000).

Biologically productive coastal watersheds are home to over 70% of the world's population, with population growth expected to continue in the foreseeable future (Vitousek 1997). North Carolina's eight coastal counties experienced a 32% increase in population from 1977 to 1997 (Mallin 2000). Population and development pressures bring with them environmental degradation in the form of increased fertilizer, pesticide, and sediment introduction into estuarine waters. These changes have led to an excess of nutrient inputs in the estuarine systems leading to a decrease in water quality and frequent algal blooms (Paerl et al. 1998). In addition to local problems, global climate changes, such as rising water temperatures and sea level rise, have altered estuarine environments. Food web disruption, coupled with the effects of shoreline erosion on sedimentation and nutrient flux in the estuaries, could lead to serious water quality problems not only for coastal residents, but also for estuarine organisms. Such changes have made coastal ecosystems more vulnerable to habitat loss and degradation.

In periods of sea level rise, landward migration of the shoreline occurs. Erosion and inundation of coastal property are inevitable in this landward migration. In North Carolina, the statewide average of relative sea level rise is 2.88 mm/yr and is likely to increase due to the effects of global warming (Zervas 2004). Faced with the potential to lose their valuable coastal property, significant shoreline alterations are being undertaken by property owners.

Tourism in North Carolina is based largely on the availability of coastal vacation spots, but not simply for the ocean and the beautiful view. The commercial and recreational fisheries along the Carolina coast are a significant revenue source for local economies. The decline of the North Carolina oyster industry is a prime example of how vulnerable estuarine fauna can be to ecological disruption. If development continues along North Carolina's estuarine shorelines, the coastal ecosystem will look vastly different 100 years from now. Not only does sea level rise have an immediate negative impact on coastal property values due to the risk associated with building so close to rising waters, shoreline hardening could potentially alter the coastline so as to make waterfront properties much less attractive to buyers. Unproductive fisheries, eroding shorelines, rising waters, and disappearing marshes could all serve to severely inhibit coastal real estate, thereby eliminating millions of revenue dollars from the coastal North Carolina economy every year.

Shoreline stabilization is the modification of natural shoreline in order to reduce erosion of land and protect the owner's property. Marsh rehabilitation, oyster reef restoration, biologs, and beach fill are considered to be “soft” stabilization methods, whereas sills, groins, breakwaters, revetments, riprap, seawalls, and bulkheads are forms of “hard” shoreline stabilization (Figure I-1). These forms differ in their cost, effectiveness, and environmental impact, and it is likely that they will be utilized more frequently as people continue to move to the coast.

Soft shoreline stabilization methods, termed “living shorelines,” are recommended as more environmentally friendly than hardening structures. Biologs are coils of biodegradable fibrous material. Marsh rehabilitation and oyster reef restoration involve the planting or replanting of marsh grass and establishment of oyster reefs along shorelines, respectively. These methods act as a buffer to dissipate wave energy and prevent erosion. Beach fill, the adding of sand to an eroded beach, is another soft stabilization technique, and it can be maintained indefinitely by adding amounts of sediment equal to the amount lost by erosion. While the reduced cost, habitat value, and lack of required permits make “living shorelines” a favorable alternative to hardened shorelines, private property owners have not yet embraced these techniques on a wide scale (Berman et al. 2005; NCDCM 2006).

Hard shoreline stabilization techniques, termed shoreline hardening structures (SHS), are an increasingly popular erosion prevention method among landowners. Breakwaters and sills are submerged structures that parallel the shoreline. Groins are barriers that project into the water, perpendicular to the shoreline. Revetments are stone or concrete blocks installed on existing shoreline to absorb wave energy. Bulkheads and seawalls are vertical walls that protect the shoreline (NCDCM 2006; Dean and Dalrymple 2004).

Biologs

Marsh Restoration

Oyster Reef Restoration

Beach Fill

Rock Sills

Riprap

Bulkhead Revetment Breakwater

Figure I-1: Various Shoreline Stabilization Methods[1]

The shoreline, defined as the mean high tide watermark, is the legal boundary between private and public lands. However, temporal variations of both the beach profile and the sea level blur the line between public intertidal lands and private coastland. Consequently, SHS are often installed in areas where no significant erosion is taking place, but rather are being used as a means of delineation or even extension of individuals' private property. Lax permitting regulations and enforcement have allowed some individuals to claim public land as their own by building bulkheads that extend out from the shoreline into public trust waters.

Increases in bulkhead permits seem to correlate with times of economic prosperity and periods after large storm events. North Carolina's Department of Coastal Management issued permits to install bulkheads on 11.7% of the state's estimated 3,900 miles of estuarine shoreline between 1984 and 2000 (Figure I-2). Permitted bulkheads are not necessarily built, and until 2001 permits were not required to build a bulkhead less than 500 ft. long. Therefore, the actual amount of bulkheaded shoreline could be more or less than estimated (Street et al. 2005).

[1] **Sources:**
www.pcei.org/water/project.htm?ID=0042
http://www.nmfs.noaa.gov/habitat/restoration/projects_programs/research/funded_projects/5.html
http://www.nmfs.noaa.gov/habitat/restoration/whatsnew/articles/crp_04projects.html
http://www.iadc-dredging.com/types1.html
http://coastalmanagement.noaa.gov/initiatives/definitions.html
http://www.norfolk.gov/utilities/resources/ShorelineProtection.asp
http://drake.marin.k12.ca.us/stuwork/rockwater/Beach%20Erosion%20-%20Water%20Project/Solutions.html

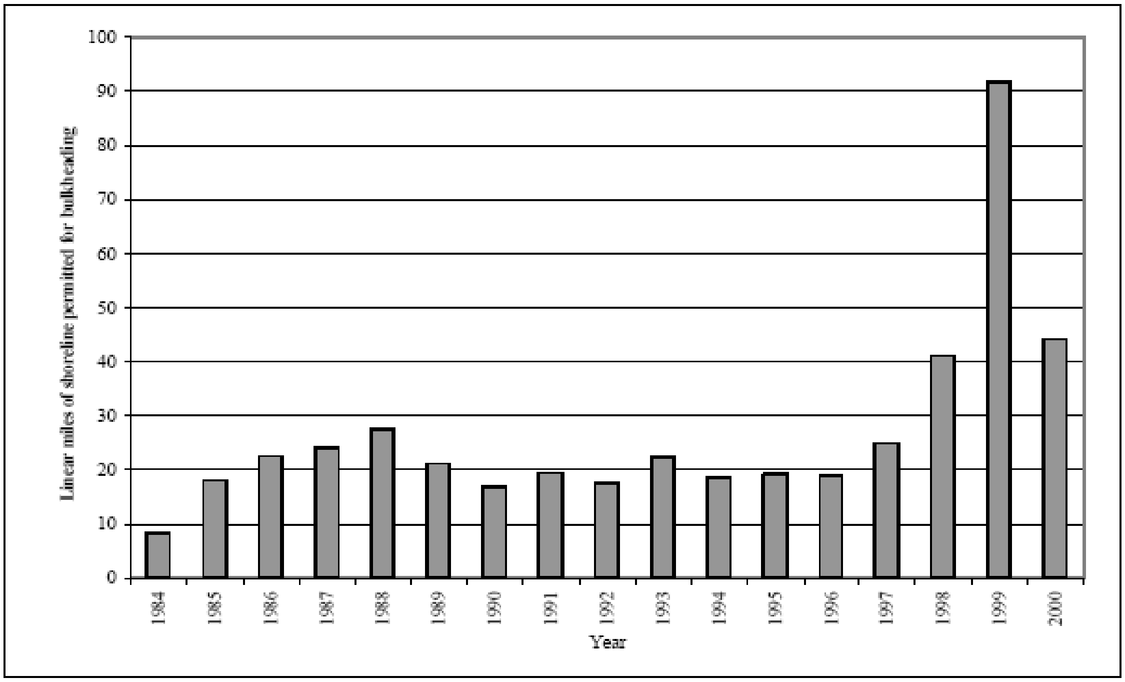

Figure I-2: Linear miles of bulkheading authorized by Division of Coastal Management permits annually, 1986-2000.
(DCM, unpub.)[2]

Increased population pressure and rising sea levels in coastal areas will almost certainly lead to an increased use of SHS. Coastal states must devise management plans that strike a balance between protection of property and maintaining the natural integrity of public waters. In order for policymakers to effectively manage the public trust and make informed decisions on which types of structures to allow in certain areas, they must first be aware of the potential physical and biological impacts SHS may have on the estuarine ecosystem.

[2] http://www.ncfisheries.net/habitat/chppdocs/F_Wetlands.pdf

Structural Design

There are many types of SHS, ranging from off-shore breakwaters to groins situated perpendicular to the shoreline. Based on their design these structures affect the physical environment differently; therefore, an understanding of their design is needed. A breakwater is built offshore in hopes of preventing erosion by dissipating wave energy before it reaches the shoreline. Breakwaters are sometimes designed as submerged structures. Figure I-3 shows a series of breakwaters which are composed of waste materials, including rock and broken concrete.


Figure I-3: A series of breakwaters

A revetment is a type of a SHS that armors the slope face of the shoreline. Its primary purpose is to reinforce part of the beach profile in an attempt to protect it from erosion. A revetment is typically constructed with one or more layers of rip-rap, as well as waste materials, such as car bodies, building materials, and broken asphalt (Figure I-4). A revetment is often installed as a hurried attempt to save the shoreline, and results in accelerating erosion instead of retarding it.


Figure I-4: Stone revetment on the Potomac River, VA

Groins, along with breakwaters and revetments, protect oceanic shorelines. A groin is designed to protect the shoreline against erosion from longshore currents. It is positioned perpendicular to the threatened shoreline. Groins are designed to either be curved, fish tailed, straight, or have a T-head at the seaward end (Figure I-5). A groin is composed of rubble or sheet-piles, and is often constructed as a series, due to the accretion of sediment on the updrift side of the groin and erosion on the downdrift side, resulting in a saw-toothed shaped shoreline, as shown in figure I-6.

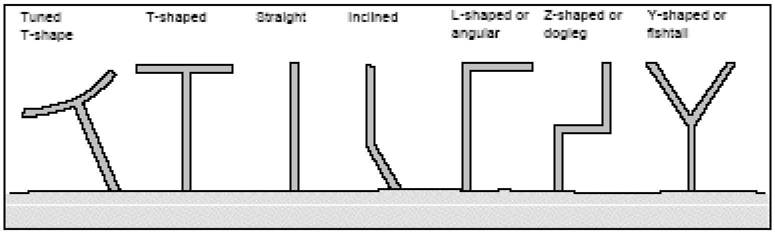

Figure I-5: Structural types of a groin

Figure I-6: Shoreline along the Rappahannock River, Virginia as a result of groin construction

Sills (Figure I-7), designed to protect a vulnerable salt marsh against shore erosion, are constructed with stone or treated wood. A sill is built parallel to the shore, and has a relatively short height when compared to other SHS. The height of this structure reduces wave action by forcing waves to break before entering the marsh (NRC 2006). Sills are constructed as a series, so that marine fauna can still enter and leave the marsh, but also so that sediment is restricted from the marsh.


Figure I-7: A stone sill found along St. Mary's River, MD.

Bulkheads and seawalls are built parallel to the shore to reinforce the shoreline as well as the soil bank. A bulkhead prevents erosion of the land adjacent to a body of water by resisting wave attack. Wave overtopping, as a result of a storm, leads to water retention behind the bulkhead because water is prevented from retreating back off the land. A seawall, similar to a bulkhead, is used in areas of high wave action. Seawalls are typically used on open ocean water, while bulkheads can be found in estuarine or closed waters. Both bulkheads and seawalls can be composed of wood, concrete, steel, or piles of stone. Figure I-8 is an example of a wooden bulkhead, the type most commonly found in the sounds and bays of North Carolina, South Carolina, and Georgia (NRC 2006). This study will focus on bulkheads, which are the most common shoreline hardening structure used in North Carolina estuaries.


Figure I-8: Wooden Bulkhead as used in NC Sounds

A bulkhead can be built vertical, curved, or sloped. The structure of a vertical bulkhead, the simplest design, can be made up of massive gravity concrete walls, tied walls using steel or concrete piling, or stone-filled cribwork. It can also be sloped, reinforced with concrete slabs, concrete armor units, or stone rubble (Army Corps 2002).

Physical Effects

All SHS are installed to prevent a particular dynamic of erosion and sediment transport. Most have been constructed with the assumption that sediment retention is the immediate result of their utilization, but research has shown that many structures simply redistribute physical stresses from private property into public waters. Because design and function are so dramatically different for all of the structures, it is important to understand the extent to which they affect the physical processes in adjacent soils, neighboring marshes, and estuarine waters.

Wave Energy

Bulkheads dissipate wave energy by causing the waves to break against the wall, as opposed to on the beach. The reflection coefficient, which is the amount of energy reflected back into the ocean, for each design varies. The smaller sloped bulkheads dissipate the most wave energy by forcing the waves to break; therefore, they have a greater wave coefficient (Neelamani and Sandhya 2005). Though sloped bulkheads have been proven to be more efficient than vertical in terms of reducing sediment erosion at the base of the structure, a recent study has shown that a serrated vertical bulkhead is up to 40% better than a just vertical (Neelamani and Sandhya 2005). A serrated bulkhead of any angle reduces wave reflection, run-up and run-down, as well as wave pressures by forcing the waves to break by spilling.

Hydrologic Functions

SHS can change distribution and circulation of water along the estuarine shoreline. Surface water storage is the capacity for the sediment to hold water above the surface. For example, bulkhead reduces water storage capacity by creating an impermeable surface that prevents water exchange. Without this water exchange, erosion, accretion, biogeochemical cycling, and aquatic habitats are negatively impacted (Brinson et al. 1995).

Another important component of estuaries influenced by the installation of a SHS is groundwater storage capacity, which is the ability of the shoreline to hold water in the pores of the sediment. This water helps to replenish the water table. Groundwater storage also influences the biogeochemical processes in the soil, which helps to establish and maintain benthic communities (Brinson et al. 1995). Sediment suspension caused by the bulkhead decreases water table capacity. The non-porous bulkhead eliminates the exchange of groundwater between shoreline and the water.

Vegetation along estuarine shorelines acts as a buffer to the land by dissipating wave energy. SHS concentrate the effects immediately on the coastline. SHS, such as bulkheads may increase water turbulence and erosion by reflecting waves. Wave reflection off of bulkheads can lead to scour and deepening of near shore environments (Brinson et al. 1995).

The presence of marsh grasses helps to increase the bed load. By baffling water flow, grasses increase sedimentation of organic and inorganic particles. Vegetation stabilizes the sediment such that these areas are more likely to accrete than to erode. SHS remove vegetation that reduces the baffling flow and increases sheer stress caused by increased water velocities, making the shoreline more susceptible to erosion (Brinson et al. 1995). These hydrologic changes to the shoreline that are caused by SHS alter the chemical and biological environment.

Sediment Erosion

Though bulkheads stabilize landward sediments, they increase erosion at their base and sides. A bulkhead decreases wave dissipation time leading to erosion and sediment scour. As the waves break against the wall, deflection of their energy occurs upward and downward. The downward force results in scouring at the toe of the seawall (Watts 1987). The depth of the scour is proportional to the water depth: for example, a bulkhead in 0.5m of water will deepen the sediment bottom by 0.5m (Army Corps 1977). Standing water in front of the bulkhead increases due to the loss of sediment. Waves double in height when reflected by the bulkhead, exerting force on the toe of the bulkhead scouring out bottom sediments (Figure I-9, NRC 2006). Water movement around the ends of the bulkhead can lead to erosion at the sides and slightly behind the bulkhead (Segar 1998). Wave refraction around the ends of the bulkhead can lead to scouring at the sides of the structure. Said water movement can scour sediments from behind the bulkhead (Figure I-10).

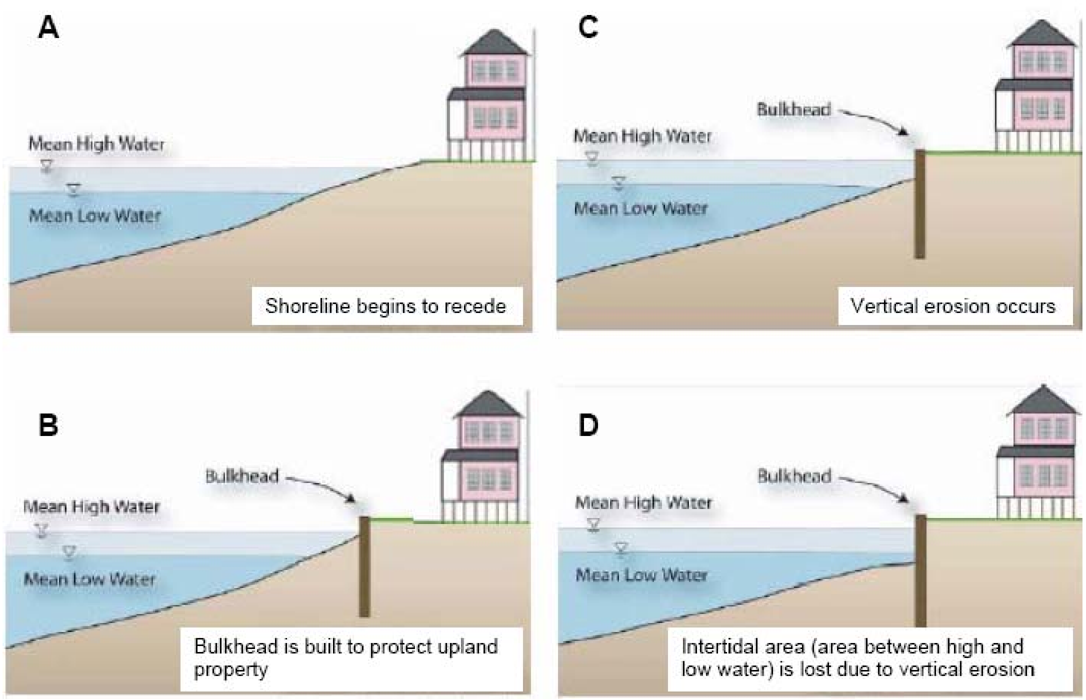

Figure I-9: Depiction of how bulkheads affect the intertidal zone (NRC 2006)

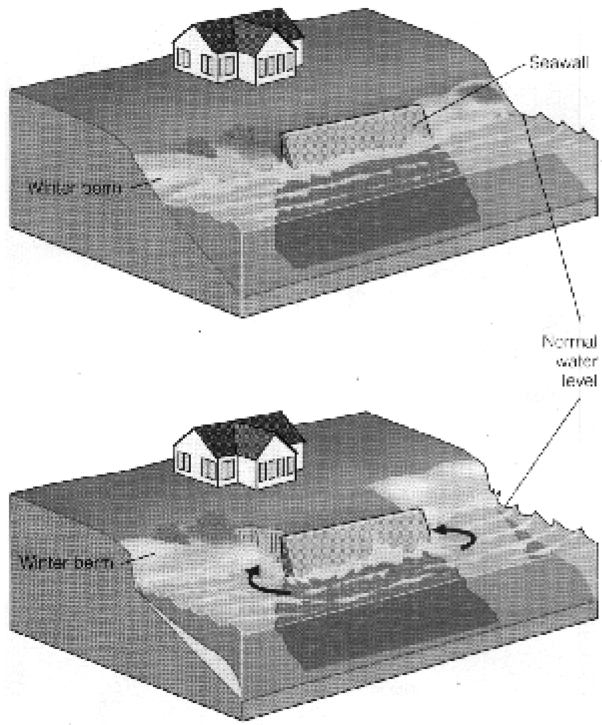

Figure I-10: The flow of water at the sides of the bulkhead can lead to erosion behind the bulkhead as well as sediment scour at the sides.

Erosion and changes in sediment transport are two problems associated with bulkheads, yet most people build a bulkhead to prevent erosion on the landward side of an adjacent marsh. The bulkhead not only affects the erosion on the marsh in front of it, but also on the neighboring marsh by causing changes in the movement of water and sediment. Bulkhead construction usually occurs on an eroding marsh. This type of structure affects the marsh in three ways: permanent removal of sand that nourishes down current beaches, over-steepened shore faces, and reduction or loss of the intertidal zone. Installation of bulkheads interferes with near shore processes such as sediment transportation and wave attenuation. This leads to vertical erosion and loss of intertidal habitat (NRC 2006). Ironically, the volume of erosion on a shoreline bound by a continuous bulkhead has been shown to be the same as for a beach without a bulkhead (Rakha and Kamphuis 1997). However, the majority of the erosion occurs seaward of the bulkhead rather than along the shoreline. Thus, there is no net change in the amount of sediment loss.

Consequences of Bulkheads

The construction of SHS involves many risks, including sediment erosion, toe scouring, and variations in water level. Bulkheads are able to reduce wave reflection given the nature of their design. According to Miles et al. (2001), the reflection coefficient is greater at bulkheads than on the natural beach. However, a greater amount of reflected wave energy from the bulkhead leads to erosion along the beach face. A larger reflection coefficient also means that there is less dissipation and less interaction between the waves and the sediment bottom;

however, this only holds true for bulkheads at greater water depths (Miles et al. 2001). Bulkheads in deeper water maintain a larger reflection coefficient and cause an increase in sediment transport as the waves propagating into the structure mix with reflected waves. The study Miles conducted only concerns wind-generated waves. Waves generated from recreational and commercial boat traffic carry more energy and have a larger impact on erosion (NRC 2006). Although bulkheads may reduce the impact of waves on the land behind it, it has an impact on sediment transportation in front of it. The design of the bulkhead has many implications regarding the effects of waves on the marsh (Neelamani and Sandhya 2001).

Another risk to consider is wave overtopping of bulkheads. Wave overtopping occurs when waves travel over the bulkheads. This often occurs during storm events, or other periods of high wave energy, and results in flooding and erosion. These problems can be avoided by determining the correct bulkhead height needed to prevent wave overtopping. There are many different engineering formulas associated with the determination of appropriate bulkhead height based on water discharge. Besley et al. (1998) conducted a study to test theoretical and empirical models for bulkhead to reduce wave overtopping. He found that the current method may underestimate the height needed for protection. The most extreme cases of wave overtopping at bulkheads can include the destruction of buildings and loss of human life (Allsop et al. 2000). Since there is no sound method of bulkhead design that prevents wave overtopping, it is an important issue to consider when installing a bulkhead. A bulkhead alters the natural slope of the shoreline by replacing a natural shore with a physical structure. This change reduces the buffer zone between property and water making coastal communities more vulnerable to storm events.

Despite a property owner's desire to protect his land from erosion, the cumulative effects of SHS along major portions of the estuary can cause the loss of natural beach, a reduction in sand supply and transport, as well as a deeper near-shore region in front of the bulkhead. Landowners are often only concerned with erosion on their shoreline, ignoring implications for neighboring properties. Bulkheads lead to changes in water flow and sediment dynamics that affect the entire estuary. The construction and implementation of a bulkhead reduces the volume of sand that is available for shoreline transport, causing adjacent sites to become starved of sediment (Lee et al. 1998). To remedy this situation, a neighborhood bulkhead effort, involving contractors and government officials who understand the potential cumulative impacts, is critical (NRC 2006).

Biological Effects

The biological impacts associated with SHS range from immediate impacts caused by bulkhead construction, to post-construction changes in biodiversity, community structure, and ecosystem function in tidal marsh and other intertidal habitats adjacent to hardening structures.

The construction process for all SHS causes some degree of immediate, short-term ecosystem disturbance. Hard-bottom structures, such as rock jetties, groins, and revetments, initially eliminate benthic and infaunal organisms at the construction site. The intrusion of heavy equipment may also elicit behavioral responses from mobile marine organisms and nesting seabirds that cause them to relocate (Feist et al. 1996; Mulvihill et al. 1980). Over the long-term, SHS perpendicular to the shore may indirectly alter neighboring soft-bottom benthic communities by modifying the transport of sediment and organic matter by longshore currents. In addition, maintenance of jetties may involve repeated dredging and therefore continual disturbance of benthic and infaunal communities (Williams and Thom 2001).

The construction of SHS parallel to the shore, such as bulkheads or rip-rap, is likely to cause direct physical damage to fringing salt marsh vegetation which often characterizes the estuarine water line. If this removed native vegetation, which includes marsh grasses *Spartina spp.* and *Juncus roemerianus*, is replaced by non-native lawn grasses, the biological functions of the marsh, including erosion control and filtering of stormwater by nutrient transformation, may be diminished (Street et al. 2005; Watts 1987). Furthermore, the vegetation in the upper marsh, or land-sea transition zone, is more likely to be destroyed by the construction process. This upper marsh vegetation is typically more diverse than that found in the lower marsh, possibly because the milder environment allows a greater range of species to survive here.

A study in the Great Bay Estuary, New Hampshire of five paired salt marsh sites, each with a bulkhead adjacent to natural shoreline, found complete loss of the transition community in bulkheaded sites. The result of this loss is decreased biodiversity in marshes adjacent to bulkheads, with potential implications for productivity and the community structure supported by the habitat. The between-site variation in plant species composition was higher for the transition zone compared to lower marsh (Bozek and Burdick 2005). In addition to vegetation loss, the disturbance of soil along the shoreline during construction can cause increased sediment loads to enter the water, resulting in higher turbidity in the water column that may reduce primary productivity by light attenuation, interfere with visual feeding by fish, and smother benthic organisms (Watts 1987).

There is evidence that the ecological consequences of bulkhead construction for the salt marsh in front of these structures are not limited to initial construction-related disturbances, but persist as a result of the physical presence of the bulkhead. Whereas fringing salt marsh would normally migrate further upshore to avoid being permanently submerged by rising sea level, the presence of a bulkhead prevents this from occurring, potentially resulting in a reduction in total marsh area over time (Titus 1988). Any marsh that might have existed prior to bulkhead construction will be permanently flooded, leading to an increase in turbulence and scouring which prevents vegetated communities from re-establishing (Watts 1987). In 1973, Garbisch et al. found that *Spartina* seeds planted in front of a bulkhead experienced 63% mortality after 2.5 months while the seeds along the natural shoreline had a mortality rate of 12%. This likely resulted from the increase in erosion or re-suspension of sediment caused by the bulkhead.

There is additional evidence that the placement of the bulkhead can influence the magnitude of biological impacts. A field survey of Raritan Bay, New Jersey found lower meiofaunal abundance and increased eroded sediment in estuarine sandy beach foreshore associated with bulkheads constructed lower on the intertidal profile, while the sites with a bulkhead built high on the profile had meifoaunal abundances comparable to sites with no bulkhead present (Spalding and Jackson 2001).

As previously mentioned, scouring at the base of the bulkhead can result in long-term increases in mean suspended sediment in the water column, causing chronic increases in turbidity (Miles et al. 2001). Impacts on marsh vegetation from sediment removal may include decreased growth from the removal of nutrients, burial by erosion, destabilization, or complete removal of plants (Kennedy and Bruno 2000). The species composition and ecosystem function of marsh vegetation can also be altered if tidal influences are reduced as a result of SHS. For instance, as marsh salinity decreases, it provides more favorable habitat for the invasive marsh grass *Phragmites,* which may out-compete native species (NRC 2006).

Estuarine salt marsh provides habitat for a number of resident finfish, shellfish, and crustaceans. Transient nekton also use the marsh edges for seasonal spawning and nursery grounds. Among these organisms are economically important fisheries species such as spot, croaker, red drum, and penaid shrimp (Street et al. 2005). Some studies have indicated decreased nekton abundances and lower diversity of taxa found in salt marshes in front of bulkheads. For example, in *Juncus/Spartina* marshes along the Gulf Coast, bulkhead presence corresponded with lower abundances of both demersal resident species and transient species, as well as lower overall species diversity (Peterson et al. 2000). Hendon et. al (2000) found significantly fewer larval naked gobies, a common benthic fish, in bulkheaded marshes compared to natural marsh. These studies suggest that the value of salt marsh as a nursery habitat may be reduced by the presence of a bulkhead.

However, some researchers argue that bulkheads offer a unique habitat for colonization. Studies have shown that algae and invertebrates settle on the artificial structures, though the recruitment and settlement rates may differ from natural assemblages (Bulleri 2005). Bulkheads also appear to supply suitable habitat for mollusks, although the lack of spatial heterogeneity may exclude rare taxa (Chapman 2006). As mentioned above, mobile species appear to be less common in bulkheaded areas than natural areas (Chapman 2003). Chapman asserts that the potential value of bulkheads as viable habitats will be dependent on their ability to support a full range of species, including rare taxa (2003). No conclusive evidence exists that the artificial bulkhead environment can successfully mirror, or take the place of, the natural habitat that would exist without the bulkhead.

Other SHS, particularly those that are not vertical, may provide habitat for a greater variety of species, including mobile organisms. Rubble structures, such as jetties and groins, provide hard substrate for colonization by macroalgae and sessile invertebrates such as oysters, barnacles, and mussels. Macroalgae and the epiphytic algal species they host provide food for fish, small crustaceans, and other benthic grazers. The most abundant resident fish documented at jetties in the South Atlantic Bight, are pinfish, spottail pinfish, black sea bass, and pigfish, as well as blennies and gobies. These smaller fish in turn attract larger piscivorous fish species and transient fish that migrate seasonally (Hay and Sutherland 1988). Jetties often extend from the intertidal into the subtidal zone, which accounts for their ability to support higher trophic levels compared to vertical shoreline structures (Williams and Thom 2001). In general, greater structural complexity accommodates a higher diversity of species due to the presence of additional microhabitats, such as protective crevices and gaps.

Rip-rap, like jetties and groins, supports more diverse communities than its vertical counterparts. A comparison between natural marsh and marsh in front of rip-rap and bulkheads in two tributaries of the Chesapeake Bay found higher bivalve densities and benthic species diversity in natural marsh; however, in the more pristine system, overall benthic diversity and abundance in marsh adjacent to rip-rap more closely paralleled those of the natural marsh. This suggests that adjacent marsh may be less affected by rip-rap when a smaller percentage of the total shoreline is developed (Seitz et al. 2005). While species richness is typically greater in natural shoreline compared to hardened sites, rip-rap in San Diego Bay provides a unique habitat, supporting species that thrive in an environment with less wave energy and higher turbidity. This SHS also supports open-coast species that favor hard-bottom substrate. Organisms that colonize the rock surfaces can also provide food for highly motile fish at high tide, and foraging shorebirds at low tide (Davis et al. 2002).

All of the previously cited impacts of SHS on biodiversity, recruitment, and community structure in intertidal environments have implications for the overall productivity of these habitats. Detrital material is a major component of most aquatic food webs and influences secondary production. When marsh vegetation is destroyed it reduces organic matter as well as production and export of detritus, leading to a decrease in productivity of the shoreline. The amplification of waves and currents caused by SHS removes detritus, further decreasing productivity (Brinson et. al 1995). Retention of nutrients and benthic primary productivity are reduced as a result of higher energy shorelines. Loss of vegetated habitat will affect nutrient exchange at the sediment-water interface.

Policy Implications

Since the passage of the Rivers and Harbors Act in 1899, the US Army Corps of Engineers has maintained jurisdiction over all permitting for coastal projects which may affect the navigability of public waters. General permits, which landowners need not apply for, are granted for activities that the Corps has deemed acceptable and even beneficial on a nationwide scale. These permits require no review process or approval by the USACE and include actions such as the restoration of degraded wetland areas. However, one such general permit includes permission to construct shoreline protection structures shorter than 500 feet in order to prevent erosion losses. This general permit enabled anyone to construct a small bulkhead in any location they deemed appropriate. In contrast, individual permits are required for any activity that involves sills or breakwaters since the proposed structures would be located offshore, within navigable waters (NRC 2006). Since United States public waters are so tightly regulated, this has led many landowners to avoid the expensive and time-consuming individual permitting processes with a stronger inclination toward bulkheads landward of the mean high tide line. Therefore, the general permit process has effectively created an incentive for landowners to only concern themselves with terrestrial sediment protection and abandon the protection of eroding marshes.

In 1972, the United States Government adopted the Federal Coastal Zone Management Act (CZMA). This required state governments to designate specific boundaries for their coastal zones, and to identify a host of natural features with particular environmental and ecological significance. The Coastal Area Management Act (CAMA) was passed by North Carolina legislators two years later in response to CZMA requirements (Finnell 1978). In an effort to standardize an inefficient system and adopt restrictive policies that involved general permits issued by the USACE, this legislation outlined the specific roles of local and state governments in coastal area development. The Coastal Resources Commission (CRC), under the jurisdiction of the North Carolina Division of Coastal Management (DCM) and the North Carolina Department of Environment and Natural Resources, is responsible for the scrutiny and approval of all permits for bulkhead construction in the coastal region (DCM 2003).

According to state law, local residents must apply to the CRC in order to build a shoreline stabilization structure. Under the permit process outlined by CAMA, permission to develop infrastructure in coastal areas is refused where proposed constructions would negatively impact the productivity of nearby land and water resources (DCM 2003). Current CRC policies prohibit the construction of a hard SHS within or immediately seaward of wetland habitats (Street et al. 2005). Additionally, they prohibit the infilling of any wetlands that may occur on the landward side of said SHS. Much like the general permits issued by the USACE, the CRC has issued a general permit allowing the enhancement of marshes via sill construction rather than bulkhead construction. However, that permit's greatest obstacle exists in the stipulation that it cannot be utilized if there are "unresolved questions concerning the proposed activity's impact on adjoining properties or on water quality, air quality, coastal wetlands; cultural or historic sites; wildlife; fisheries resources; or public trust rights" (DCM 2003). CAMA is explicit in their recommendation to avoid bulkhead construction in situations where soft shoreline stabilization structures are appropriate. However, soft shoreline stabilization methods have never matched the prevalence of bulkheads and other SHS. Current policy changes are being formulated that will only allow the construction of a bulkhead in an area where erosion has been documented (Street et al. 2005).

This effort presents an interesting paradox, however, since bulkheads have been widely used for many years. Currently, the Coastal Resources Commission approves permits for about 30 miles of bulkhead per year (Skrabal, unpublished). As previously mentioned, a bulkhead on a property owner's shoreline increases erosion on nearby natural shorelines. These situations, since erosion has already become a problem due to neighboring bulkheads, justify a CAMA permit for bulkhead construction. As a result of new policies, current bulkhead extent increases the need for bulkheads on adjacent properties. As more and more of these structures are installed, a vicious cycle is created where entire lengths of shoreline must be armored.

An important obstacle has hindered most shoreline hardening legislation from becoming proactive as opposed to reactive. Coastal development policies are designed to compensate for preexisting threats to the coastline (Holway and Burby 1993). It has also been suggested that increased shoreline hardening can provide landowners with an incentive to amplify development efforts (Burby et al. 2000). Current policies do not adequately limit development in areas susceptible to erosion as a proactive solution (Holway and Burby 1993).

One method of developing a proactive solution would involve setback lines, seaward of which no construction is allowed to take place. These setback lines could be identified in areas that are particularly sensitive to erosional or even sea level rise pressures. Appropriate local zoning regulations, also effective at preventing erosion problems, often include setback lines. They can help create buffer zones by relocating preexisting infrastructure and acquiring waterfront properties in order to preserve them as public conservation areas. Local governments, with uniquely effective oversight for their municipal areas, are powerful tools that can help build small-scale coalitions based on the most up-to-date and comprehensive information (NRC 2006). Their close contact with local developers and landowners allows them to adopt the most specifically appropriate measures to ensure erosion protection and ecosystem vitality.

Originally, the private encroachment on public trust areas was the main issue of concern in the shoreline hardening debate. Overall, what mattered to policymakers was whether or not shoreline alterations would affect areas over which the federal government maintained jurisdiction. The very nature of the effects private actions may have on public goods has changed; what was once considered an effect on navigability can now be considered an effect on biological productivity. The "takings clause" of the US Constitution claims that no amount of private property can be stripped by the government without just compensation to the original owner. Said clause has been redefined so as to account for any negative consequences certain private actions may have on the public good (Finnell 1978). Navigable waters have come to include all wetland areas below mean high tide line. This gives the federal government control over the important biological communities that are not directly valuable for the transport of material on ships, but which are inevitably valuable as resources that promote the ecological health of coastal waterbodies (Finnell 1978). Changes have also occurred in the problem's perception by landowners, interest groups, and local decision-makers. Jurisdictional alterations have evolved to include concerns about wetland loss, fisheries, tourism, property values, and relative sea level rise.

Under most current legislation, policies are reactive, but efforts are being made to develop proactive policies for the protection of our coastal ecosystems. The North Carolina Division of Coastal Management's Estuarine Shoreline Subcommittee, established in 2000 under CAMA, has identified erosion management goals. Specifically, they urge land-use planning, with an emphasis on maintaining natural shorelines. The recommendations encourage new wetland plantings, preservation of preexisting wetland areas, and utilization of beach fill as an alternative to shoreline hardening techniques. They have emphasized, however, that beach fill should only take place in a manner that preserves the natural state of the shoreline. Since SHS are often preferred by local residents, the subcommittee has explicitly recommended sills over other hard shoreline stabilization techniques like rock jetties or bulkheads.

Government and non-government organizations currently encourage the use of soft stabilization methods in low energy estuarine environments. Preferred nonstructural practices center around constructed wetlands, many times in conjunction with rip-rap or sills that assist fragile wetlands in sediment accretion (NCCF). The combination of erosion control strategies and wetland restoration could prove invaluable in protecting both our eroding shorelines and the fragile estuarine ecosystem. By maintaining a significant marsh buffer on a large percent of the waterfront properties in our coastal counties, local residents could alleviate much of the stress from both erosion and stormwater runoff. Many times coastal areas are struggling to adequately deal with stormwater runoff that increases with more impervious surfaces. This leads to results in rapid pulses of water movement through the estuarine system, creating sheer stress along shorelines that amplifies erosion potential (Street et al. 2005). More effective policies could be developed if state stormwater rules were developed simultaneously with shoreline hardening and erosion prevention policies. If landowners are given a clear picture of the importance of marshes in their stormwater buffering capacity as well as erosion protection potential, they would be more apt to favor integrated legislation. Said legislation could help combat what seems to be the positive feedback loop between stormwater runoff, coastal erosion, shoreline hardening, wetland disappearance, and estuarine ecosystem disturbance.

Science in Action

It has been speculated that bulkheads are detrimental to marsh health. However, many unanswered questions remain as to the exact to which bulkheads alter marsh habitats. Many factors influence salt marsh habitats, leading to difficulty in methodologically determining marsh health. Physical factors such as the effects of winds, sedimentation, tides and wave refraction are difficult to quantify. In addition, measuring marsh health using chemical parameters, such as differences between sediment and water column nutrient concentration could give a different indication of health than if examined using biological parameters such as stem counts, chlorophyll *a* (chl *a*) concentrations, or organism densities. A thorough examination would incorporate multiple factors that influence marsh health using an assortment of measurement techniques. Unfortunately, such a comprehensive study has not been conducted. Our short study attempted to quantify the biological health of the marsh using metrics such as stem counts, stem heights, chl *a*, and concentrations of organic matter in marsh sediment cores. Our study also includes suggestions for future research to better improve our understanding of the ramifications of armoring a shoreline.

II. The Effects of Bulkheads on Salt Marsh Habitats

Introduction

Salt marshes are critical components of the coastal ecosystem and are widely acknowledged as vulnerable to human influence. Shoreline modifications such as bulkheads may alter the natural erosional and depositional processes that help marshes survive and flourish. Located in the transition zone between marine and terrestrial environments, these areas perform a variety of important functions. Salt marshes provide valuable nursery habitat for a wide range of organisms, including many commercially important fisheries species (Street et al. 2005). Salt marshes act as a buffer for stormwater runoff, thereby reducing the amount of sediments, pollutants, and pathogens introduced into estuarine environments (Mallin 2000). In addition, salt marsh vegetation stabilizes the sediments, encouraging accretion rather than erosion (Brinson et al. 1995).

Rising sea level, storm events, and boat wake all contribute to erosion of coastal and estuarine property. Landowners have attempted to halt this process by installing bulkheads, a common shoreline stabilization method. Estuarine bulkheads are walls built along the shoreline designed to protect and retain sediments above the mean high tide line. Bulkheads shield the shoreline from wave energy by providing a hard surface upon which waves can break. However, they cause wave energy to be redistributed away from the protected property to nearby marshes, unprotected shoreline, and other aquatic habitats

North Carolina's coastal region includes approximately 3,900 miles of estuarine shoreline, and between the years of 1984 and 2000, bulkhead permits were issued for an estimated 11.7% of these shorelines. However, there is no way of knowing how many of these permitted projects were actually completed. Until 2001, bulkheads less than 500 feet in length required no permit or application process. Therefore, the amount of shoreline that has been bulkheaded could be significantly more or less than previously estimated (Street et al. 2005). As development increases, it can be expected that more shoreline hardening structures (SHS) will be utilized in order to protect eroding coastlines (Bozek and Burdick 2005).

Consequently, it is important that we develop a thorough understanding of the impacts of structures, such as bulkheads, on shoreline erosion and the estuarine ecosystems. Many unanswered questions remain as to the influence of bulkheads on salt marsh health. Relatively few studies have examined the effects of bulkheads on the physical and biological processes occurring in salt marshes.

Theoretically, a bulkhead dissipates wave energy by forcing the waves to break against the wall, but studies have shown that the displaced energy may increase scour and erosion at the toe of the wall and around the edges (Segar 1998). Since bulkheads have low permeability, they can reduce freshwater inputs through groundwater exchange. This assists the invasion of salt-tolerant species of plants, as well as disrupting biogeochemical cycling (Brinson et al. 1995).

These physical changes impact biological processes that allow diverse communities of plants and benthic invertebrates to survive. Scour and erosion can selectively remove fine sediments and nutrients, effectively lowering the growth rates of marsh grasses (Keddy 1985). The increased sediment suspension may inhibit seedling emergence or result in the destabilization, uprooting or burial of vegetation (Kennedy and Bruno 2000). The presence of a bulkhead has been shown to correlate with reductions in fish biodiversity (Peterson et al. 2000; Hendon et al. 2000). In contrast, other studies assert that bulkheads can serve as viable habitats for a range of primarily immobile species (Chapman 2003). These contrary findings indicate the current uncertainty of the degree to which marsh ecosystems are affected by bulkheads and other SHS.

Some believe bulkheads negatively impact marsh health and inhibit natural ecosystem functioning. This study attempted to quantify the ecological condition of marshes seaward of bulkheads relative to natural marshes. Relative condition was determined by comparing *Spartina spp.* stem counts and heights, chlorophyll *a* (chl *a*) concentrations, and sediment organic matter at four selected sites in eastern NC. An observational survey was also conducted to determine the number of bulkheads with marshes in relation to the total number of bulkheads along the shorelines of Bogue Sound, NC.

Methods and Materials

Study Sites

Located south-west of Cape Lookout lighthouse in the Outer Banks barrier islands of North Carolina are several shallow coastal water bodies that can be divided into two sections: the Newport River Estuary and Bogue Sound. The Newport River Estuary is a relatively small estuary of approximately 163 km^2 and a watershed draining area of 595 km^2 (Kirby-Smith and Costlow 1989). This study focuses on Bogue Sound (Figure II-1). Bogue Sound is a brackish lagoon separating Morehead City on the mainland side from the barrier island Bogue Banks, where the towns of Pine Knoll Shores and Atlantic Beach are found. Bogue Sound serves many commercial and residential uses and has salt marsh along its shoreline.

Figure II-1: The Southeast Region of the US showing Bogue Sound, NC (NOAA)

Four study sites were selected in Bogue Sound, three on the northern bank and one on the southern bank. The first study site was located on the north side of Bogue Sound, in Mitchell Village (MV), at $34^0$42N, $76^0$48W. The second site was on the south side of Bogue Sound in the town of Pine Knoll Shores (PKS) at $34^0$43N, $76^0$46W, the third (MC) and the fourth (AB) sites were located on the north side at $34^0$43N, $76^0$49W, and $34^0$43N, $76^0$48W, respectively (Figure II-2).

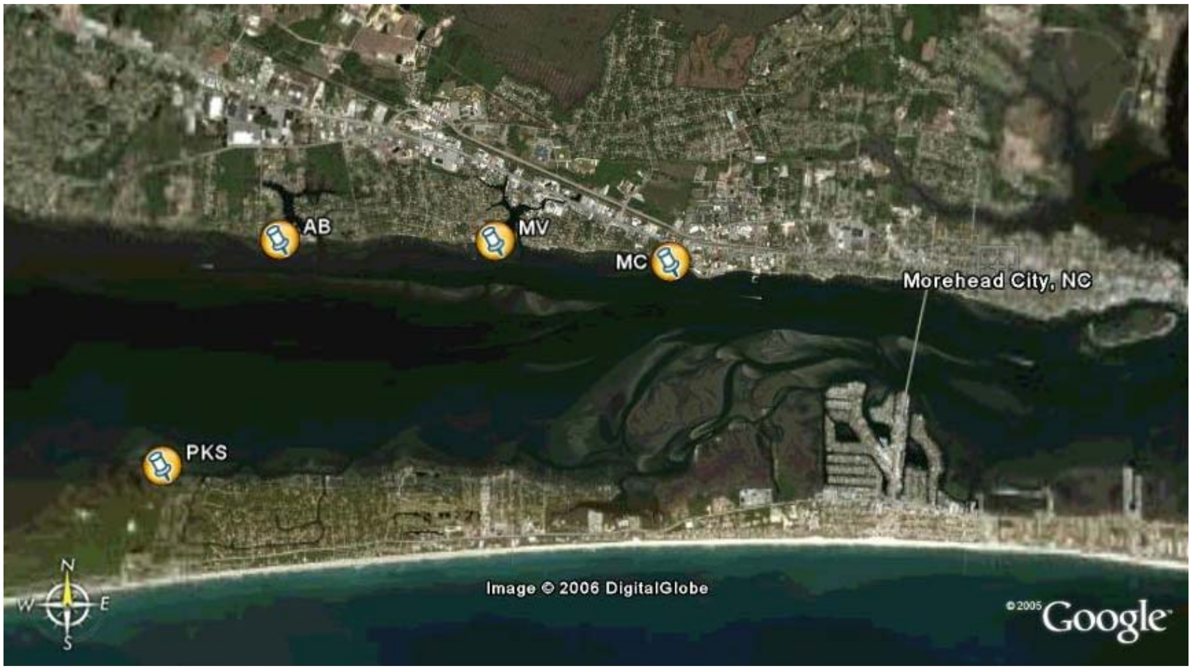

Figure II-2: Location of our four study sites (MV, PKS, MC, and AB) (Google Earth)

Study sites were selected as bulkhead, no-bulkhead pairs (Figure II-3). The study sites were selected based upon the presence of the following criteria: a shoreline that had a section of bulkhead with marsh in front of it, adjacent to a salt marsh with no bulkhead. Therefore, the marsh with no bulkhead served as the healthy marsh control in order to properly assess the bulkhead's effect on marsh health.

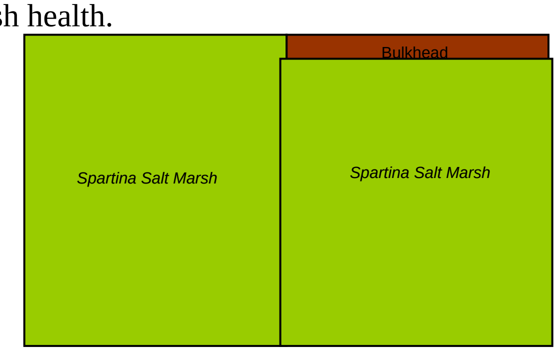

Figure II-3: Schematic diagram of selected sample sites

Boat Survey

In order to determine the number of bulkheads with and without marsh on Bogue Banks, a boat survey was conducted on November 1, 2006, at low tide. Bulkheads adjacent to channels and rivers were not included because they are subjected to different flow regimes.

Field Sampling

During sampling the control (natural marsh) and bulkhead marshes were each divided into three transects, making a total of six vertical transects per site. These transects were further divided horizontally. Samples were taken approximately every 3-5m, depending on the length of the marsh. Sampling only occurred on one side of the transect to minimize disturbance to the marsh and our samples (Figure II-4). Measurements along the transect were taken at the first occurrence of *Spartina spp.*.

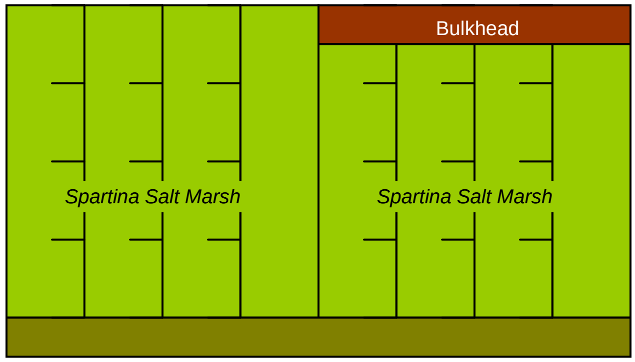

Figure II-4:Schematic diagram showing sample transects

All sampling occurred during low tide. At each of the sample areas, a 0.5m by 0.5m quadrant was sectioned off for assessment of the vegetation. Within this quadrant the following measurements were taken: percent coverage, type of dominant vegetation, *Spartina spp.* stem counts, and average plant height. *Spartina spp.* was counted because it is a dominant salt marsh species and an indicator of ecosystem health (Odum 1988). Sample metrics along each transect were divided in half, with the portion closest to the land designated as landward and the other portion seaward.

Cores for organic matter were taken twice per transect, once at the beginning (landward) and once at the end (seaward). Cores were 4cm long and had a diameter of 2.20cm. These cores were divided into surface (0-2cm) and depth (2-4cm). A subsample was taken to determine organic matter content which was estimated by weight lost on ignition at 525^{o}C (Byers et al. 1978). Sediment sections taken from the sub-samples were dried at 105^{0}C for 3h and weighed (A). The samples were then placed into a terminal muffle oven at 525^{o}C for 3h and weighed again (B). Percent organic matter was calculated using Equation 1. Percent organic matter is used to determine the organic content of the sediment, an indicator of sediment quality (Schlesinger 1991). A higher percentage of organic matter in the sediment correlates to a greater amount of vegetation

$$Percent\ Organic\ Matter = \left(\frac{A-B}{A}\right) x\, 100\%$$

Equation 1: Equation for the determination of Percent Organic Matter in Sediment

The final parameter used for the determination of marsh health and quality was a measure of chl *a* per square meter, indicating the amount of benthic microalgae, which correlates to the amount of primary production. Benthic microalgae are a food source for many marsh organisms and regulate nutrient exchange within the ecosystem. Two cores, 1.0 cm in length with a diameter of 0.8 cm, were collected for chl *a* beginning at the first quadrant where *Spartina spp.* was present.

Table 1 shows the number of samples taken for each metric.

Table 1: Table indicating the sample size (n) for the field study metrics for each site.

	Organic Matter	Chl *a*	Stem Height	Stem Count
AB	24	41	22	22
MC	24	39	18	18
MV	24	58	30	30
PKS	24	54	26	26

Chl *a* was extracted from the sediment by sonicating the sample over ice in 10mL of 45:45:10 methanol: acetone: water mixture for 30 seconds, and then chilled for twenty four hours to allow for self-extraction. After extraction, 4ml of the sample was filtered through a Whitman CCF glass fiber filter (25mm) and analyzed (Stickland and Parsons 1972). The concentration of chl *a* was determined using a fluorometer (Triology Flourometer, Turner Designs) using chl *a* NA method, measuring raw fluorescence in RFU). For raw fluorescence over 6000 RFU, samples were analyzed in a spectrophotometer for absorbance at wavelengths of 750, 664, 647, and 630 nm (Tri-Chromatic detection using Mini 1240 UV-Vis spectrophotometer (Shimadzu)).

Statistical Analysis

All data collected was analyzed for statistical significance. SigmaStat (SPSS 2003) software was used to perform ANOVA relationships. Kruskal-Wallis One Way Analysis of Variance on Ranks was used to evaluate one-way variance. Student-Newman-Keuls Method was used for pair-wise multiple comparisons, and two-way analysis. For the running of statistical tests, outliers were removed from the dataset (i.e. negative values for organic matter measurements).

Results

Our field study, conducted at four sound-side locations in eastern North Carolina, examined the effects of bulkhead presence on marshes. We studied two different types of environments: marshes in front of bulkheads and natural marshes, defined as those without bulkheads. Marsh health was assessed using the following metrics: percent organic matter in sediment cores, chl *a* concentration, and vegetative characteristics (stem heights and live and dead standing stem counts). For all parameters, we found significant site variability, but overall, bulkhead presence did not have a significant effect. Significance was determined by a confidence interval of 95% ($p<0.050$). A site survey of Bogue Sound revealed the interesting observation that bulkheads with marsh present on the seaward side were more common than bulkheads with no marsh present (Figure II-5).

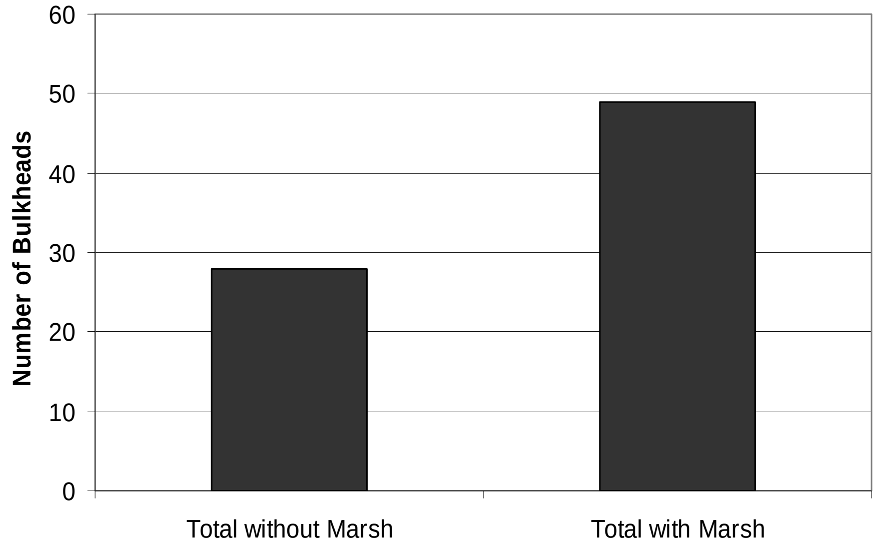

Figure II-5: Numbers of bulkheads on Bogue Sound with and without marsh

Organic Matter

Percent organic matter at the natural and bulkhead marshes was plotted at each site for depth (2-4cm) and surface (0-2cm). The average difference in organic matter between the bulkheaded and natural marshes at each of the four field sites is portrayed in Figure II-6 and II-7 for landward and seaward margins, respectively. Standard error of means was used to determine the error associated with the measurements.

There was no significant relationship between samples from marshes with bulkheads compared to natural marshes ($p=0.110$), and no significant difference between surface and depth samples. There was high site variability ($p=0.039$), and a significant difference between landward and seaward samples across all sites ($p<0.001$). By expanding the confidence interval to 90%, landward organic matter was significantly influenced by the presence of a bulkhead ($p=0.072$).

Samples were divided into two locations based on their location in the marsh: landward and seaward. Samples were also divided based on their core depth, where surface samples represented 0-2cm and depth samples represented 2-4 cm. Landward samples showed no significant bulkhead effect, site effect, or depth effect. Seaward samples also showed no significance with relation to bulkhead presence, site selection, or core depth. Both depth and surface samples showed a significant seaward/ landward dependency, $p=0.001$ and $p=0.007$, respectively. With a 90% confidence interval, the presence of a bulkhead significantly affected the organic matter at depth ($p=0.084$).

Site specific variation was also examined. Organic matter at sites AB and PKS varied significantly with respect to landward and seaward samples ($p=<0.001$ in both cases). This factor was insignificant at sites MC and MV. Neither bulkhead nor depth was significant at any of the four sites. However, the bulkhead had a significant relationship with organic matter at site MC ($p=0.073$), if the definition of significance was expanded to $p<0.10$.

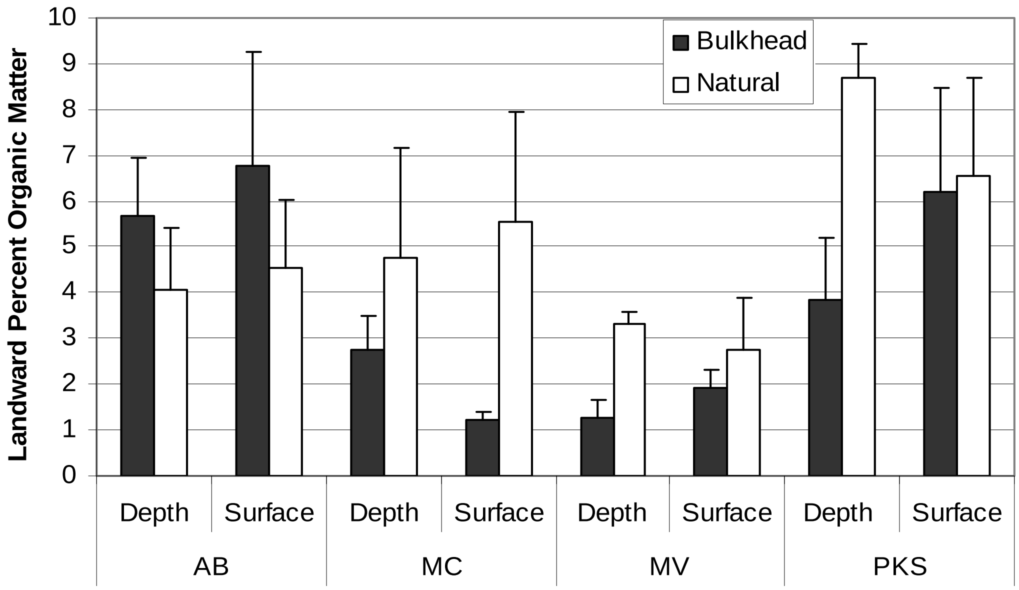

Figure II-6: Average percent organic matter on the landward side of each site from both the cores taken at depth and surface. Sites include: Atlantic Beach (AB), Morehead City (MC), Mitchell Village (MV), and Pine Knoll Shores (PKS). Error indicated as the standard error of means.

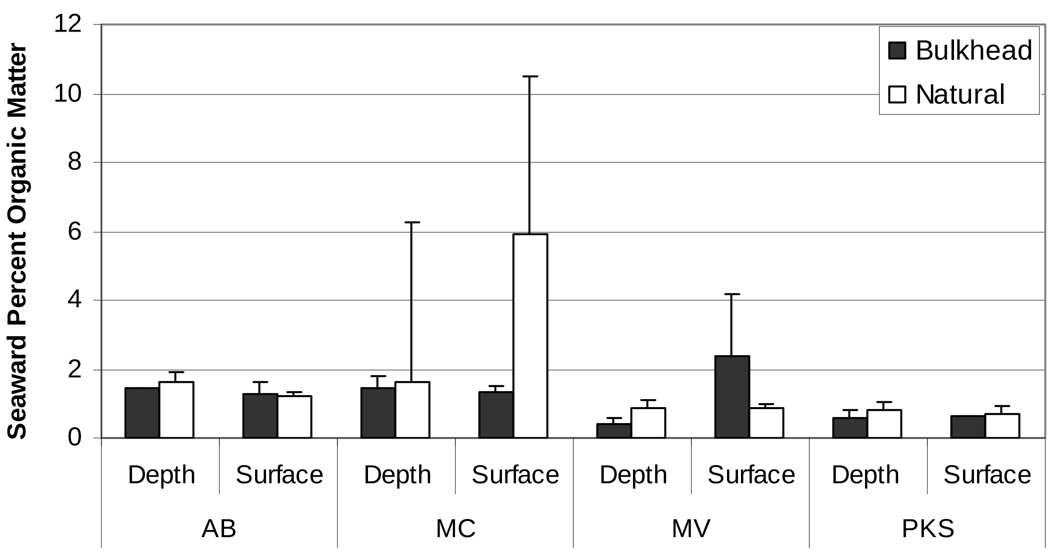

Figure II-7: Average percent organic matter for the seaward side of each site from both the cores taken at depth and surface. Sites include: Atlantic Beach (AB), Morehead City (MC), Mitchell Village (MV), and Pine Knoll Shores (PKS). Error indicated as the standard error of means.

Chlorophyll a

Average chl *a* concentrations (mg/m^2) for landward and seaward locations in the marsh were plotted for marsh with a bulkhead and natural marsh at each site (Figure II-8). Standard error of means was used to determine the error associated with the measurements. In a 2-way ANOVA, there was a significant site effect on chl *a* concentrations ($p<0.001$). However, there was no statistically significant difference in concentrations based on bulkhead presence ($p=0.985$). Location within the marsh also had no significant effect, although the interaction between the site and location within the marsh was significant ($p=0.736$, $p=0.007$, respectively).

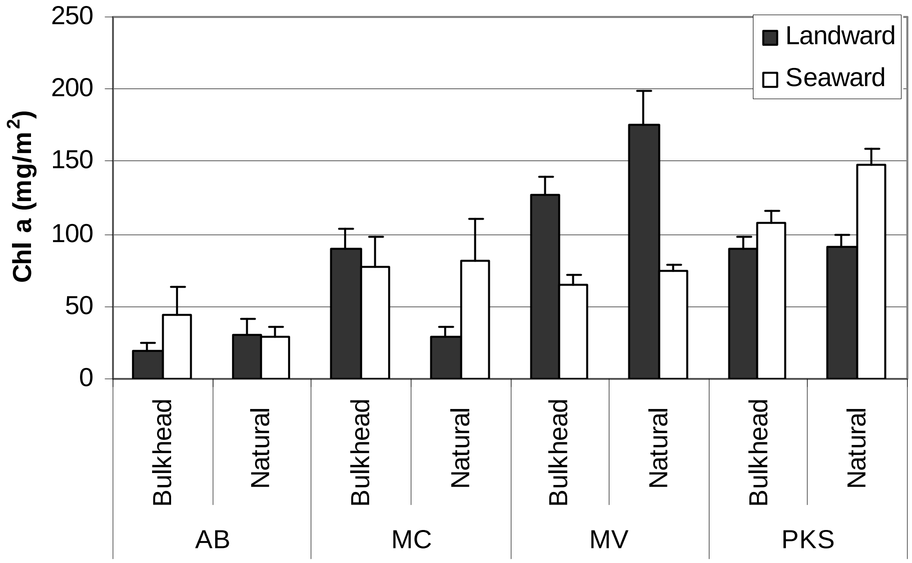

Figure II-8: Average chlorophyll-*a* concentration (mg/m^2) for three transects in marsh with and without bulkhead. Sites include: Atlantic Beach (AB), Morehead City (MC), Mitchell Village (MV), and Pine Knoll Shores (PKS). Error indicated as the standard error of means.

Vegetative Characteristics

Spartina stem height (cm) was averaged for landward and seaward locations in each transect and plotted for each site (Figure II-9). Figure II-10 shows the total average *Spartina* stem density per 0.25m^2, and the proportion of live and dead stems, for transects in natural marsh and marsh in front of a bulkhead at each site. Error associated with these measurements was assessed using standard error of means.

All vegetative characteristics exhibited significant variation by site: average stem height ($p<0.001$), average number of live stems standing per m^2 ($p=0.023$), and average number of dead stems standing per m^2 ($p=0.006$). Neither live nor dead stem counts were significantly impacted by bulkhead presence ($p=0.744$, $p=0.511$), though there was a significant interaction between the site and bulkhead presence ($p=0.014$). The effect of the bulkhead on average vegetation height was not significant by the standard 95% confidence interval used in our analysis, however there was a significant effect at a 90% confidence interval ($p=0.069$).

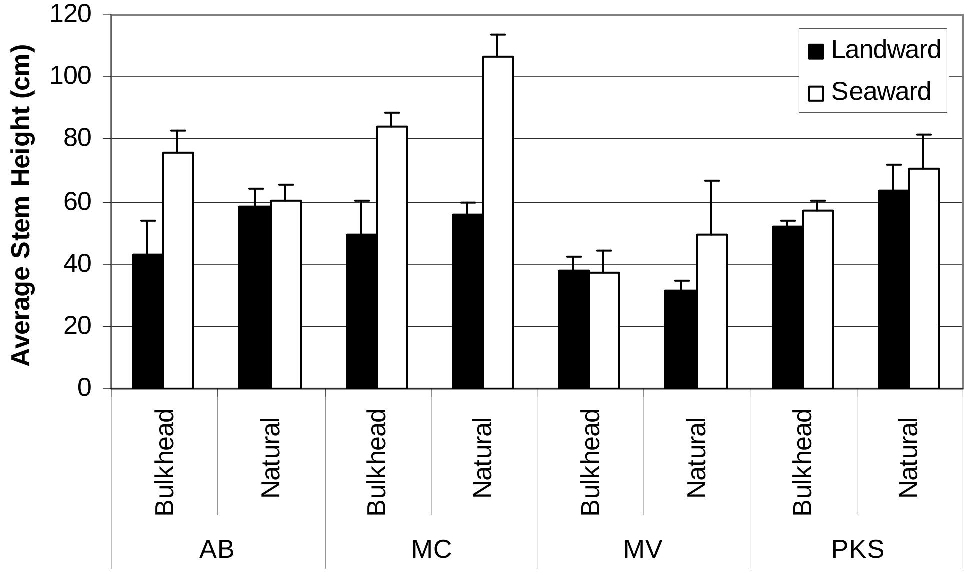

Figure II-9: Average Stem Height (cm) for *Spartina* in 3 transects for marsh with and without bulkhead. Sites include: Atlantic Beach (AB), Morehead City (MC), Mitchell Village (MV), and Pine Knoll Shores (PKS). Error indicated as the standard error of means.

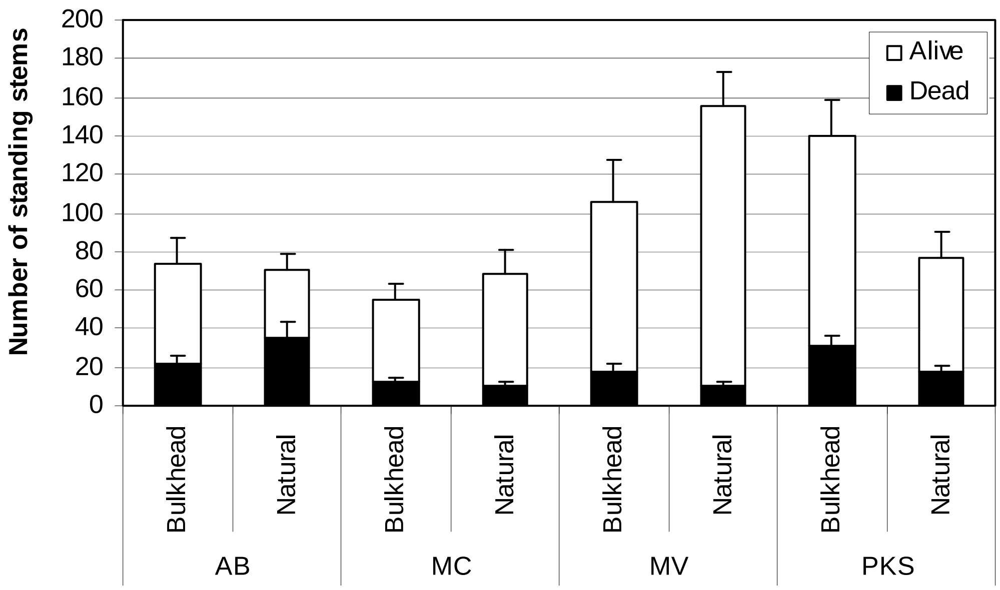

Figure II-10: Average live and dead stem counts per $0.25m^2$ for 3 transects in marsh with and without bulkhead. Each bar represents the total additive live and dead stem counts per m^2. Sites include: Atlantic Beach (AB), Morehead City (MC), Mitchell Village (MV), and Pine Knoll Shores (PKS). Error indicated as the standard error of means.

Discussion

Conventional scientific wisdom has assumed that bulkheads adversely affect coastal productivity and ecosystem health. In highly developed areas, the amount of bulkheaded shoreline present and visible from waterways is often assumed to have replaced what was once salt marsh. Our observational survey concluded that approximately 64% of bulkheads on Bogue Sound support marsh. This suggests limited negative effects of bulkheads on marsh. The exclusion of bulkheaded sites adjacent to creeks and channels provides a reasonable basis for a sound analysis, since the effect of boat wakes on these areas would have been exacerbated. Our survey sites are relatively isolated from such impacts and should be expected to accurately reflect current trends.

Based on analysis of all the metrics that were included in our study, none of the biological parameters were significantly different between bulkheaded and natural marshes at any of our four sample sites. The only statistical difference we found indicated a very high site-to-site variability, suggesting that complex local environmental conditions influence marsh productivity more so than do shoreline alterations. Such an effect was unexpected, given the fact that all sample sites were within several kilometers of each other. Seasonal wind patterns and tides, dramatically influence hydrodynamics along the waterfront edge of marsh areas. A deep boat channel and added boat traffic, approximately 500 meters off the shore, could create a different wave dynamic at our 3 mainland sites as compared to site PKS. The scouring by wave action increases the erosion on the seaward marsh edges. This could serve to flush benthic microalgae, sediment organic matter, and vegetation from the marsh. Three of the sites were on the south-facing shore. These sites may receive more photosynthetically available radiation than the other side. Adjacent to site AB, upland construction may have significantly altered the composition of stormwater runoff that enters the salt marshes in this area. These are just a few of the factors that could have lead to the dramatic local variation seen in our four sites, thereby preventing a sound comparison of the data.

With respect to entire coastal ecosystems, the fact that we found such high site variability within a study area of 13 square kilometers indicates that future studies must utilize locally stratified sampling regimes in order to accurately compare different locations. In order to develop a significant data set, more replicated samples must be collected. Our analysis has shown that site differences must be controlled before definitive conclusions can be drawn. Based on our results, we suspect that at least 10 natural-bulkhead marsh pairs, stratified by local conditions, are needed for a more thorough investigation.

Though none of our metrics were significant within a 95% confidence interval, some data were statistically significant at a 90% confidence level, suggesting important trends that should be considered; with additional sampling these differences would likely become statistically significant. At this expanded interval, site MC measurements indicate lower sediment organic matter content in front of the bulkhead as compared to the natural marsh. In addition, vegetation height measurements at bulkheads are significantly lower across all sites. Thus, there is reason to suspect that vegetation heights may be suppressed due to the presence of a bulkhead. Since bulkheads reflect wave energies, it is possible that these reflected waves are scouring finer sediments. The presence of high organic matter concentrations in landward samples as compared to seaward samples tends to support such a situation. Organic matter concentrations seem to depend on proximity to water, leading us to conclude significant environmental interactions have greater influence on marsh health than does the presence of a shoreline hardening structure.

Chl *a* measurements collected at all four sites, though not statistically significant, fell within the expected range of values for estuarine environments in coastal North Carolina (Mike Piehler: personal communication). This suggests that our values may be representative of real biological trends in bulkheaded marshes, but further replication may reduce variability. Based on our data, there is no definitive effect of bulkhead presence on the biomass of benthic microalgae in these marshes.

Living and dead *Spartina* stem count differences were insignificant between bulkheaded and natural marshes for all sites. When individual sites were isolated, we found significant differences between bulkheaded and control marshes- different sites reacted in different ways to the presence of a bulkhead. Site MV showed a much greater number of living *Spartina* plants in the natural marsh, but the same natural marsh maintained fewer dead stems than its bulkheaded counterpart. At site PKS, the natural marsh supported much fewer living and dead stems. Sites MC and AB showed no differences. Even if a discernible pattern had emerged, conclusions about relative marsh health would be difficult to ascertain from alive-dead ratios as indicators. It is usually assumed that a larger proportion of living plants correlates with a higher degree of marsh health. However, standing dead stems contribute to primary productivity, and the overall health of a salt marsh ecosystem (Currin et al. 2006). By serving as important structure for benthic microalgae, these stems provide a great deal of surface area for trophic energy transfer and nutrient cycling. Moreover, the increased structural complexity provided by standing dead stems can serve to increase current baffling throughout the marsh. This hinders sediment scouring by waves, and allows for the deposition of sediments. Standing dead stems facilitate accretion of the marsh, protect fragile seedlings, and recruit new vegetation. The lack of a definitive pattern suggests that the marsh vegetation in front of bulkheads is as healthy as vegetation in adjacent areas free from bulkhead influence.

Despite limited sampling breadth, our data indicates that bulkheads do not negatively impact marsh health, as defined by our parameters. However, our results do not exclude the possibility of negative impacts occurring at and after a certain threshold value for wave action. We suggest that under moderate stress levels caused by usual tides, boat wakes, and wind-waves, bulkheads do not harm marsh health, but we cannot conclude anything about marsh health during periods of high stress, potentially caused by large storm events, exacerbated wave action, or sea level rise and subsequent inundation. The degree to which sediment deposition can sustain these marshes in the face of rising water levels is uncertain. We cannot predict marsh-bulkhead behavior in this environment, and further investigation is recommended.

Literature Cited

Allsop, William, Tom Bruce and Jon Pearson. Violent Overtopping of Waves at Seawalls (VOWS) - Physical Model Study.Poster Presented at ICCE 2000. <http://www.vows.ac.uk/> (3 Oct. 2006)

Besley, P., Stewart, T. & Allsop, N.W.H. (1998), "Overtopping of vertical structures: new prediction methods to account for shallow water conditions", Proc. Conf. Coastlines, Structures and Breakwaters, Institution of Civil Engineers, March 1998,

Berman, M.R., Berquist, H.E., and P. Mason. 2005 Building Arguments for Living Shorelines. Proceedings of the 14th Biennial Coastal Zone Conference. < http://www.csc.noaa.gov/cz/2005/CZ05_Proceedings_CD/pdf%20files/posters/Berman.pdf>

Boorman L.A. 1992. The environmental consequences of climatic change on British salt marsh vegetation. Wetlands Ecology Management. 2(1/2): 11-21.

Boorman L. and Hazelden J. 1995. Salt marsh creation and management for coastal defense. In: Healy M.G. and Doody J.P. (eds), Directions in European Coastal Management. Samara Publishing Limited, Cardigan, UK, pp. 175-183.

Bozek, Catherine M., and David M. Burdick. 2005. Impacts of seawalls on the saltmarsh plant communities in the Great Bay Estuary, New Hampshire USA. *Wetlands Ecology and Management*, 13: 553-568.

Brinson, M.M., F. R. Hauer, L.C. Lee, W.L. Nutter, R.D. Rheinhardt, R.D. Smith, and D. Whigham. 1995. Guidebook for application of hydrogeomorphic assessments to riverine wetlands. Technical Report TR-WRP DE-11, Waterways Experiment Station, Army Corps of Engineers, Vicksburg, Mississippi. <http://el.erdc.usace.army.mil/wetlands/guidebooks.html>

Bulleri, Fabio. 2005. Experimental evaluation of early patterns of colonization of space on rocky shores and seawalls. *Marine Environmental Research*, 60: 355-374.

Burby, R.J., R.E. Doyle, D.R. Godschalk, and R.B. Olshansky. 2000. Creating hazard resistant communities through land-use planning. *Natural Hazards Review* 1:99-106.

Byers, S.C., E.L. Mills, and P.L. Stewart. 1978. A comparison of methods of determining organic carbon in marine sediments, with suggestions for a standard method. *Hydrobiologia*. 58: 43-47.

Chapman, M.G. 2003. Paucity of mobile species on constructed seawalls: effects of urbanization on biodiversity.
Marine Ecology Progress Series, 264: 21-29.

Chapman, M.G. 2006. Intertidal Seawalls as Habitats for Molluscs. *Journal of Molluscan Studies*. 72: 247-257.

Currin CA, Newell SY, Paerl HW, 2006. The role of standing dead Spartina alterniflora and benthic microalgae in salt marsh food webs: considerations based on multiple stable isotope analysis. *Marine Ecology Progress Series*, 121:99-116.

Davis, J.L.D., L.A. Levin, and S.M. Walker. 2002. Artificial Armored Shorelines: Sites for Open-Coast
Species in a Southern California Bay. *Marine Biology*, 140: 1249-1262.

Dean, R.G. and R.A. Dalrymple. *Coastal Processes: with Engineering Applications*. Cambridge, UK. Cambridge
University Press, 2004. 1st ed.

Division of Coastal Management. CAMA Rules & Policies: The Coastal Area Management Act. 2003.
<http://dcm2.enr.state.nc.us/Rules/cama.htm>

Environmental Protection Agency. *Recent Climate Change - Sea Level Changes* [internet]. 19 October
2006. [cited 2006 November 8]; Available from:
<http://www.epa.gov/climatechange/science/recentslc.html>

Feist, B.E., J.J. Anderson, and R. Miyamoto. 1996. Potential Impacts of Pile Driving on Juvenile Pink
(Oncorhynchus gorbuscha) and Chum (O. keta) Salmon Behavior and Distribution. Fisheries Research Institute, School f Fisheries, University of Washington, Seattle. FRI-UW-9603.

Finnell, Gilbert L. Jr. 1978. The Federal Regulatory Role in Coastal Land Management. *American Bar*
Foundation Research Journal.

Garbisch, E. W., P.B. Woller, W.J. Bostian, and R.J. McCallum 1973. “Biotic techniques for shore Stabilization”. p. 405-407 *in* L.E. Cronin (ed.). Estuarine Research. Academic Press Inc., New York, NY, II.

Hay, Mark E., and John P. Sutherland. 1988. The Ecology of Rubble Structures of the South Atlantic Bight:
A Community Profile. *U.S. Fish Wildl. Serv. Biol. Rep.* 85(7.20). 67 pp.

Heinz Center. 2000. *Evaluation of Erosion Hazards*. Heinz Center, Washington, DC.

Hendon, J. Read., Mark S. Peterson, and Bruce H. Comyns. 2000. Spatio-temporal Distribution of Larval *Gobiosomal bosc* in Waters Adjacent to Natural and Altered Marsh-Edge Habitats of Mississippi Coastal Waters. *Bulletin of Marine Science*, 66(1): 143-156.

Holway, J.M. and R.J. Burby. 1993. Reducing flood losses: Local planning and land use controls. *Journal*
of the American Planning Association 59:202-216.

Keddy P.A. 1985. Wave disturbance on lakeshores and the within-lake distribution of Ontario's Atlantic
coastal plain flora. Canada Journal of Botany 63: 656-660.

Kennedy, Coleman F., and John F. Bruno. 2000. Restriction of the Upper Distribution of New England Cobble Beach Plants by Wave-Related Disturbance. *Journal of Ecology*, 88(5): 856-868.

Kirby-Smith, William, John Costlow. "The Newport River Estuarine System" UNC Sea Grant College
Publications UNC-SG-89-04, April 1989

Lee, Hee Jun, Yong, Shik Chu, Yong, Ahn Park 1999. "Sedimentary processes of fine0grained material and the effect of seawall construction in the Daeho macrotidal flat-nearshore area, northern west coast of Korea". Marine Geology, 157, 171-184.

Mallin, Michael, Joann Burkholder, Lawerence Cahoon, Martin Posey 2000 . "North and South Carolina Coasts" Marine Pollution Bulletin. 41. 1-6, 56-57.

McConchie, J.A. and E.J. Toleman. 2003. Boat wakes as a cause of riverbank erosion: a case study from the Waikato River, New Zealand. *Journal of hydrology*. 42:163-179

McGee, B.L., Schlekat, C.E., Boward, D.M. and T.L. Wade. 2004. Sediment contamination and biological effects in a Chesapeake Bay marina. *Ecotoxicology*. 4:39-59.

Miles, J.R., Russell, P.E. and Huntley, D.A., 2001. "Field measurements of the effect of seawalls on sediment transport". Journal of Coastal Research, 17 (1), 195-206

Mulvihill, E.L., C.A. Francisco, J.B. Glad, K.B. Kaser, and R.E. Wilson. 1980. Biological Impact of Minor Shoreline Structures on the Coastal Environment. U.S. Fish Wildl. Serv., Biol. Services Program. FWS/OBS-77/51, 2 vol.

National Research Council [NRC]. "Mitigating Shore Erosion Along Sheltered Coasts". National Academy of Science, 2006.

Neelamani, S., Sandhya, N. (2005), "Surface roughness effect of vertical and sloped seawalls in incident random wave fields". Ocean Engineering, 32, 395-416.

North Carolina Division of Coastal Management [NCDCM]. 2006. "Recommendations for Appropriate Shoreline Stabilization Methods for the Different North Carolina Estuarine Shoreline Types". *Unpublished.* Accessed Oct. 2006.

North Carolina Coastal Federation. *Erosion Control: Non-Structural Alternatives, A Shorefront Property Owner's Guide*. Shorekeeper Program. Ocean, NC.

Nuttle W.K., Brinson M.M., Cahoon D., Callaway J.C., Christian R.R., Chmura G.L., Conner W.H., Day R.H., Ford M., Grace J., Lynch J.C., Orson R.A., Parkinson R.W., Reed D., Rybczyk J.M., Smith T.J. III, Stumpf R.P. and Williams K. 1997. Conserving coastal wetlands despite sea level rise. EOS 78(25): 257-264.

Odum, William E. "Comparative Ecology of Tidal Freshwater and Salt Marshes". Annual Review of Ecology Systems, 1988, 19: 147-76.

Paerl, H., Pinckney JL, Fear JM, et al. 1998. Ecosystem responses to internal and watershed organic matter loading: consequences for hypoxia in the eutrophying Neuse river estuary, North Carolina, USA. Marine Ecology Progress Series 166:17-25.

Peterson, M.S., B.H. Comyns, J.R. Hendon, P.J. Bond, and G.A. Duff. 2000. Habitat use by early Life-history stages of fished and crustaceans along a changing estuarine landscape: Differences between natural and altered shoreline sites. *Wetlands Ecology and Management*, 8: 209-219.

Piehler, Mike. *UNC Institute of Marine Sciences.* Personal Communication. October 2006.

Pope J. 1997. Responding to coastal erosion and flooding damages. Journal of Coastal Research 13(3): 704-710.

Rakha, K.A., J.W. Kamphuis. "A morphology model for eroding beach backed by a seawall." *Coastal Engineering*, 30 (1997), 53-75.

Riggs, S.R., O'Connor, M.P., and Bellis, V.J. 1978. *Estuarine Shoreline Erosion in North Carolina*:

University of North Carolina Sea Grant College Publication, Raleigh.

Riggs, Stanley R. 2001. *The Soundfront Series: Shoreline Erosion in North Carolina Estuaries*. North Carolina Sea Grant 11: 38-55.

Sanger, D.M., Holland, F.A., and C. Gainey. 2004. Cumulative Impacts of Dock Shading on *Spartina alterniflora* in South Carolina Estuaries. *Environmental Management*. 33:741-748.

Schlesinger, William H., Biogeochemistry: An Analysis of Global Change. San Diego, CA: Academic Press, 1991.

Segar, D. A., 1998, Introduction to ocean sciences, Wadsworth publishing company, Belmont CA., pp. 118

Seitz, R.D., R.N. Lipcius, N.H. Olmstead, M.S. Seebo, and D.M. Lambert. 2005. Influences of shallow-water habitats and shoreline development upon abundances, biomass, and diversity of benthic prey and predators in Chesapeake Bay. Virginia Institute of Marine Science, College of William and Mary.

Spalding, Valerie L., and Nancy L. Jackson. 2001. Field Investigation of the Influence of Bulkheads on Meiofaunal Abundance in the Foreshore of an Estuarine Sand Beach. *Journal of Coastal Research*, 17(2): 363-370.

Street, M.W., A.S. Deaton, W.S. Chappell, and P.D. Mooreside. 2005. North Carolina Coastal Habitat Protection Plan. North Caroline Department of Environment and Natural Resouces, Division of Marine Fisheries, Morehead City, NC. 656 pp. <http://www.ncfisheries.net/habitat/chpp28.html> Accessed Oct 2006.

Strickland, J. D. H. and Parsons, T. R., 1971. A practical handbook of seawater analysis. Bulletin of Fisheries Research p. 167

Titus, J.G. 1988. Greenhouse Effect, Sea Level Rise, and Coastal Wetlands. U.S. EPA Office of Policy, Planning, and Evaluation, Washington, DC. 186pp. EPA 230-05-86-013 <http://yosemite.epa.gov/OAR%5Cglobalwarming.nsf/content/ResourceCenterPublicationsSLRCoastalWetlands.html>

US Army Corps of Engineers (1995) Engineering Manual *Design of Coastal Revetments, Seawalls, and Bulkheads*, EM 1110-2-1614

US Army Corps of Engineers (2002) Engineering Manual *Types and Functions of Coastal Structures*, EM 1110-2-1100 (Part VI).

Vitousek, P. 1997. Human domination of Earth's ecosystems. Science 278:21.

Watts, J. G. 1987. Physical and biological impacts of bulkheads on North Carolina's estuarine shoreline. Division of Coastal Management, North Carolina Department of Environment, Health, and Natural Resources.

Williams, G.D., and R.M. Thom. 2001. Marine and Estuarine Shoreline Modification Issues. Battelle Marine Sciences Laboratory, Sequim, WA.

Zervas, C.E. 2004. North Carolina Bathymetry/Topography Sea Level Rise Project: Determination of Sea Level Trends. NOAA Tech. Rep. NOS CO-OPS 041.

Appendix 1: **Research Needs**

In addition to the research conducted in this study, we have discovered several research needs that are essential in order to better understand the impacts of bulkheads on the surrounding salt marsh habitat. Listed below are future research suggestions.

- Bulkheads, typically installed in order to prevent land erosion, may alter water flow and sediment suspension. Bulkheads increase rates of sedimentation and erosion by eliminating the natural shoreline buffer that reduces water flow and decreases sediment suspension. Herein lies a contradiction to the role of a bulkhead, therefore further research is needed in order to determine if bulkheads decrease net shoreline erosion and water turbidity.

- Increased sediment suspension, caused by alterations in current flow by the presence of a bulkhead, is thought to have a negative effect on marsh productivity. Impacts of increased turbidity are not exclusively limited to marshes, as seagrass beds and other submerged aquatic vegetation may also be negatively affected. Additional research is needed in order to further quantify these proposed effects.

- Bulkheads act as a roadblock for groundwater transportation of organic and inorganic particles. This has the potential to make the land behind the bulkhead contaminated with pathogens and pollutants, as well as the potential to pollute well water. There has been little done to examine the effect on the landward side of the bulkhead, therefore an assessment of the impact of bulkheads on the transport of nutrients, pathogens and other pollutants from groundwater into estuarine waters needs to be conducted in order to gain a better understanding of the bulkheads' landward environmental footprint.

- Research assessing how bulkheads alter waves and long shore currents is lacking. Models have predicted the effects of SHS on waves and currents, but have reached varying conclusions. Field experiments have yet to quantify these physical processes to confirm modeling predictions. Until concrete conclusions are reached, the affects of SHS on wave attenuation remain speculative.

- Another research need that should be addressed is the biological impacts of non-native species inhabiting the bulkhead. The placement of a hard substrate, such as a SHS, welcomes barnacles and other non-native species to this habitat. This could potentially have a negative impact on native species, therefore more experiments need to be conducted testing these non-native species introductions.

- Further research needs to be conducted regarding the motivation behind a landowner's decision to install a SHS. This decision could stem from socioeconomic influences or out of a desire to protect one's property. Observational methods, such as door-to-door or mail in surveys, could prove to be a vital research tool. The type of SHS chosen should also be studied, in order to determine if structural preferences vary geographically or among different income groups.

- The citing of a bulkhead, its location relative to the shoreline profile and to adjacent marsh, may impact the range, magnitude, and duration of habitat disruption. For instance, Spalding and Jackson (2001) found that bulkheads constructed lower on the profile had a negative impact on meiofaunal abundance. To determine the proper citing of a bulkhead, similar field studies are needed to assess the specific impacts of a bulkhead's location on additional flora, fauna, sediment, and physical processes.

- A rise in sea level is currently ongoing and expected to continue in response to global climate change. As a result, salt marshes will be submerged and transformed, forcing a shift in marsh habitat. The potential impact bulkheads can have on adjacent marshes due to expected sea level rise needs to be determined. Bulkheads physically alter the biological and chemical processes of the marsh; therefore, the impact of bulkheads on retreating marshes must be quantified in order to improve management strategies.

- In order to formulate effective policies that can efficiently manage shoreline erosion in our estuarine waters, it is critical to determine the extent to which the North Carolina coast is actually armored and how much of the coast is still in its natural state. Only when local county officials can accurately assess large scale erosional stresses can they set out to develop comprehensive rules and procedures to address system-wide problems. As long as erosion is handled on a case-by-case basis, it is impossible for regional decision makers to work together toward any kind of proactive solution.