EFFECTS OF BULKHEADS ON ESTUARINE BEACH SWASH ZONE PROCESSES AND CHARACTERISTICS

by

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ABSTRACT OF THE THESIS

Effects of Bulkheads on Estuarine Beach Swash Zone Processes and Characteristics

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This thesis combines the study of geomorphic effects of beach topography, sediment characteristics, and transport with physical processes of waves, swash, and reflected energies to evaluate the effects of bulkheads on estuarine beaches. I hypothesize that the truncation of a beach by a bulkhead will (1) concentrate and increase turbulence directly seaward of the structure increasing sediment activation depth; (2) create interference and patterns of swash/wave and reflected energy interactions, increasing the topographic variability of the foreshore; and (3) increase turbulent energies enough to remove finer grained sand. Measurements of topographic variability, sediment activation depth, and net change were made over 21 tidal cycles on the foreshore at two wooden sheet pile bulkheads and a control site 45 m south of the bulkheads at Fortescue, New Jersey. Sediment cores were taken seaward of the bulkhead and at equivalent elevations on the control site to the depth of sediment activation. A video record was taken of swash and waves interacting with the bulkhead. The main conclusions are that since the swash and waves are precluded from migrating higher up the foreshore with the tide, the increased concentration of incident and reflected energies at bulkheads more than doubles the depth of sediment activation directly seaward, increasing the potential for sediment transport under higher energy conditions. Though no significant net surface change occurred seaward of the bulkheads, there are more frequent erosional/depositional cycles. The bulkheaded beaches have a more undulatory profile and a steeper slope within 0.5 to 1.5 m of the structure. The surface sediment on the bulkheaded beaches have a smaller amount of coarse sand and granules, although this may be an artifact of horseshoe crab burrowing on the control site. The type of bulkhead construction influences processes and beach response. One bulkhead that has buttress pilings on the bayward side has a steeper beach out to a greater distance (1.5 m) and smaller depth of sediment activation than the planar bulkhead due to sediment accumulation between the buttresses, which broke up the reflected energy. The 8.58 m long beach enclave between the two bulkheads has characteristics similar to bulkhead sites.

ACKNOWLEDGEMENTS

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INTRODUCTION

This study is about the geomorphic effects bulkheads have on estuarine beaches. As humans move to the shore in increasing numbers to live, recreate, utilize resources, and enjoy the coast's natural beauty, more stresses are being placed on the environment (Panetta, 2003). Most the of the world's coastlines are undergoing inundation due to sea level rise, which is exacerbated in some areas by sediment compaction and subsidence, decrease in sediment supply to the shore due to river and stream controls, and increased storminess during El Nino years and active hurricane seasons (Komar and Allen, 2007; Mann and Emanuel, 2006; Zhang et al., 2004; Nicholls, 1998). People who live on the coast have four options when their homes or businesses are threatened by the ocean: 1. Nourish the beach with sand to increase the protective beach width, 2. Protect their homes with hard structures including groins, breakwaters, and bulkheads, 3. Retreat by moving the building farther inland, 4. Do nothing (Pilkey, 1991).

One of the most public debates in shoreline management is between homeowners who want to use permanent structures for protection from the sea and conservationists or other recreational beach-users who believe these structures permanently and deleteriously alter the shoreline by enhancing erosion, reducing beach access, and degrading the aesthetic and environmental quality (Pilkey and Dixon, 1996; Maier and Riley, 1998; Riley, 1998). Constructing a shore-parallel structure, which has a life span of about 20-25 years, is expensive, for example, ranging from $6,000-25,000/m in California (Griggs, 2005). Before these structures are built, the short- and long-term impact should be assessed so that developers, engineers, and homeowners can make judicious decisions on their placement and use.

Shore-parallel structures are commonly used on both oceanic and estuarine beaches. While information about shore parallel structure effects on ocean beach morphology exists (Plant and Griggs, 1992; Griggs et al., 1994; Kraus and McDougal, 1996), the literature on effects on estuarine beaches is sparse (Jackson and Nordstrom, 1994). Estuarine beaches are important ecologically as spawning, nesting, and foraging areas for animals like meiofauna, horseshoe crabs, turtles, and shorebirds (Spaulding and Jackson, 2001; Smith et al., 2002). Shore parallel structures are expected to have a different effect on estuarine beaches than on ocean beaches because estuarine beaches are typically steeper, have coarser-grained sediments, and a narrow and more concentrated zone of wave and swash energies than ocean beaches (Nordstrom and Jackson, 1992). Although the wave energies on estuarine beaches are smaller, there is a concentration of energy in the swash zone because breaking waves are converted directly into swash. This project evaluates geomorphic changes in the swash zone of estuarine beaches caused by bulkheads using field data on sediment characteristics, sediment disturbance, topographic variability, and type and location of swash-bulkhead-backwash interactions. Since a bulkhead truncates the swash zone, it will reflect energy that will interact with incident waves and swash. It is hypothesized that the patterns of energy interactions, along with the concentration of breaking wave and swash energy at the bulkhead will lead to more variable topography, greater depth of sediment activation, and a net loss of sediment. Due to increased turbulence, the lost sediment will primarily be the finer sediment, which will leave coarser sediment just seaward of bulkheads.

BACKGROUND

The purpose of shore parallel structures, which include bulkheads, sea walls, and revetments, is to protect areas landward from erosion due to wave attack, landslides, storm surge, and sea level rise. Bulkheads are vertical, shore-perpendicular protection structures made of wood, metal, concrete, plastic, fiberglass or rock. Seawalls are more massive than bulkheads and are used in more energetic (ocean) environments and may be terraced (MacDonald et al., 1995). Revetments are sloped in order to dissipate wave-energy and are usually made of riprap (MacDonald et al., 1995). These structures, hereafter referred to as bulkheads, are not meant to protect an eroding beach, as any area on the seaward side of a bulkhead will continue to retreat due to three main factors: placement loss, passive erosion, and active erosion (Hall and Pilkey, 1991).

Placement loss is the reduction in beach width due to placement of a bulkhead below the high-tide line and also the loss of sediment exchange between the beach and the area behind the bulkhead (Figure 1), which are typically sand dunes on the east coast. By preventing sediment from entering the littoral system, the beach in seaward of the bulkhead and surrounding areas will erode to make up for the deficit in sediment. This passive or ambient erosion without deposition will lead to a narrowing of the beach in front of the bulkhead (MacDonald et al., 1994). Bulkheads become problematic because they are static barriers armoring the land, preventing a transgression of beach environments (Figure 1). There is much more controversy over the erosion caused by bulkheads, which is called active erosion.

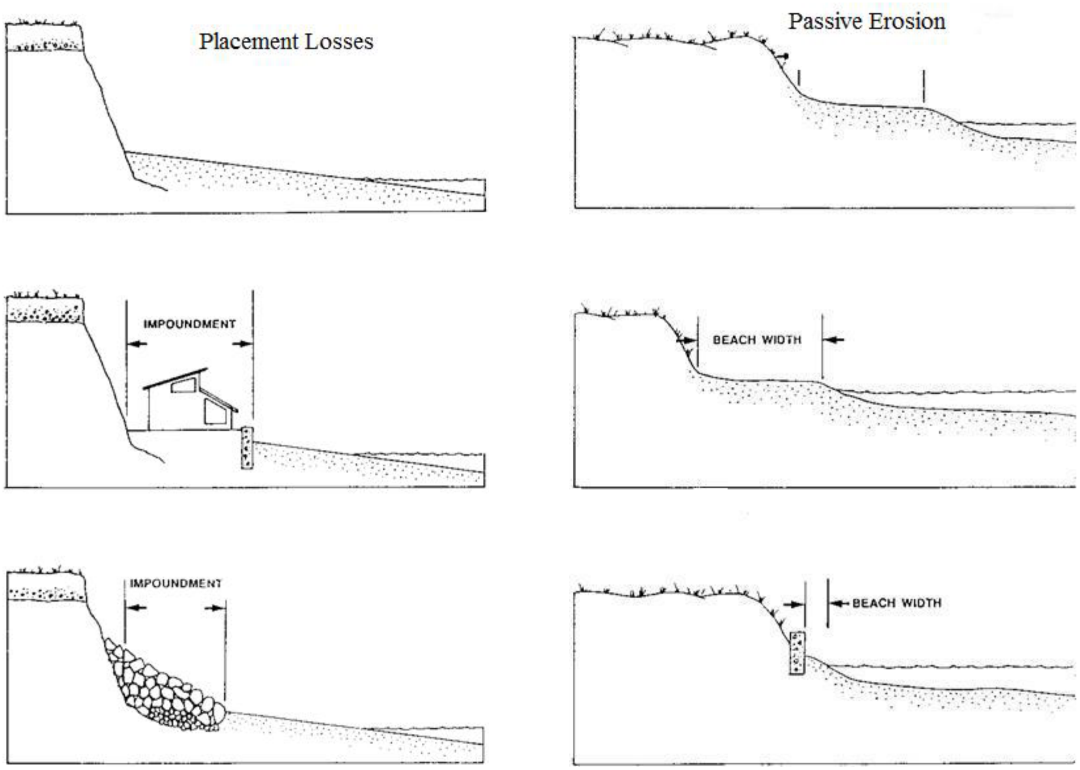


Figure 1 Placement loss (left panels) and passive erosion loss (right panels) due to bulkheads (Modified from Griggs et al., 1994) The top left panel shows the initial beach with sediment supplied from the unconsolidated bluffs, dunes, or seacliff. The middle left panel shows the placement loss due to the construction of a bulkhead and structure on the beach, reducing both beach width and sediment supply from the bluffs, dune, or seacliff. The bottom left panel shows that placement loss also occurs if the shore protection is placed at the toe of a cliff, bluff, or dune, by reduction of beach width and loss of a sediment source to the coast. The top right panel shows the initial beach width of an eroding coast. The middle right shows the transgression of the beach after erosion with no bulkhead, and bottom right panel is the beach width after erosion on a bulkheaded beach, preventing transgression.

Active erosion is the loss of beach due to bulkhead interference with natural processes. Active erosion includes the erosion of adjacent beaches or beaches seaward of bulkheads due to an increase in longshore transport. Beaches adjacent to or seaward of a bulkhead will lose sediment as geomorphic processes continue to move sediment to maintain beaches undergoing passive erosion. One of the best documented effects of active erosion due to bulkheads on oceanic beaches, is the interception of longshore transport on the updrift side of a protruding bulkhead the interruption of longshore sediment transport, known as the “groin effect” (Kraus 1988; Basco 2006; Weggel 1988). Van de Graff (2004) terms this type of bulkhead-induced erosion “structural erosion” as it is the result of a reduction in longshore transported sediment in front of bulkheads due to a landward shift in the beach profile on surrounding beaches. Active erosion due to bulkheads is linked to steeper and more variable topography, and increased sediment loss under storm conditions on oceanic beaches (Kraus, 1988; Plant and Griggs, 1992). Other studies have shown that ocean beaches in front of shore parallel structures are statistically narrower, but fail to separate the factors causing this change (Hall and Pilkey, 1991). Many reports on the effects of bulkheads on the shoreline are based on conceptual arguments rather than empirical studies, so hard data is needed to show how bulkheads affect swash processes and actively erode the shoreline (Nordstrom, 2000). This study will identify processes and signs that reveal whether bulkheads increase active erosion seaward of them.

FACTORS IMPORTANT IN DETERMINING THE GEOMORPHIC IMPACT OF BULKHEADS

The main independent and dependent variables that affect the geomorphic impact of bulkheads are: wave height and periodicity, wave reflection, sediment size, position of the bulkhead on the beach, and beach slope (McDougal et al., 1996; Weggel, 1988). As the deepwater, incident, and reflected wave height increase, the effects on beach morphology increases (McDougal et al., 1996). The force of wave impact on the bulkhead increases with increasing wave height and wave length (Cuomo and Allsop, 2004). Increased forces at the wall lead to increased turbulence and activation of sediments. Empirically it is expected that the greater the deep water wave height, the greater the scour depth at the wall, as there is more energy available to move sediment in larger waves. If there is scour in front of a bulkhead, larger waves can break in front of a bulkhead further increasing sediment movement.

The importance of wave reflection is uncertain (Weggel, 1988; McDougal et al., 1996). The energy added to the system is a result of the incident and reflected energies and can create zones of increased sediment suspension (Weggel, 1988). But without a shear in the longshore or cross-shore currents, there is no net accretion or erosion. Weggel suggests that the effect of the reflected wave on beach scour is related to a ratio of the height of the reflected wave to the height of the incident wave (1988). Reflected waves can also make incident waves break farther offshore, dissipating wave energy in front of a bulkhead (McDougal et al., 1996). The location of breaking of the incident wave will depend on wave periodicity and reflected wave velocity.

Miles et al. (2001) measured the reflected and incident wave energies at bulkheads under varying wave frequencies and found that as wave frequencies decrease, reflection coefficients increase, increasing suspended sediment concentrations. McDougal et al. (1996) show in wave tank experiments that wave reflection is of minimal importance in altering the beach. Other scientists have postulated that the reflection of waves and swash off a bulkhead will increase erosion and form scour trenches in front of the wall (Kraus, 1988). Reflection, along with increased flows at a bulkhead on a dissipative beach, produced a maximum in suspended sediment concentration in front of bulkheads at a location where wave heights are largest and water depth is smallest (Miles et al., 2001). Although suspended sediment concentrations may increase, most recent studies of bulkheads on oceanic beaches have concluded that aside from a small and temporary scour trench forming in front of some bulkheads, the reflection of waves does not significantly change beach topography (McDougal et al., 1996). Long-term studies also show that if scour trenches form in front of bulkheads, they are temporary features. Aside from an initial increase in the rate of seasonal sediment movement offshore in the fall and winter, beaches backed by bulkheads reach the same seasonal equilibrium profiles (Griggs et al., 1994). Geomorphic effects are expected to vary based on the beach slope and the type of shore-parallel structure. For instance, Griggs et al. (1994) studied the effects of sloped ("dissipative") seawalls on gently-sloping, dissipative beaches. Swash and wave processes and interactions with bulkheads will be different on reflective estuarine beaches seaward of completely vertical (reflective) bulkheads.

Due to alterations to swash energy seaward of bulkheads, which are responsible for sediment sorting, scientists have reasoned that there will be a loss of finer-grained sand in front of bulkheads (Pilkey and Neal, 1980). Alterations in the amount of fine versus coarse grained sediment will influence beach slope, drainage, and the mobility of sediment. The slope of a beach is a factor of grain size and wave and swash conditions. Grain size and beach steepness are positively correlated (Lorang, 2002). Under similar process conditions, larger grain sizes have a greater angle of repose (Lorang, 2002). Larger grain sizes also have greater permeability, which allows the swash to drain into the beach, stabilizing the steeper slopes of beaches that contain a higher proportion of gravel. Beaches composed of larger-grained sediments tend to erode less than beaches of finer-grained sediments, however due to their steepness, coarser-grained beaches experience greater swash and wave energies over a narrower distance, resulting in a potential for more scour in a localized area (McDougal et al., 1996). Review papers (e.g. Gabriel and Terich, 2005; Kraus, 1988) refer to obscure studies that report that bulkheads cause a loss of fine grained sediments, which could explain why there is a steepening of the beach profile in front of bulkheads, however, these studies do not refer to actual data. MacDonald et al. (1994) report that the loss of fine-grained sediment on beaches in front of bulkheads is hypothetical and based on the assumption that there is an increase in offshore directed flow velocity in front of the bulkhead due to reflected wave energies, particularly during storms. In a wave tank experiment, McDougal et al. (1996) found that finer sediments were eroded first in front of the bulkhead. Through the examination of several case studies of oceanic bulkhead projects on the west coast, Wiegel (Parts 2 and 3, 2002) reports that there is no validity to assertions that bulkheads cause beach steepening or erosion of sediment, but he presents limited scientific evidence to support his conclusions. The hypothetical nature of other studies warrants a closer examination of the effect of bulkheads on grain size, beach topography, and net sediment movement. Studying these variables and processes on estuarine beaches will provide information and insights on an environment largely ignored in previous bulkhead studies.

ESTUARINE BEACH CHARACTERISTICS

Estuarine beaches cannot be considered micro versions of oceanic beaches (Nordstrom, 2000). Estuarine beaches are located in sheltered environments and are subject to low-energy waves generated by local meteorological conditions. Since wind speed, direction, and duration determine the height and periodicity of waves entering estuaries, beach morphology is tied to local wind conditions (Jackson, 1995). Ocean swell will be conspicuous on estuarine shorelines on days when the local winds blow offshore, suppressing local wind-waves. Ocean wave energy is dissipated as swell travels through the estuary due to shoaling, refraction, and diffraction. Due to the low-energy environment, estuarine beaches are narrower than oceanic beaches. Shoreline orientation, distance from the mouth of the estuary, and sediment characteristics also determine the way a beach responds to wind and waves (Jackson, 1995). Estuarine beaches have coarser sediment than oceanic beaches because the fine sediment that is normally delivered to oceanic beaches via long, flat waves, are absent on estuarine beaches (MacDonald et al., 1994). In addition, the fine-grained sediment on estuarine beaches tends to be removed by waves, while the coarser sand and gravel armors the sand. Estuarine beaches are steeper than ocean beaches because they have more coarse-grained sediment, which increases beach permeability, leading to greater transport capacity on the wave uprush than backwash, enhancing deposition on the upper beach (MacDonald et al., 1994 and Austin and Masselink, 2006).

WAVE AND SWASH PROCESSES

Before considering how swash processes are altered on estuarine beaches by bulkheads, it is important to know how swash normally affects beach morphology. Estuarine beach foreshores lack a dissipative surf zone and swash begins where the wave breaks, when waves are converted into a landward-traveling bore. The bore moves up the beach in what is called “uprush”, loses momentum, and travels back down the beach as “backwash”. The swash zone is often considered the most dynamic portion of the beach, as it is an area of great amounts of turbulence, high flow velocities, and large amounts of sediment movement (Masselink et al., 2005). The uprush and the backwash are distinct from each other based on the amount of sediment in suspension and where the sediment in suspension is located (Longo et al., 2002). Bore turbulence is the main driver of sediment movement in the uprush (Longo et al., 2002). This is important because not all sediment movement in the swash zone is of local origin, a significant portion is entrained by bore collapse seaward of the swash zone (Jackson et al., 2004). Local sediment is entrained in the latter part of uprush due to shear stress, which causes *in situ* sediment to be transported as a sheet flow (Jackson et al., 2004). Uprush moves more sediment than backwash because of infiltration and an increased amount of sediment introduced to the swash during bore collapse, which suggests that turbulence and friction are also greater in uprush than backwash (Masselink and Russell, 2006). There is also an asymmetry of sediment movement throughout the tidal cycle: during rising tide there is a lower water table, allowing more of the swash to infiltrate the beach, which results in a smaller backwash. This generally allows sediment to move onshore in the swash during rising tide (Nordstrom and Jackson, 1992). During falling tide, the water table is high, so there is less infiltration of swash, greater backwash and less sediment deposition. Since uprush is a more efficient sediment transport mechanism even though it typically is shorter in duration than backwash, swash is a beach-building process (Masselink et al., 2005).

Swash processes are altered by bulkheads that truncate the swash zone. Bulkheads will shorten the uprush and create reflected swash, altering swash velocity, duration, and elevation (Plant and Griggs, 1992). Backwash velocity and duration can be increased due to reflection, uprush duration can be abbreviated, and there can be an increased backwash volume due to both reflection of uprush and saturation of the beach. Studies have also shown an increase in turbulence in backwash at bulkheads (Plant and Griggs, 1992). Interactions between incident and reflected energies create orbital velocities that can be twice the velocity of incident waves and may result in greater sediment suspension at bulkheads (Hsu et al., 1980). If the characteristics that make swash a beach-building process are reversed, then under certain conditions swash may cause a removal of sediment in front of bulkheads.

When waves break just in front of or at a bulkhead, the excess cross-shore momentum creates a reflected wave (Silvester and Hsu, 1993). There are two main types of interactions between incident and reflected waves: constructive and destructive (Figure 2). Constructive or additive interference occurs when the incident wave has more energy than the reflected wave and meets the reflected wave just prior to breaking. The incident wave increases in height, increasing subsequent swash and backwash energy, but diminishing the reflected wave height and velocity (Silvester and Hsu, 1993). Standing wave interactions are another form of additive interference at the bulkheads. Destructive interactions decrease the height and velocity of either reflected or incident waves or both. Destructive interactions occur when the reflected wave meets the incident wave directly before the incident wave breaks. Provided the reflected wave energy is large enough, the incident wave loses momentum and height, decreasing the subsequent reflected wave and swash energies and turbulence.

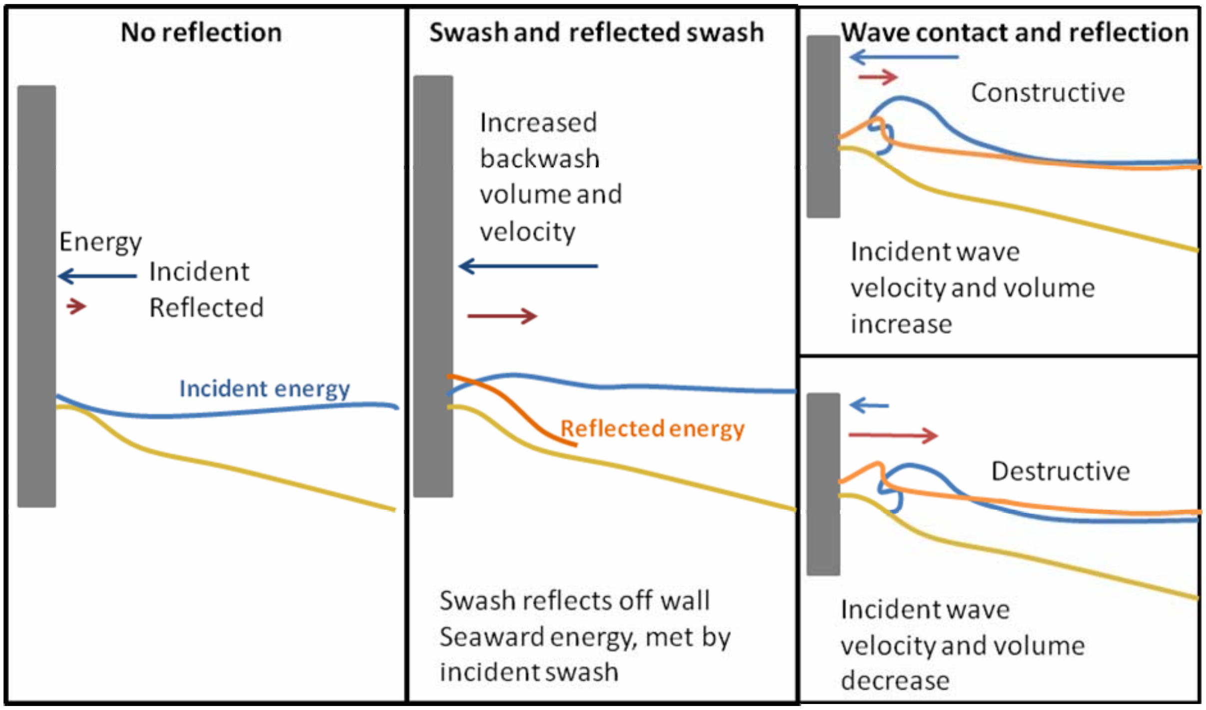


Figure 2 Types of incident and reflected energy interactions. (Length of arrows proportional to relative energy level)

STUDY DESIGN

This study focuses on depth of sediment activation, beach topography, and sediment size characteristics in the swash zone because studies on oceanic beaches reveal that these characteristics are altered and can potentially affect long-term beach morphology (Griggs et al., 1994; Weggel, 1988; McDougal et al., 1996). Since the amount of sediment in suspension is a key factor in the potential for beach erosion, the depth of sediment activation is a proxy for the amount of sediment stirred by swash- and wave-generated turbulence. The sediment activation depth defined here, is the amount of sediment that is activated over a tidal cycle by waves and swash. The location of maximum depth of sediment activation occurs on the beach profile where waves break most commonly, which is a factor of beach slope (Jackson and Nordstrom, 1993). While on dissipative beaches there is a bimodal peak in maximum depth of sediment activation, with maxima in the breaker and swash zones and a minimum in the surf zone (Jackson and Nordstrom, 1993), steep, reflective beaches, which include most estuarine beaches, have one maximum where the plunging breakers are concentrated at the high tide stillstand (Jackson and Nordstrom, 1993; Otvos, 1965). A steep profile leads to increased scour under destructive wave conditions in wave tank experiments (McDougal et al., 1996), so research on the effect of bulkheads on beach steepness and depth of sediment activation can be linked in this study.

Beach topography can be altered on oceanic beaches in front of bulkheads (Plant and Griggs, 1992). A removal of sediment from the subaerial berm, which is the beach response to storm events, is greater and occurs more frequently in front of bulkheads (Plant and Griggs, 1992). In addition, the topographic variability that occurs on unprotected beaches is displaced offshore on protected beaches (Plant and Griggs, 1992). A more undulatory cross-shore topography is indicated by laboratory and theoretical studies, but not in the field (Kraus, 1988).

The effect of bulkheads on sediment size is the third aspect of this study. King (1951) found that there is a positive correlation between sediment activation depth and sediment size, although Williams (1971) refutes this argument. Regardless, since beach slope is related to sediment size, and both factors are affected by bulkheads, knowing how sediment size changes is important to understanding bulkhead effects. If estuarine beaches become steeper due to bulkheads, they will be more reflective, which will increase the backwash-incident wave interactions, increasing sediment mobilization, particularly during high tide (Anfuso et al., 2000; Mason and Coates, 2001).

Several limitations of the study occur because it was part of a larger project to study the effects of horseshoe crab egg exhumation and transport in front of bulkheads and the effects on horseshoe crab spawning and migratory bird populations. Compromises with this study meant that the research took place for two weeks during the spawning season and limited the choice of control site location. Low-energy conditions prevailed during this time and spawning effected measurements of sediment activation and grain size on the control site.

OBJECTIVES

The goal of this study is to understand the interactions between bulkheads and swash, and the geomorphic changes that result from these interactions. Knowing how bulkheads affect these variables is important for understanding things like long-term beach erosion or accretion, the loss or gain of vital ecosystem and habitat characteristics, and the potential for exhumation and transport of eggs and larvae. The study addresses three main hypotheses:

1. The depth of sediment activation in front of a bulkhead will increase, because the bulkhead truncates the beach, creating a more focused zone of swash, wave, and reflected energy, increasing the amount of turbulence and sediment mixing.

2. The topographic variability in front of a bulkhead will increase because the truncated beach will experience complicated patterns of swash, backwash, wave and reflected energies, which will mobilize and redistribute sediment.

3. The sediment characteristics in front of the bulkhead will coarsen, as the finer sediments are transported away due to increased turbulence in front of the bulkhead.

These hypotheses were tested in a 14-day study conducted between June 8 and 22, 2007. The effects of two types of bulkheads and a bulkheaded enclave on swash zone profile and sediment characteristics were compared to a control site located 45 m south of the bulkhead sites. The bulkheads extended out onto the foreshore, whereas at the control site the bulkhead was above normal spring high water, and hence acted as an un-bulkheaded beach under most conditions. A video record was made of the swash and wave characteristics at the bulkhead to describe periodicity, magnitude, and type of interaction associated with different wind events. Measurements each day or after each tidal cycle (21 in total) of cross-shore topographic change indicated net erosion or accretion at each site. Depth of disturbance was measured after each tidal cycle to determine differences in the cross-shore and alongshore availability of sediment for transport. Sediment samples on five days were taken at comparable elevations to detect possible effects of the bulkhead on grain size distribution and gravel/sand ratio. Average conditions are presented and represent the change on typical days. June 22nd was a high energy day and results from this day are representative of stormy days, which is when estuarine beaches experience significant geomorphic changes.

STUDY SITES

The study took place on private beaches in Fortescue, New Jersey in Delaware Bay (Figures 3 and 4). This site was used because the bulkheads intersected the shore in the intertidal zone, allowing a comparison of a complete arrange of swash conditions during each rise and fall of the tide. In addition there was about 11 m of beach seaward of each bulkhead during low tide, allowing measurement of geomorphic conditions across sizeable foreshore width. The bay is largely comprised of washover barriers in front of marsh, with low-elevation Holocene highlands providing sediment (Kraft et al., 1979). The beaches are composed mostly of medium grained quartz and feldspar sand with a pronounced sub-population of granule and pebble-sized material (Jackson et al., 2005). Delaware Bay is a microtidal estuary with a mean tidal range of 1.6 m and a spring tidal range of 1.9 m at Cape Shore Lab (Figure 3) (NOAA, 2006). Northeasterly winds result in non-local (ocean) wave dominance (Jackson, 1995). In Fortescue, winds from the northwest will produce smaller waves, capable of transporting less sediment since the water depths are smaller and fetch distances shorter. Winds from the southeast are expected to cause the most sediment transport since there is a greater fetch distance and water depth, which will allow larger, more powerful waves to form (Figure 3b). Typically, waves are less than 0.25 m high (Jackson et al., 2005).

Non-bulkheaded beaches are narrow, only 30 m wide at low tide, with a steep, 6.3º foreshore, and flat (< 0.5º) low-tide terrace (Jackson et al., 2005). The beach at Fortescue is highly developed, with a row of summer and permanent houses lining the shore. Most of these houses are protected by bulkheads, so the beach is truncated at some point. The bulkheads do not form a continuous line, but are built at different cross-shore locations and leave small beach enclaves between properties. There are several different common bulkhead construction types.

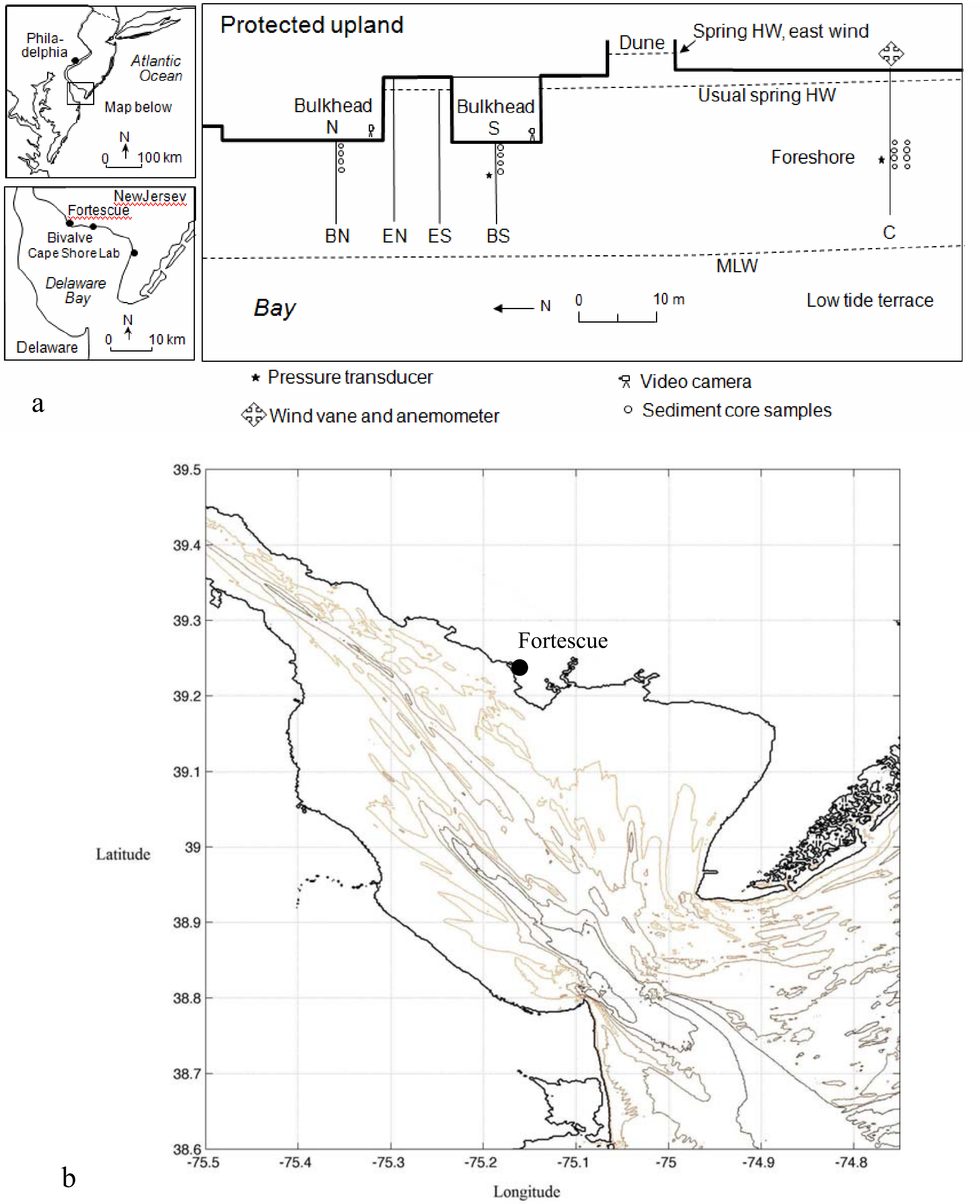


Figure 3 Map of study location and schematic of the field design (a). Bathymetric map of Delaware Bay with 5, 10, 15, and 20 m isobaths (b).

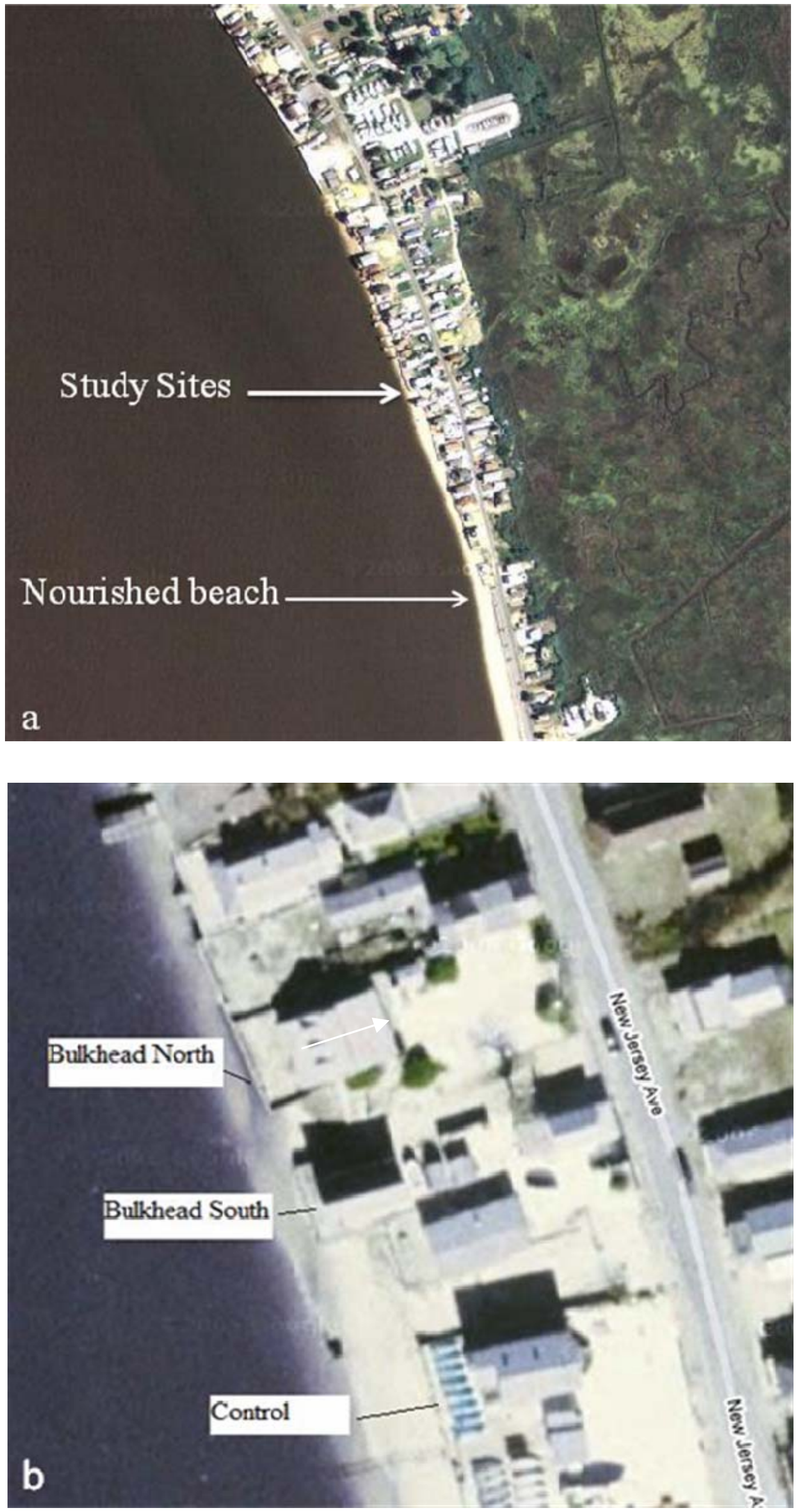


Figure 4 Aerial views of Fortescue (a) and the sites (b) near mid-tide. (From Googlemap.com, 2008)

Most bulkheads are made of wood; PVC sheetpile is another common construction material. Of the wooden bulkheads some are built of planks, with only gunwales near the top and/or bottom; others are built of planks with buttresses, and some have buttresses and vertical pilings that on the seaward side of the wall.

The four sites included in this study (Figure 3) are: two bulkheaded sites, two sites within an enclave, and a control site. A public beach 250 m to the south of the control site was nourished in 1999 with 55,000 yd^3 of sand as part of a feasibility study, so the system is not sand deficient and has had sufficient time to equilibrate (Jackson et al., 2005). Accretion at the ends of bulkheads indicates longshore transport is from south to north in this area.

Bulkhead south (BS) is separated from the north bulkhead site by an 8.58 m long enclave. Profile line BS is located in the middle (5.5 m from the north end) of the 11 m long bulkhead. BS is constructed of wooden planks perpendicular to the beach with a parallel wooden wale near the base, with vertical round wooden pilings spaced at 1.5 m intervals, with round wooden buttresses on the north side of each piling (Figure 5a).

Bulkhead north (BN) is across the enclave from BS. Profile line BN is located 5.5 m from the south end of the bulkhead (Figure 3). The bulkhead is constructed of wooden planks perpendicular to the beach and is flat-fronted, with a wooden wale parallel to the beach along the bottom (Figure 5b). Both bulkheads intersect the beach at the intertidal zone and are subject to both swash and wave interaction during the rising and falling tides. BN intersects the beach slightly more seaward (~0.5 m) than BS.

Figure 5 Bulkhead south (a) and bulkhead north (b) construction designs.

The control site (C) is located about 45 m south of the south end the bulkhead at BS (Figures 3 and 6). The beach orientation changes slightly between the control site and the bulkhead sites (Figure 4). All potential control sites at Fortescue have bulkheads somewhere on the beach. This control site was chosen because the swash and waves only interact with the bulkhead during storms or especially high spring tides, and sediment movement normally occurs as it would on an unbulkheaded beach. The bulkhead is set back 7 m landward of the front of the north bulkhead, so meter 8 on the control site (measured from the bulkhead) is at the equivalent elevation as 0 m at BN. There was no beach that met these qualifications to the north of the bulkheads.

Beach change in the enclave between BN and BS was studied to determine the significance of the small breaks in the bulkheads on beach morphology (Figure 7). The enclave is 8.58 m wide and is backed by a bulkhead that is 8 m landward of the bayward side of the bulkhead at BS. The north enclave (EN) line starts at -8 m and is 1 m from the end of the north bulkhead (Figure 3). The south enclave (ES) profile begins at -7 m, due to a staircase that obstructs the beach at -8 m and is 1 m from the end of the south bulkhead.

Figure 6 The control site with a bulkhead above normal spring high water and the anemometer and wind vane located on the bulkhead. A pressure transducer is visible on the foreshore.

Figure 7 Photo of the enclave between BN (left) and BS (right).

METHODS

FIELD PROCEDURES

Wind and Wave Processes

Wind velocity and direction were measured with a Gill three-cup anemometer and microvane located at the bulkhead at the control site. Wind velocity was measured because it determines wave height during onshore winds. Wind direction influences the types of wave or swell that impact the beach each day. Wave characteristics were measured with 2 mini pressure transducers located 4 m bayward of bulkhead BS and at an equivalent elevation at C (Figure 3). A Marsh-McBirney Model 511 electromagnetic current meter was located midway between the end of BN and BS in the enclave. Each instrument recorded data for 20 minutes at 4 Hz each hour. Wave height determines the amount of turbulent energy and sediment transport and the location of wave breaking.

Breaking Wave and Swash Characteristics

Video records of the swash were taken at both rising and falling tides for 3 minutes at 15 minute intervals to capture characteristics of swash width, wave periodicity, breaking wave location, and swash- and wave-bulkhead interactions. Wave reflection distance is important in determining the amount of offshore directed energy, the location of interaction between the incident and reflected energies, and the potential for offshore sediment transport. Incident and reflected wave periodicity is important in determining the dominant direction of potential sediment transport. Bulkhead north was filmed from the top of the south end of bulkhead south and vice versa (Figure 3). Interactions were also recorded from the top of each bulkhead shooting straight down at the area in front of each bulkhead. Five tidal events were filmed to encompass the diversity of wave conditions in the bay, including a typical low-energy tidal cycle, high energy with southwesterly winds, high energy with northwesterly winds, and a tidal cycle with sea swell.

Topographic and Surface Variability

Topographic variability and net surface change was measured using 1.5 m long, 6.4 mm diameter steel rods driven into the beach. Lines of rods at BN and BS started at the bulkhead, 5.5 m from the edge closest to the enclave, and extended offshore 11 m (Figure 3). The rods were placed at 0.5 m intervals for the first 4 m and then 1 m intervals. The enclave lines were located 1 m from the side of the bulkhead, starting at the back edge of the enclave, and were placed at 1 m intervals. The control site rods started at the front of the bulkhead at C, to a cross-shore distance of 20 meters. All profile lines ran seaward to the lower foreshore. The top and bottom of each rod were surveyed using a stadia rod and transit and tied to a datum located on the back of the enclave. The distance from the top of the rod to the surface is recorded daily. The accuracy of elevation measurements made by the rods is 0.5 mm. This method is used to explore variability in cross-shore topographic features and the amount of surface change occurring at each site, which reveals long- and short-term beach stability.

Sediment Activation Depth

Sediment activation depth affects the mobilization of sediment, larvae, and eggs. The method used to determine the sediment activation depth follows standard procedures (Greenwood and Hale, 1980) and has been used for other comparative studies (Sherman et al., 1994 and Masselink et al., 2007). A loosely fitting washer was put over each of the rods used for measuring net change variability and allowed to settle onto the beach surface. The distance from the surface of the beach to the top of the rod was recorded and then re-measured after each tidal cycle, along with the distance from the top of the rod to the top of the buried washer. Elevations were measured to the nearest millimeter and measurements always made on the north side of the rod for consistency. The washer was then reset by exhuming it and placing it on the surface after sediment was replaced and compacted to beach level with a mason's trowel.

Sediment Characteristics

Sediment size and percent gravel affects beach drainage, slope, and sediment mobilization. Sediment samples at BN, BS, and C were taken using a round 50 mm diameter clear plastic corer at 1 m intervals for 5 m across the beach starting at the bulkhead (0 m) or equivalent elevation on the control site (8 m). The cores were taken 0.5 m from the south side of the rods. Additional cores were taken at a distance of 1.5 m on the control site so that there would be as many control samples as bulkhead samples (Figure 3). The depth sampled using cores was equivalent to the maximum amount of sediment activation from the previous tidal cycle as determined by washer depth. The cores were extracted after placing a mason's trowel below them to ensure that a level and complete sample was collected. Samples were bagged and labeled with a location, time, and date. Cores were collected on 5 occasions to represent activated sediment characteristics under different wave conditions. June 9th samples at 4 m on the control site were not collected. On June 22nd there was no sediment activation at 1 and 2 m on the control site, so no samples were collected.

LAB ANALYSIS

Wave and Wind Processes

Measurements from the pressure transducers are recorded as millivolts. These records are converted to distance above the bed by subtracting the offset (averaging about 0.001) and subtracting the height of the pressure transducer from the surface, which varied from day to day based on local erosion or accretion. Wave heights are estimated calculations derived by multiplying the standard deviation of the 20 minute pressure transducer records by four, which is a standard procedure used in other studies (Komar, 1976; Nordstrom and Jackson, 1992).

The wind direction was derived by converting the number of millivolts sent back by a potentiometer in the wind vane to degrees through a calibration using 0.24 mv/degree, where 670.37 mv is equivalent to 212 visual degrees. The offset between the vane record from the field and the actual magnetic azimuth is 51.2° and is found by subtracting the number of degrees recorded, 160.8° (670.37mv*0.24mv/degree) from the visual record (212°). Therefore each wind vane record must be calibrated using the formula: (mv*0.24) + 51.2. There was instrumental dead space between 355° and 360º, so 355° was subtracted from any value that exceeded 355 º. Wind vane position minimized the effect of the dead space by aligning the dead space with the closest buildings landward of the beach.

Breaking Wave and Swash Characteristics

Each video record was reviewed in 1.5 to 3 minute intervals for location of breaking, distance of swash uprush, and reflected wave distance. 1.5 to 3 minutes is the time it takes for at least 20 waves to break. Location of wave breaking was considered the average location where the wave was converted into swash during each interval. The profile rods were used to estimate distances and locations. The wave periodicity was visually averaged over several records on each day. Periodicity was determined by counting the number of waves that broke at the break point in a 30-second interval. Types of wave, swash, and reflected wave and swash interactions were recorded for each segment. Constructive and destructive swash, wave, and reflected energy interference, details of movement of reflected swash, wave, and reflected energies, and other interaction details were noted for each interval. Visual comparisons of velocity and volume of unimpeded swash and waves with swash and wave reflected energy revealed information on relative incident and reflected energy and potential for sediment transport. The turbulence was visually gauged by comparing color and amounts of bubbles in the swash, wave, and reflected energies at times of different amount of interaction at each bulkhead. Water becomes less clear and bubbles increase with turbulence. Beach saturation and swash drainage patterns were also apparent from the color of sand and amount of backwash or reflected swash. The beach appears darker and there is a greater volume of backwash where saturation is higher.

Topographic and Surface Variability

Each profile measurement is tied to the common datum by finding the difference between the elevation of the top of the rod and the elevation of the datum, then adding that value to each subsequent elevation measurement at the rod. Daily variability within and between sites in beach profiles are compared and sweep zone profiles representing the entire period are used to compare steepness, concavity, and the amount and location of topographic change.

The net change of the volume of sand on a profile was determined by subtracting the current surface elevation from the surface elevation measured after the previous tidal cycle, so that positive values indicate accretion and negative values indicate erosion. Averages and standard deviations were calculated for each site by day and elevation. Net change was plotted as bar charts by site, with each day represented by a different bar type and cross-shore distance on the x-axis. Net change bar charts allowed a visual comparison among sites, date, and distance for how and when the changes in sediment volume occurred. Averages and standard deviations for each cross-shore location, day, and site were also calculated. A temporal average over the 20 low-energy days by cross-shore distance with standard deviation shows how much erosion or deposition occurred through the study period and how much daily variability occurred at each site.

Sediment Activation Depth

The depth of sediment activation was calculated by subtracting the washer depth from the surface elevation on the previous day. Sediment activation depth measurements are the net result of sediment accretion or erosion during the preceding tidal cycle and the sediment activated due to turbulent processes. These values will underestimate the amount of sediment activation on days of accretion. Comparing the difference between the depth of the buried washer and the post-event surface elevation with the activation depth value calculated using the surface elevation on the previous day identifies the maximum amount of sediment activation during accretion. These values were similar though the post-day calculation were generally slightly larger (~0.015-0.02 m), so the values reported using the previous day's surface may underestimate the sediment activation depth. Horseshoe crab spawning on the control and enclave sites caused large cross-shore areas of sediment activation beyond the normal range (>50 mm). These values were removed prior to calculating the average. Sediment activation depth values were plotted as bar charts for each site with each day indicated by a different bar type and cross-shore distance on the x-axis. The temporal average bar chart is for the 20 low-energy events and allows a visual comparison among sites and cross-shore distance. The standard deviations of the averages were computed for the low-energy days and represent the daily variability in the amount of sediment activation at each site. The high energy event is also presented as a bar chart by site and cross-shore distance.

Sediment Characteristics

Each of the 194 sediment samples was washed to remove organics, dried in an oven, and then weighed to the nearest 0.001 g. If the total sample weight exceeded 140 g the sample was divided using a splitter, to assure a representative subsample of 70 to 140 g. A Ro-Tap machine was used to separate the sediments by size using 200 mm diameter sieves at 0.5 Φ size intervals. Initially, each subsample was sieved, weighed, and values in each size class compared as a check for consistency in the sediment distribution of the splits. Since they proved consistent, only one of the splits was run on subsequent samples. The sediment from -4 Φ through 0 Φ was hand-sieved and weighed at 0.5 intervals between 0 and -2 Φ (see Table 1 for size conversions). The Ro-Tap was set for 15 minute intervals to sieve sediment between 0.5 to 4 Φ. The size classes commonly used in geology are phi values, which is a logarithmic scale that makes it easier to compare a wide range of sediment sizes, which in this study range from sub-millimeter to greater than 16 mm. Gravel is considered anything equal to or larger than -2 Φ; granules fall between -2 and -1 Φ, while sand is between -1 and 4 Φ. Each sieve was emptied by tapping the sieve on the lab bench and the sediment from each size fraction was weighed and recorded to the nearest 0.001 g.

Table 1 Comparison of the sediment size class, phi values, and metric size in millimeters.

Sediment Conversion Chart				
Size Class	Phi	mm		
	-4	16	Gravel	
1	-2	4		Granules
2	-1.5	2.83		
3	-1	2		
4	-0.5	1.41	v. coarse	Sand
5	0	1		
6	0.5	0.71	coarse	
7	1	0.5		
8	1.5	0.35	medium	
9	2	0.25		
10	2.5	0.18	fine	
11	3	0.13		
12	3.5	0.09	v. fine	
13	4	0.06		

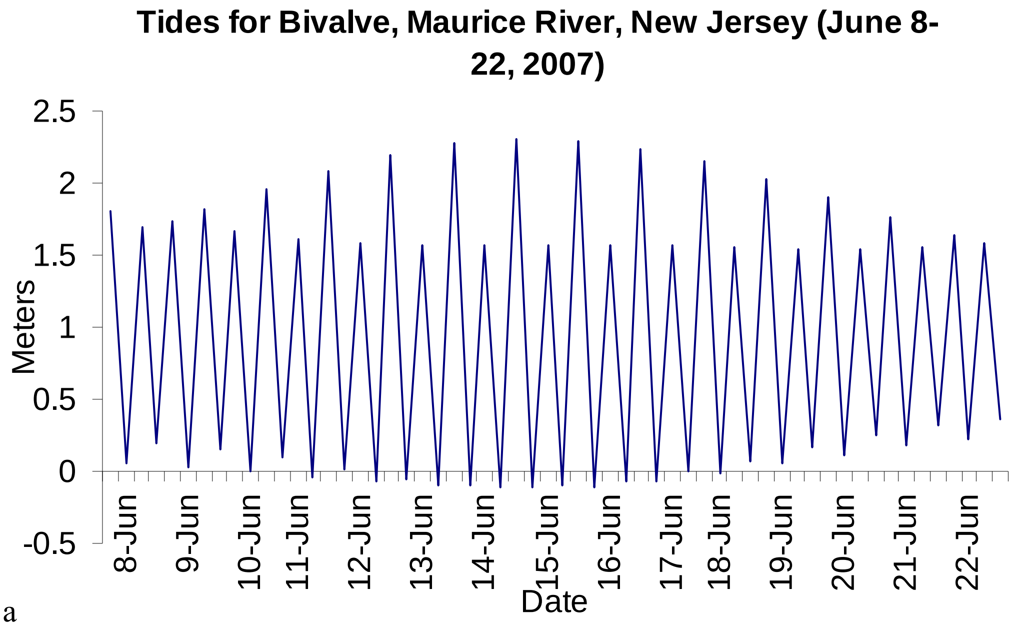
The gravel fraction in each sample was calculated using: (Sample Weight ≥4 Φ /Sample Weight) *100. The gravel fraction was removed before determining the arithmetic mean, which was calculated using the Folk and Ward (1957) method in the GRADISTAT Excel program (Blott and Pye, 2001). The gravel fraction was removed because the samples varied in weight and size distributions which rely on weight in each size class and could be biased by surface lag deposits. These surface lag deposits may only be one large clast in the sample, but could contribute greatly to the sample weight, particularly in very small samples, increasing the mean grain size. According to Mason and Coates (2001) when a beach is <25% gravel, it behaves as a sand beach. Removing the gravel before calculating the mean reveals how process alterations affect the sediment characteristics. The mean was computed using the 16, 50, and 84 Φ percentiles.

Multivariate analysis of variance (MANOVA) was used to compare differences between the means in each size class by beach type (bulkheaded or non-bulkheaded), sampling date, and cross-shore location. The power of MANOVA lies in its ability to compare large amounts of information across several variables. In MANOVA significant p and f values lead to the rejection of the null hypothesis that the arithmetic means are not significantly different (McGarigal et al., 2000). The sediment was reported as a percent weight in each size class: % Weight = 100*(Mass (g)/Total sample mass (g)). The gravel portion (>4 mm) was not given a size class, since the percent weight measure is a standardized measure and it is necessary to remove one size class from the matrix. The sediment size classes were sequentially numbered 1 through 13, starting with the coarse sediment (Table 1). Beach type (bulkheaded or control), date, distance, and each size class were the matrix rows. The partial correlation coefficients of the sites were used to determine if the sediment samples from the two bulkhead sites and at the control site behave similarly. All statistical computations were completed using the computer program SAS.

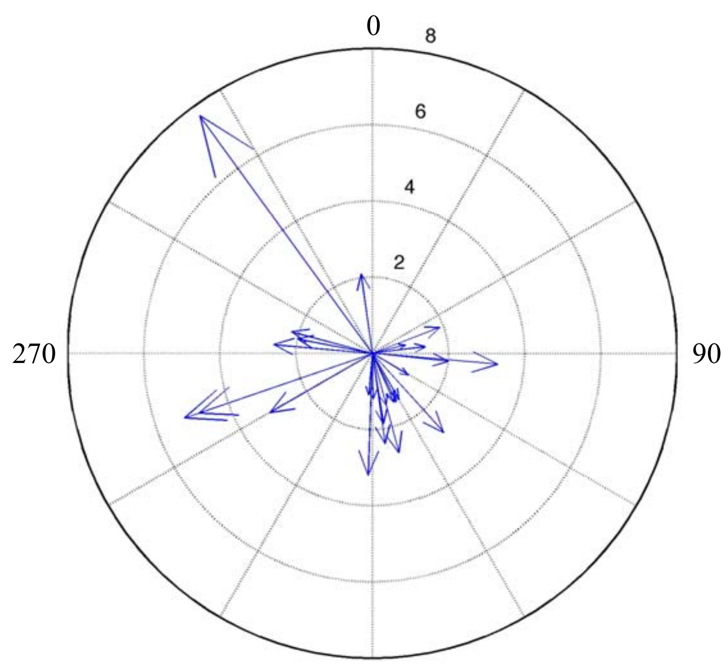
RESULTS

Wind and Wave Processes

Tidal records from Bivalve, New Jersey on the Maurice River show that over the two-week study, the tidal range varied from 1.6 to 2.3 m at high tide. The greatest tidal range was 2.3 m on June 14th and was associated with the spring tide during the new moon phase (Figure 8a). The smallest tidal range was 1.6 m June 20th. Weather conditions during the deployment range from light winds (June 10th, 12th, 15th, 19th) to storm conditions (June 22nd) (Table 2). Offshore (east) winds reduce the effects of locally-generated waves, so that ocean swell is conspicuous on some days (June 14th) or wave heights are reduced (June 10th and 13th) (Figure 8b). Strong onshore (west) winds produced energetic conditions on the 16th and 17th (Figure 8b). All days except for the 22nd have low wind speeds, which produce waves with mean significant wave heights ranging from 0.15 to 0.24 m. Beaches with mean significant wave heights < 0.25 m are considered low-energy (Jackson et al, 2002). Under these low energy conditions little geomorphic change will occur. Differences in bulkhead effects on low energy days and storm days when estuarine beaches experience the most change are determined by comparing mean results with results from June 22nd. On June 22nd strong NNW winds averaging 7.65 ms^{-1} produced high energy waves with mean significant wave height of 0.28 m.



a



b

Figure 8 Tidal range in meters at Bivalve, New Jersey on the Maurice River (a) and a wind rose with wind direction in degrees and wind speed in ms^{-1} for the study period.

Table 2 Mean wind speed and direction at C and significant wave height at C and BS during the study.

Date	Time	Direction(°)	Speed (m/s)	Sig. wave height (m) Control Site	Sig. wave height (m) Bulkhead South
8-Jun	pm	N/A	N/A	N/A	0.14
9-Jun	am	N/A	N/A	N/A	0.25
9-Jun	pm	97	2.4	N/A	0.17
10-Jun	am	83	1.4	0.14	0.14
10-Jun	pm	165	2.7	0.18	0.15
11-Jun	am	275	2.6	0.15	0.15
11-Jun	pm	165	1.4	0.17	0.16
12-Jun	am	179	1.2	0.13	0.13
12-Jun	pm	185	1.1	0.16	0.16
13-Jun	am	96	2.0	0.14	0.13
13-Jun	pm	95	3.3	0.24	0.24
14-Jun	am	69	1.9	0.18	0.15
14-Jun	pm	76	0.9	0.21	0.21
15-Jun	am	121	1.1	0.17	0.17
15-Jun	pm	172	2.4	0.22	0.22
16-Jun	am	240	3.1	0.26	0.19
16-Jun	pm	281	2.0	0.18	0.24
17-Jun	am	285	2.2	0.21	0.15
17-Jun	pm	251	4.8	0.22	0.19
18-Jun	am	182	3.2	0.15	N/A
18-Jun	pm	156	1.4	0.2	0.10
19-Jun	am	150	1.4	0.20	0.19
19-Jun	pm	138	2.8	0.25	0.17
20-Jun	am	154	1.42	0.18	0.17
20-Jun	pm	171	1.87	N/A	0.20
21-Jun	am	352	2.10	0.20	0.17
21-Jun	pm	251	5.21	0.14	0.15
22-Jun	am	324	7.7	0.28	0.29

Breaking Wave and Swash Characteristics

Video records of the swash reveal that the most common type of reflected energy occurs when the periodicity of the incident wave is long enough to allow the reflected wave to move seaward without interfering with the incident wave. When this happens the reflected wave moves past the breaking point of incident waves. There are two main types of interactions of incident and reflected wave energies: destructive and constructive (Figure 2). For example on June 19th, the strong, reflected waves diminish the velocity and volume of the incident waves, cutting off the white caps on incident waves and continuing seaward. Under low incident periodicity conditions the reflected wave can slow or diminish the energy of the incident wave by forcing it to break seaward of the normal breaking point. At times this interference results in a vertical spray of water and either complete or partial destruction of incident and reflected waves. The reflected wave sometimes breaks the crest off the incident wave; at other times the incident wave destroys the reflected wave, leaving no visible reflected energy.

There are differences in energy reflectance and sediment transport competence based on bulkhead construction type. On the overhead recording of wave-swash interactions at BS, the pilings break up the reflectance pattern and slow the water movement, allowing sediment to settle. The sharp breaking wave angle on the 19th may explain why the pilings were especially effecting at breaking the reflectance up on this day. There was a much stronger shore parallel component on the 19th, so water moved between the pilings, along the shore, slowing or trapping the reflected energy more.

A standing wave was generated at times at the bulkheads. The incident wave and the reflected wave reach a harmonic frequency, resulting in a greater momentum and energy at certain wave periodicities or velocities. When the incoming and reflected wave velocities appear to be equal, a standing wave forms with a node at 1 m that moved offshore to between 1.5 and 2.0 m with the ebb tide.

Wave and reflected energy, periodicity, and velocity appear to determine the potential for cross-shore sediment transport. Low periodicity incident waves with strong reflected energies are more likely to transport sediment offshore. Location of wave breaking is also important: when waves break within about 1 m or less of the bulkhead they interfere with the reflected wave, leaving little room for a net movement of sand in either direction as the incoming and reflected turbulent energies combat each other. Since the incident wave breaks within the zone of maximum sediment transport, it appears to prevent a net offshore sediment transport.

The beach seaward of BS has a unique drainage pattern (Figure 9). Seaward of BN the sand drains in a pattern that reflects the shape of the previous swash uprush, but at BS the areas in front of the pilings drain slower than in front of the planar portion of the bulkhead. Drainage speed decreases exponentially from the midpoint of the planar sections, which has the quickest drainage time. The slower drainage results in a higher swash uprush in front of the pilings. Observations of topography in front of the south bulkhead show mounding of sediment in front of the planar sections that reaches a low point at the pilings (Figure 10).

Recordings of the enclave during the ebb tide show that the distance the swash travels into the enclave is about equal to the distance the reflected wave travels offshore. During the record on June 14th the waves break about 1 m into the enclave and the swash moves about 2.5-3 m beyond the break point, the same distance the reflected wave moves offshore. On days when the onshore winds impede the reflected wave movement and drive the swash higher into the enclave (June 16th), the swash travels 3-4 m into the enclave, while reflected energies travel 1-2 m offshore.

Less transparent waters with increased bubbles and jetting of water is evidence of increased turbulence in front of the bulkheads. Jetting (Figure 11) occurs when the incident wave breaks at or directly seaward of the bulkhead creating vertical and seaward jets of water, along with increased bubbles and turbulence on the surface. The largest jets are produced at the planar bulkhead when water is trapped at the lower wale on the bulkhead.

Figure 9 The differential drainage in front of the north bulkhead.

Figure 10 The alongshore topographic variability in front of the south bulkhead is irregular, with mounds in front of the planar sections of the bulkhead. Also evident is the decrease in surface elevation from south to north.

Figure 11 Jets of water produced during rising tide at the north bulkhead as waves break in front of or at the bulkhead and water is trapped between the wall and lower gunwale.

Incident and reflected wave velocity and frequency determine the type of interactions. Since there are a variety of wave sizes throughout the tidal cycle, different types of wave interactions occur. Overall the largest waves and swash reflections occurred at BN, particularly on the ebb tide, which have reflections out to 1.5 m regularly and up to 2.5 m away. Reflected waves and swash are almost nonexistent at BS on the ebb tide and are small on the flood tide, normally only visible out to 0.5 m. Over one tidal cycle, the swash and waves will interact with the bulkheads for about 2 to 3 hours with significant wave height of 0.135 to 0.276 m and periods of 0.13 to 0.5 seconds.

Topographic and Surface Variability

The control site has much less topographic variability than at the equivalent position in front of and adjacent to the bulkhead sites and is less steep than at the bulkhead sites (Figure 12). The general shape of each profile does not change during the course of the study (Figure 13). Sediment is added or removed from each profile, but the location of topographic features like steps and the steepness and concavity of the profile remain the same. There is some day-to-day variability in the relief of steps. The interior of the enclave near the ends of the bulkheads experience high daily variability: between -3 and 3 m at EN and -3 and 1 m at ES. The daily variability affects the concavity of the profile over short distances.

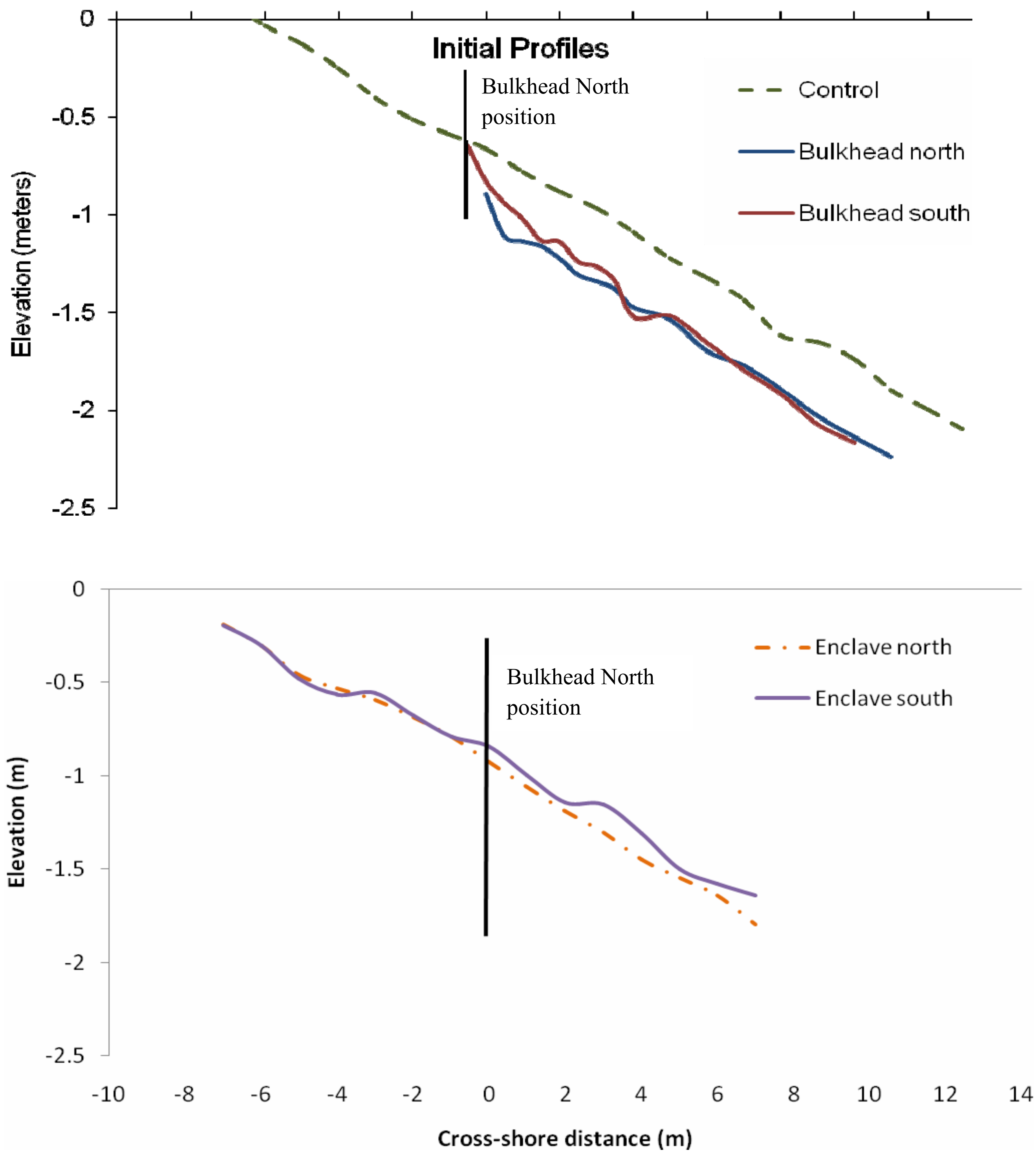
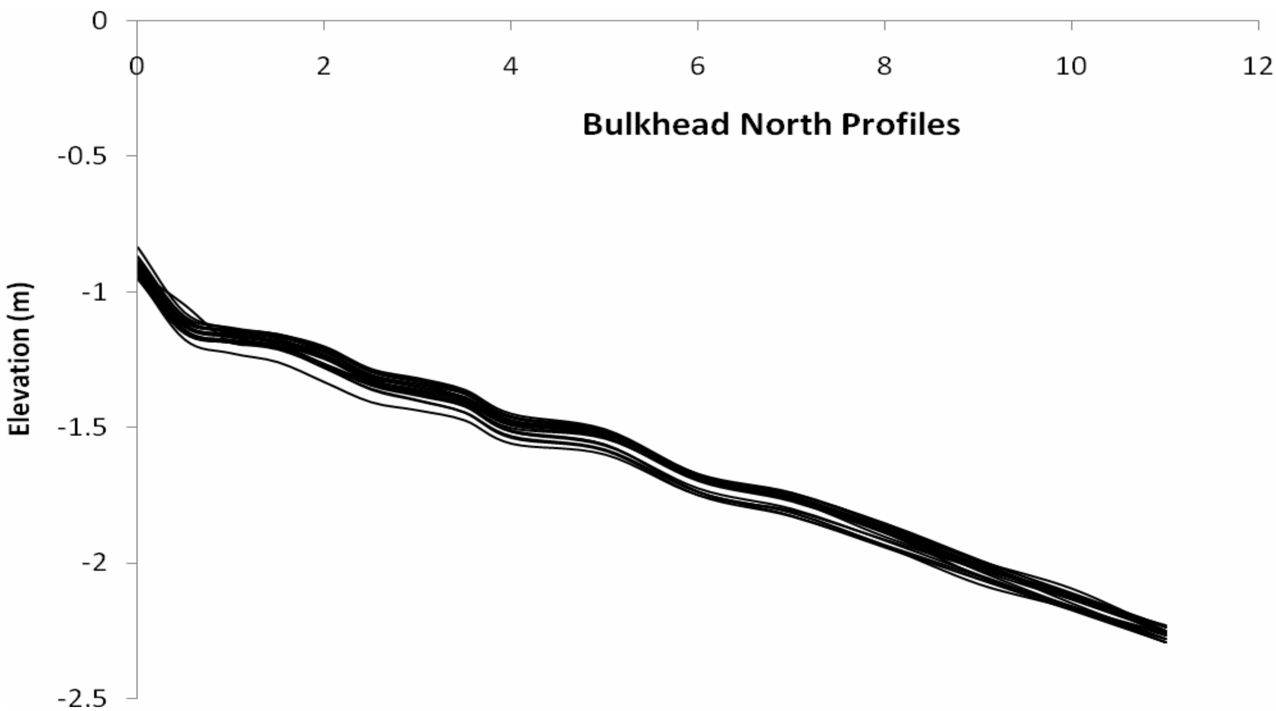
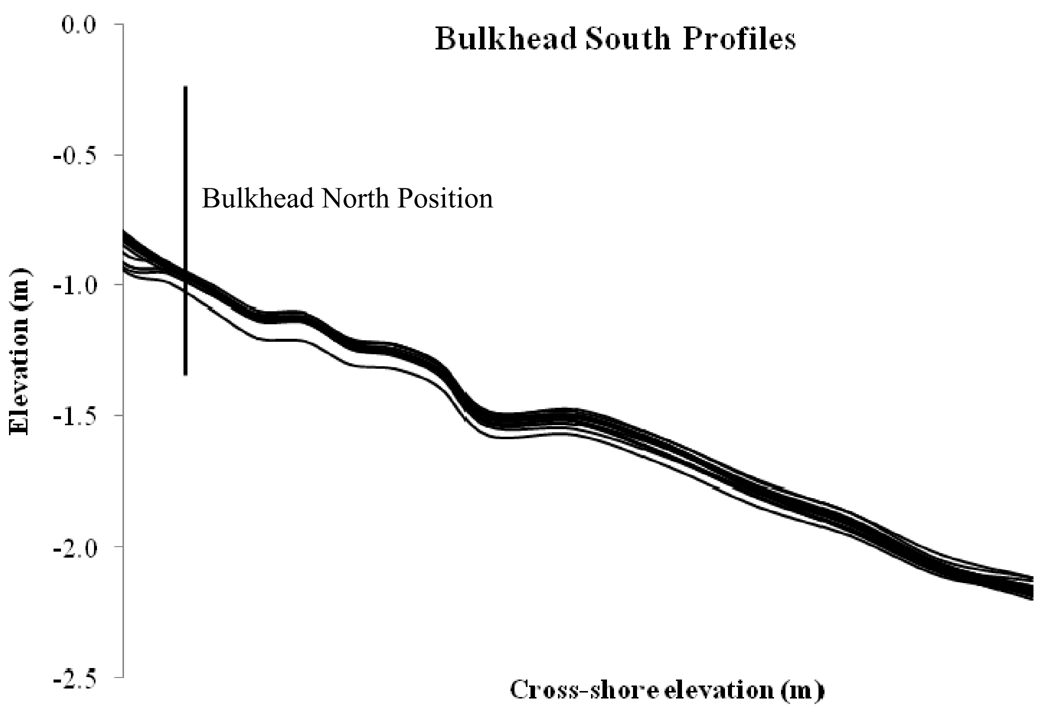
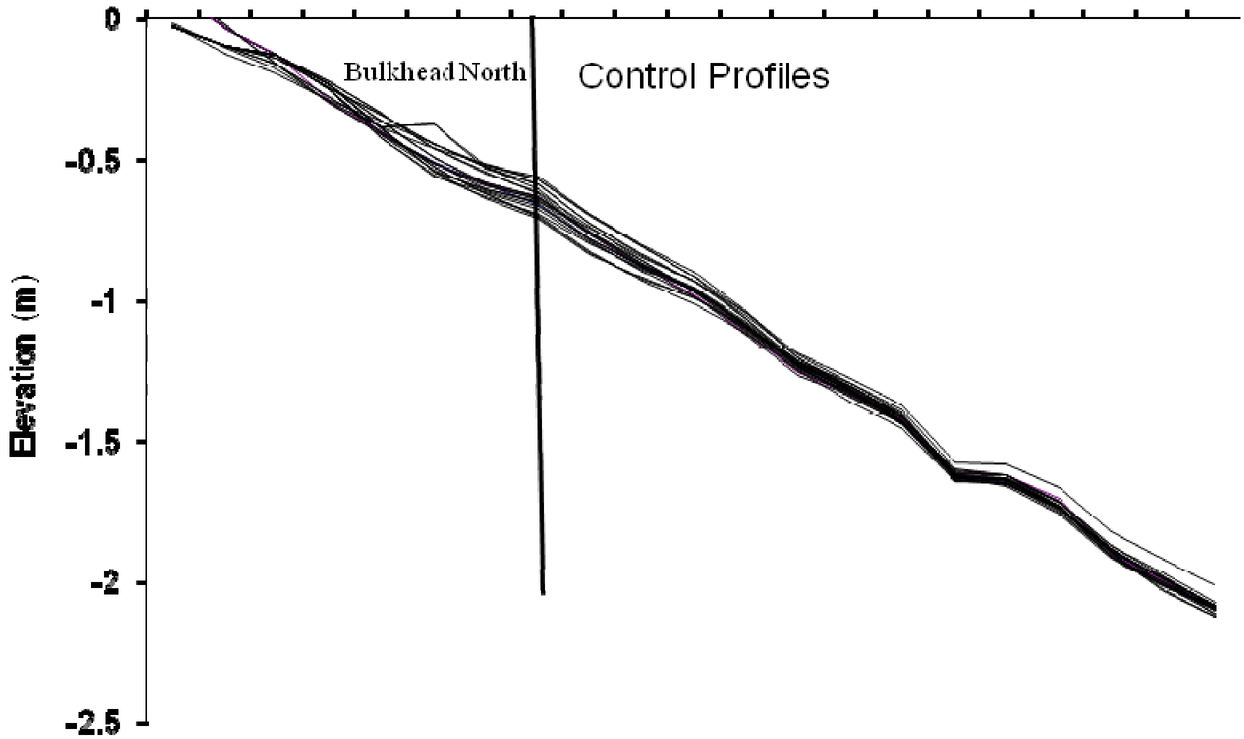
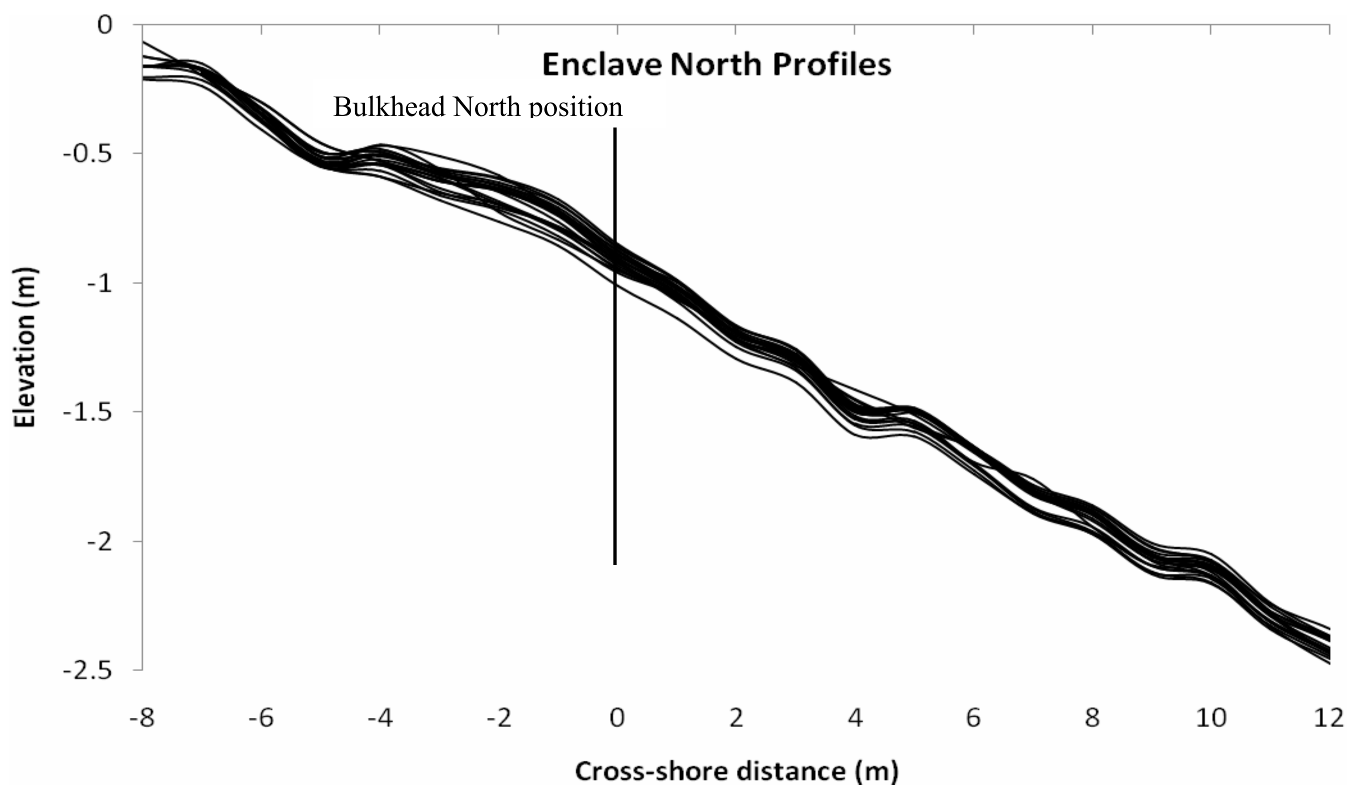


Figure 12 The initial profiles (June 8th) for the sites shows the steeper profile out to 0.5 m at BN and 1.5 m at BS and greater topographic variability of the bulkhead and enclave sites.


Bulkhead North Profiles
Elevation (m)
0
-0.5
-1
-1.5
-2
-2.5
0
2
4
6
8
10
12


Bulkhead South Profiles
Bulkhead North Position
Elevation (m)
0.0
-0.5
-1.0
-1.5
-2.0
-2.5
Cross-shore elevation (m)


Control Profiles
Bulkhead North
Elevation (m)
0
-0.5
-1
-1.5
-2
-2.5


Enclave North Profiles
Bulkhead North position
Elevation (m)
0
-0.5
-1
-1.5
-2
-2.5
-8
-6
-4
-2
0
2
4
6
8
10
12
Cross-shore distance (m)

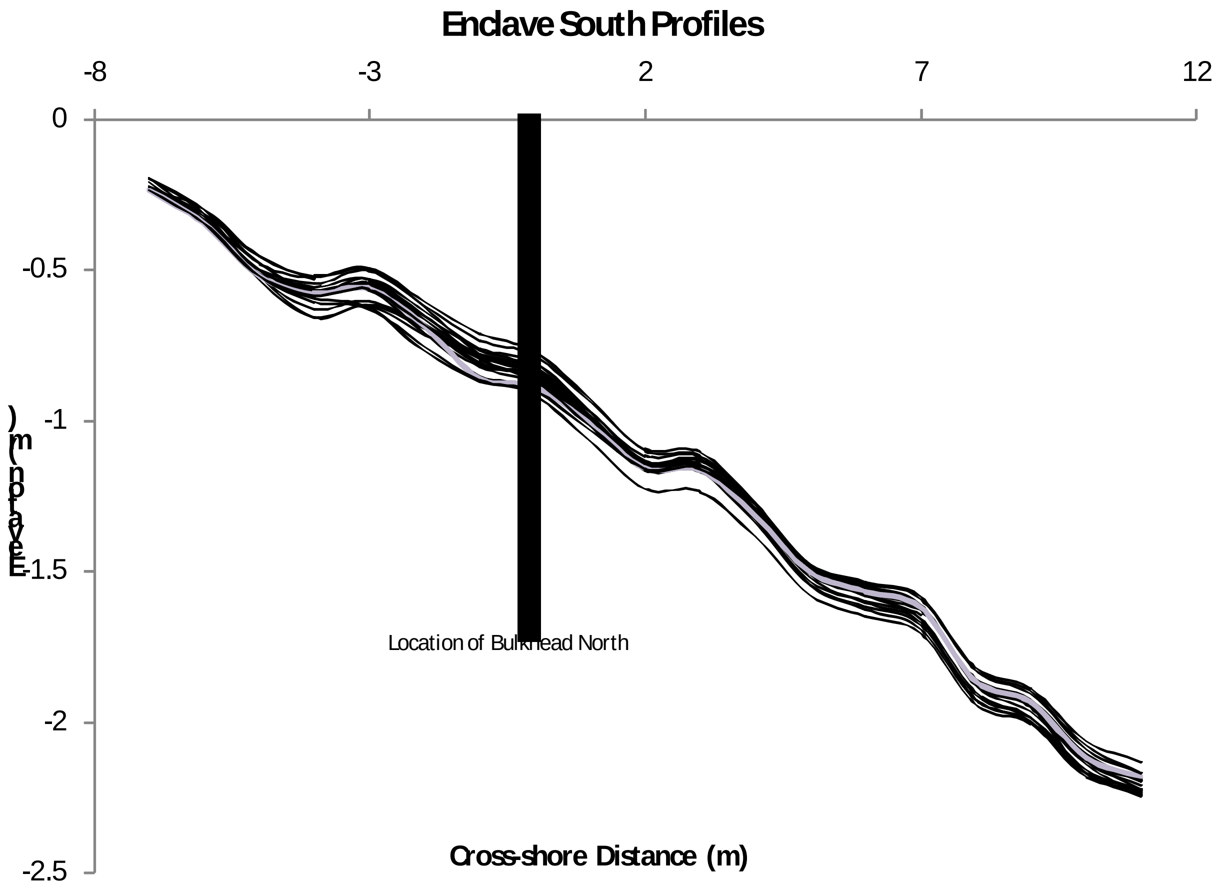


Figure 13 Sweep profiles (June 8-June 22) at BN, BS, EN, ES, and C show greater net surface variability at C, but overall stability at all sites. EN experienced the most surface change between 0 and -3 m. The vertical line identifies the elevation at which BN intersects the foreshore on June 8^{th}.

The amount of topographic variability increases towards the north (Figure 12). C has a linear profile with the exception of a step at 8 m. BS has three steps at 2, 3, 5 m and a steeper profile in front of the bulkhead out to 1.5 m. ES also has three steps located at -3, 0, and 3 m. EN has four steps located at -5, 2, 4, and 9. BN has four steps at 1.5, 3.5, 5, and 7 m. The beach is steeper in the first 0.5 m in front of BN. Like the beach seaward of the bulkheads, the enclaves have increased topographic variability, but unlike the beach seaward of bulkheads the enclaves do not have steeper profiles. ES and BS have higher relief changes.

The average net surface change for all low-energy days is negligible (Figure 14). ES lost almost 17 mm of sediment at -3 m, the largest average net change of any site. There is increased variability in daily surface change directly in front of the bulkheads, which have 41 (BN) and 25 (BS) mm standard deviations at 0 m over the low energy days.

Two main patterns of sediment movement occur on the beach at all sites. The first is a cross-shore shift in sediment resulting in local slope change. One example of this is at the control site on June 14th, where there is erosion on the upper portions of the profile, between -5 and -6 m and accretion between 7 and 12 m (Figure 15). The second pattern of sediment movement is a parallel slope retreat with uniform elevation change. After the high energy event on June 22nd all sites experienced parallel slope change. There was an average erosion of 51 mm across the control profile and an average gain of 46 mm and 74 mm at BN and BS respectively (Figure 16). The smallest surface changes occurred directly in front of the bulkhead. The enclaves gained an average of 80 mm of sediment during this event.

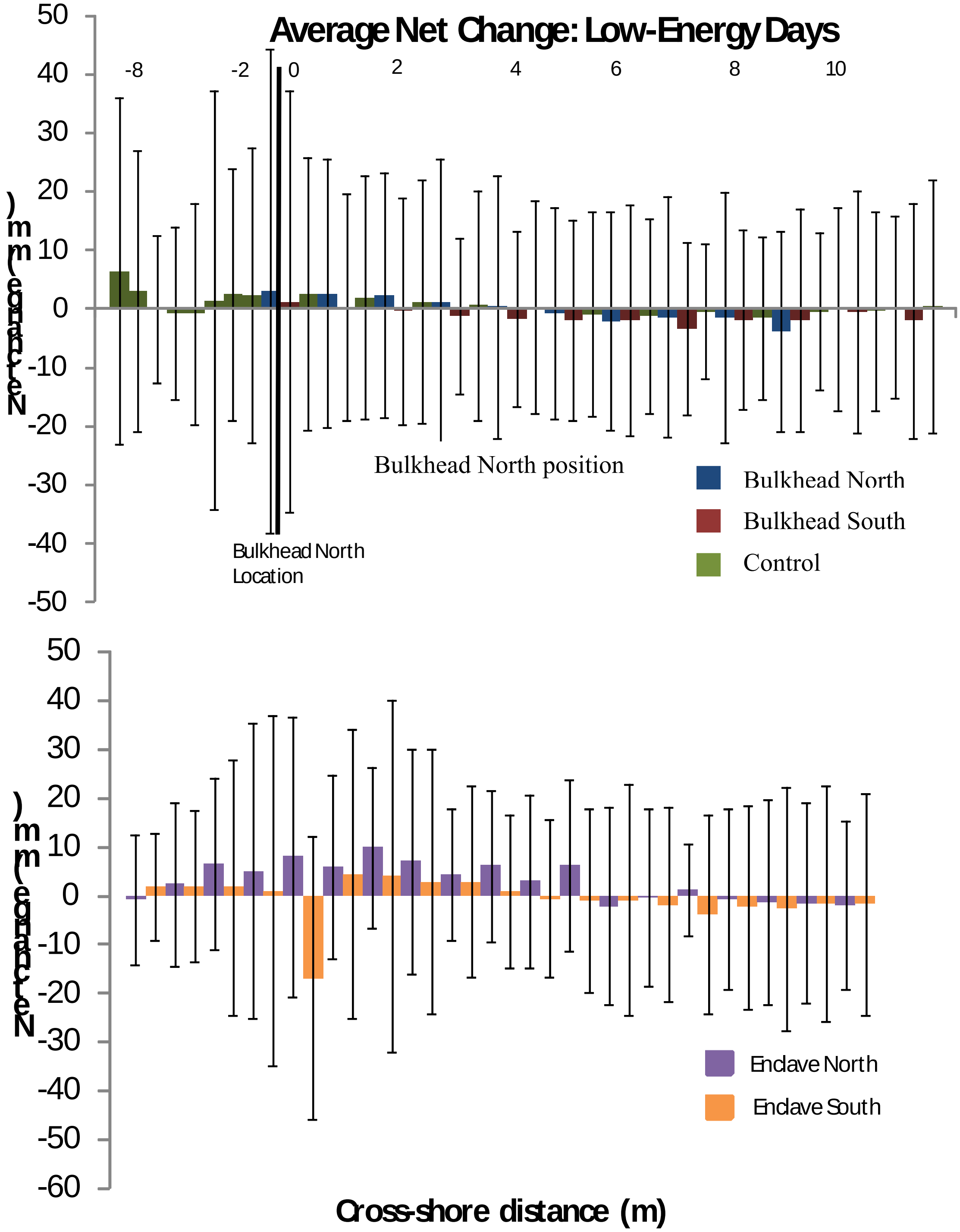


Figure 14 Average net change over the low-energy days (bars) with standard deviation (vertical lines).

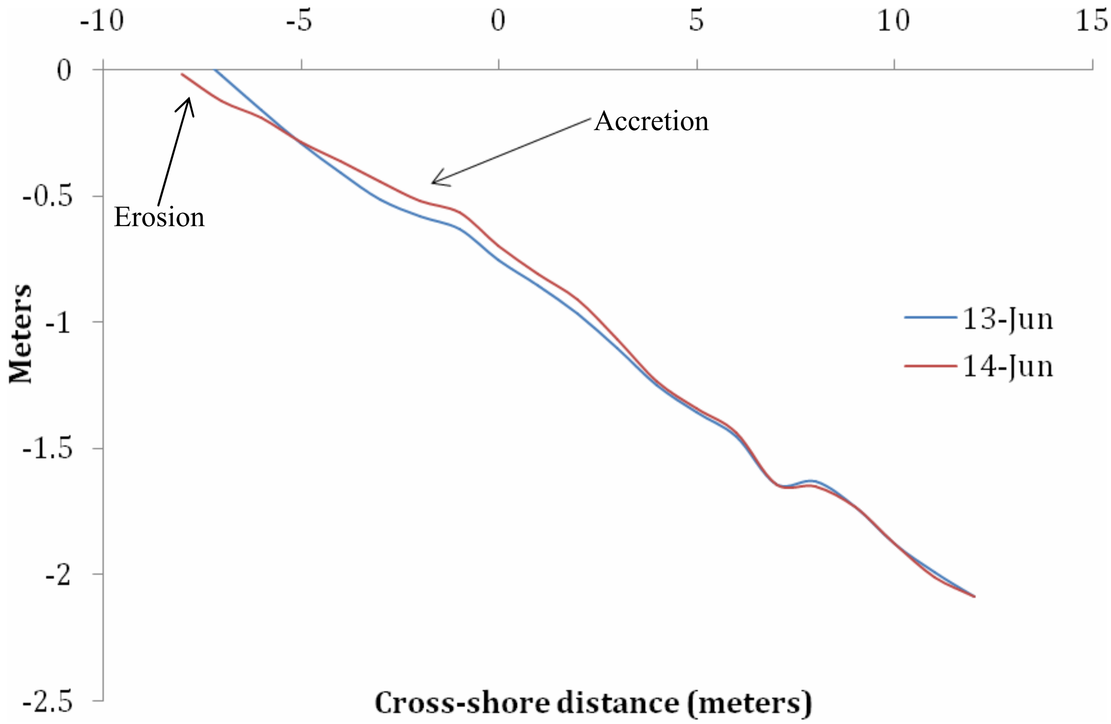


Figure 15 Cross-shore sediment shift at the control site.

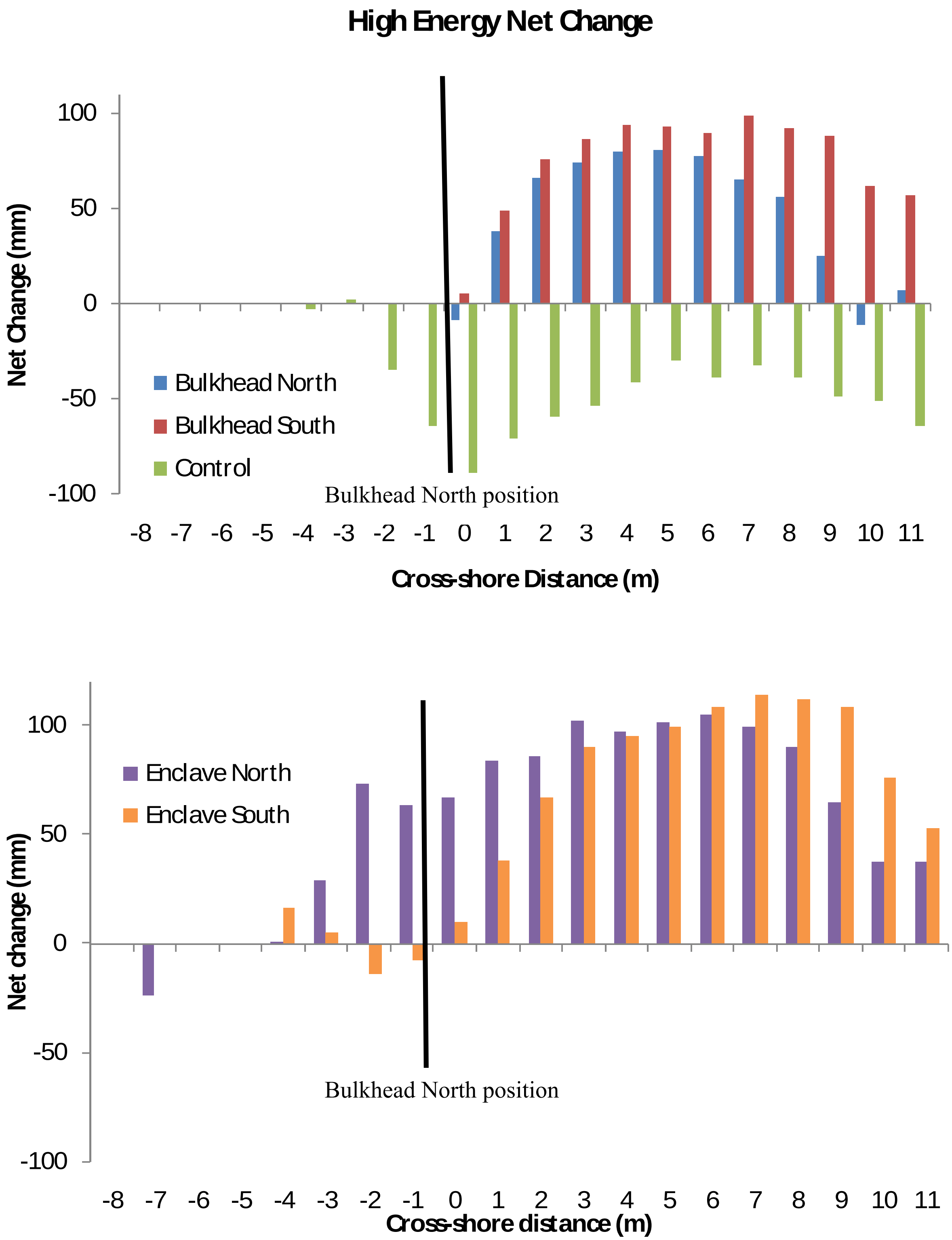


Figure 16 Net change on June 22nd, the high energy day.

Another pattern of sediment movement is a reversal in erosion and deposition that sometimes occur over consecutive tidal cycles (Figure 17). For example, on June 16th there was erosion between 0 and 2 m and between 10 and 11 m after the high tide at 2300, while after the first high tide on the 17th at 1200, there was accretion between 0 and 2 m and at 10 and 11 m.. Reversals in accretion and erosion between the two tidal cycles occur 3-5 times at each bulkhead, 2-3 times at limited portions of the enclave, and only once at the control site between 9 and 12 m. Thus this sediment movement pattern most frequently occurs on beaches seaward of or adjacent to bulkheads.

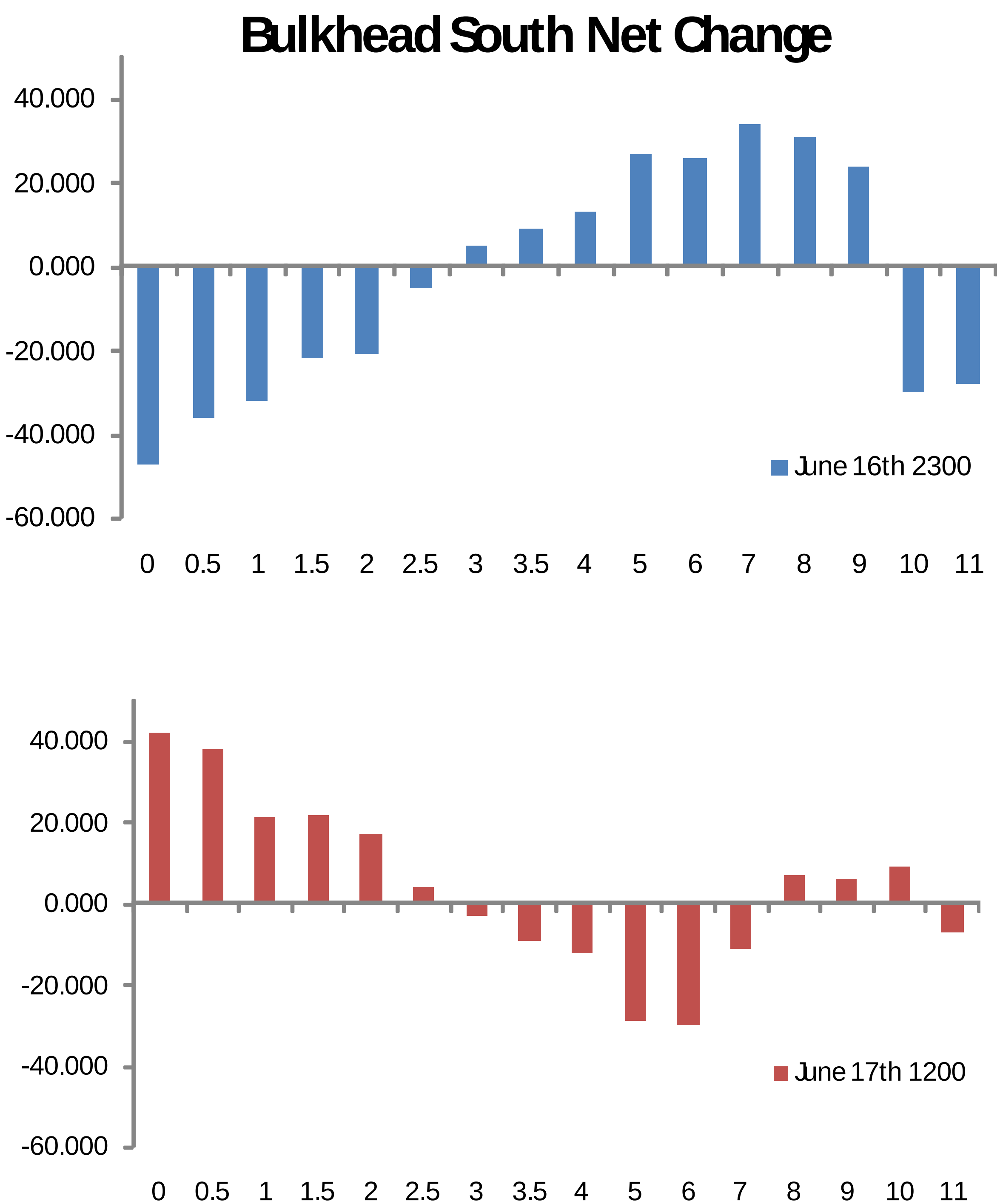


Figure 17 A shift in sediment erosion and accretion by tidal cycle is most common on beaches seaward and adjacent to bulkheads.

Sediment Activation Depth

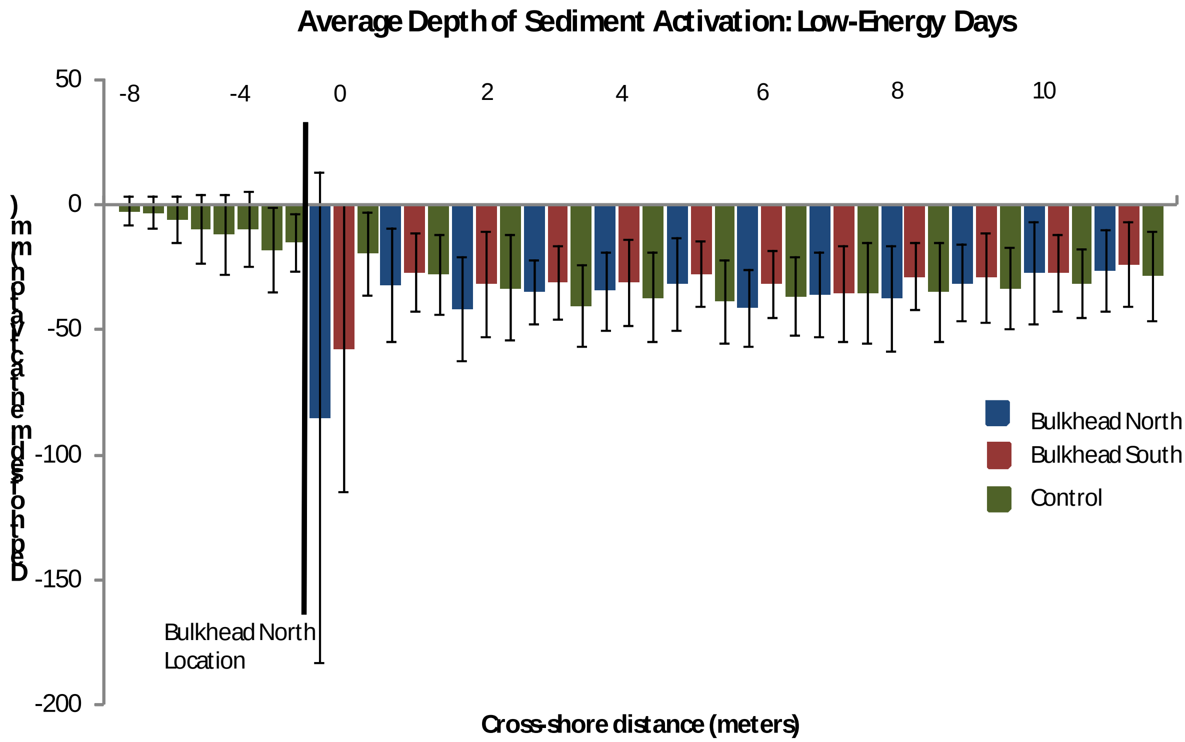
The bulkhead sites have the greatest mean sediment activation depths (BN -38 mm and BS -32 mm), followed by the enclaves (EN -25 mm and ES -30 mm); the control site has the smallest (-23 mm) (Figure 18). A comparison of the standard deviation of the means of all rods on all low energy days shows that the bulkhead and enclave sites have greatest amount of cross-shore variability in depth of activation, while the control site has the least variability (Figure 18). More sediment is activated directly in front of the bulkheads (0 m) than at any location on the control or enclave sites. BN has the greatest mean activation depths (0 to 2 m). For the rest of the cross-shore locations, the activation depths are similar at all sites.

The average maximum activation depth at C is 40 mm at 3 m. A zone of high activation depths occurs between 3 and 8 m, while landward and seaward there is a steady decrease in activation depths. The activation depth at both BN and BS varies little across the profile except at 0 m, where maximum average activation depths are 85 and 57 mm respectively. On average, the maximum activation depth is 37 mm at 6 m at EN. The greatest average activation depth of 70 mm occurs at -1 m at ES and is the maximum for this site. Landward sediment activation values gradually taper off to 2 mm of activation at -7 m, while the seaward values are between 27 and 37 mm.

On a single event, up to 277 mm of sediment was activated at BN. Even factoring in the erosion of 66 mm of sediment on June 17th, a turbulent *in situ* mixing of 211 mm at BN is large for an estuarine beach. On the same day there was 47 mm of erosion and 137 mm of turbulent mixing at BS. The west and northwest winds, which occurred during the first tidal cycle on June 11th and 17th, appear to cause the greatest amount of sediment activation at 0 m in front of both bulkheads.

Activation depths associated with the high energy event on June 22nd are higher across the shore (Figure 19). Activation depths increased at all sites, but not all of this increase was due to *in situ* turbulent mixing. The large activation depths at C are also attributed to erosion. The negligible net surface change at BN and BS mean that the large activation depths at 0 m are due entirely to turbulent mixing. The rest of the locations on BN and BS and EN and ES had sediment deposited over the profile, which could cause the sediment activation depths to be less than the amount of *in situ* mixing.

Horseshoe crab spawning on the control site resulted in some large activation depths on June 9th between 1 and 9 m, June 14th between -3 and 2 m, June 15 between -2 and 3 m, and June 16th between -3 and -1 m. Spawning at EN on June 9th between -1 and 1 m, June 15th between -5 and -4 m, June 19th between -6 and -2 m, and June 21st at -1 m caused large depths of sediment activation of up to 156 mm. These points were removed prior to calculating means. No spawning occurred at BN, BS, and ES.



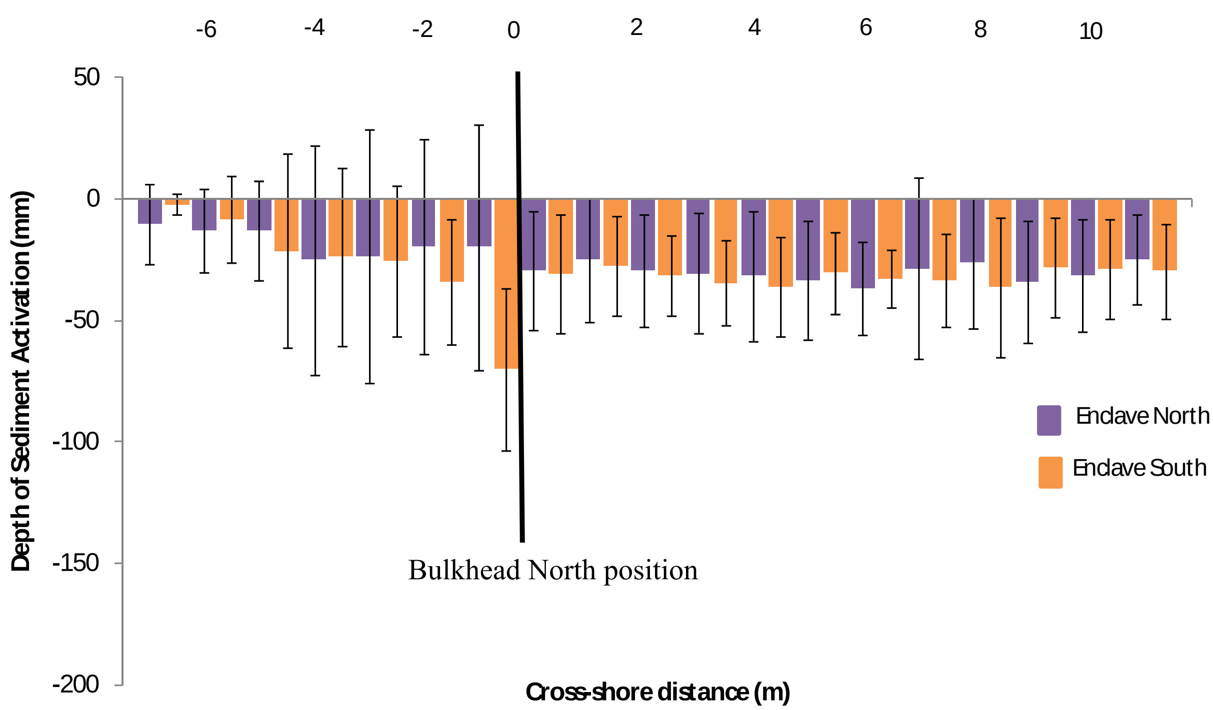
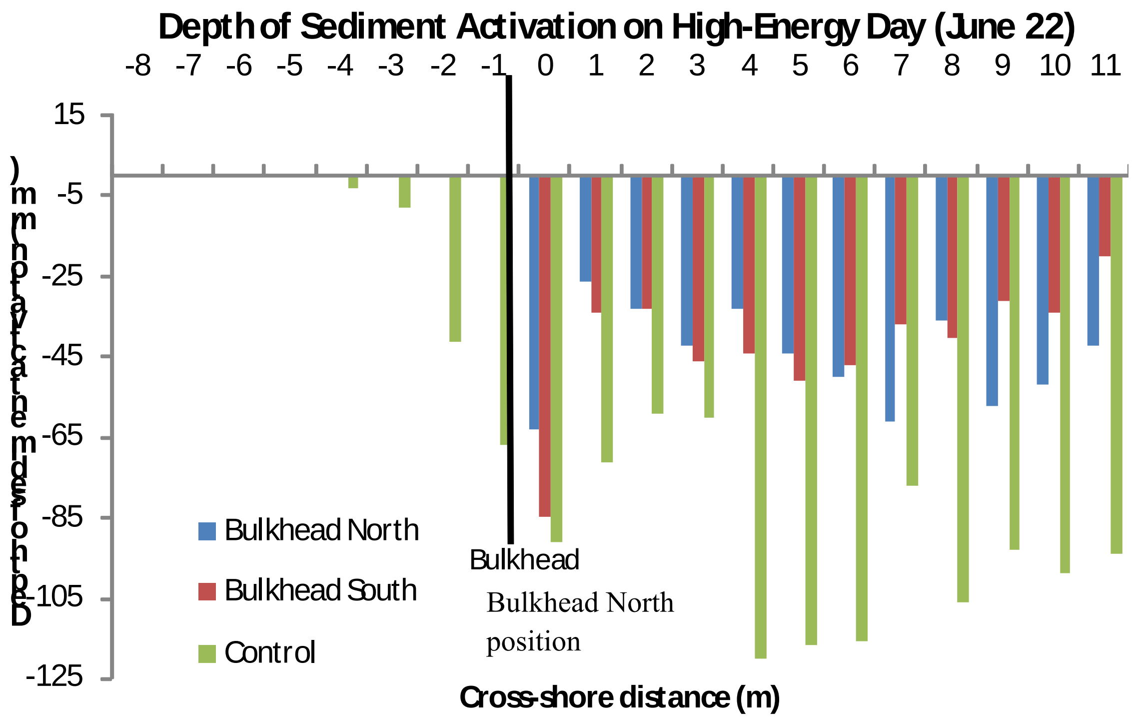


Figure 18 Average sediment activation depths on low-energy days at each site.



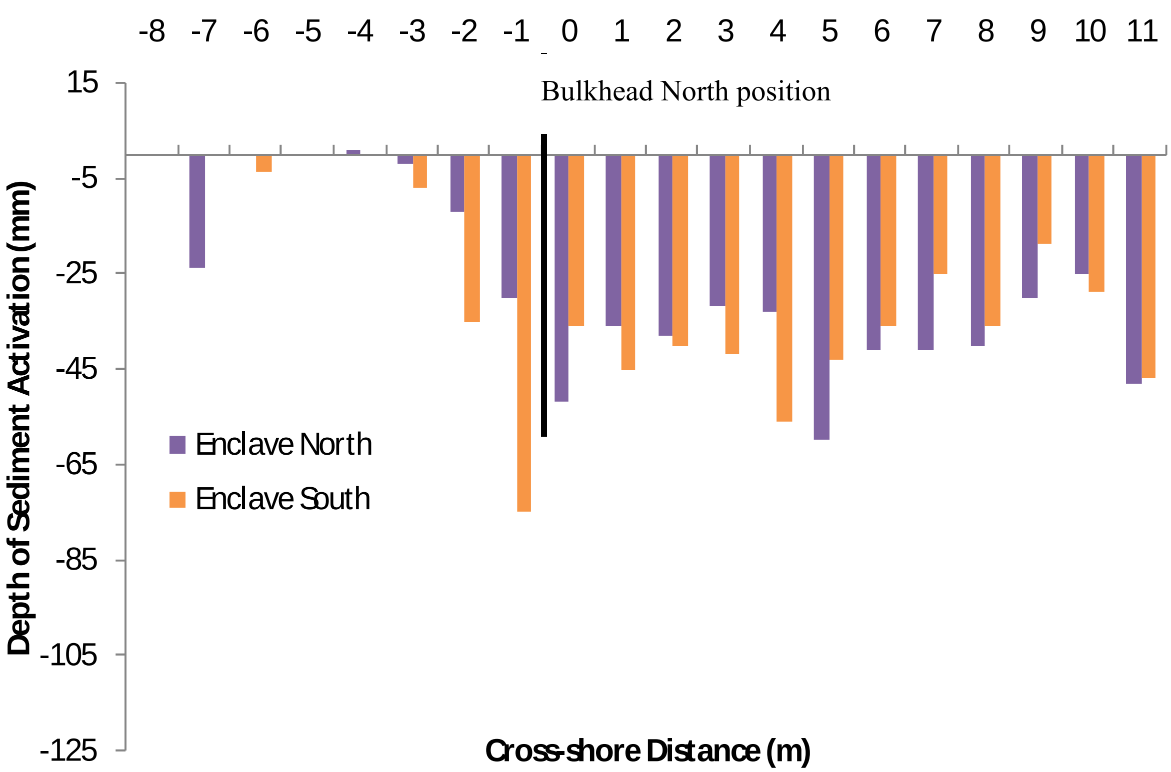


Figure 19 Sediment activation depths under high energy conditions (June 22nd 2008).

Sediment Characteristics

On the foreshore at C the mean grain size is 1.09 mm and contained about 14.5% gravel. Both bulkhead sites have smaller mean sediment size in the sand and granule size fractions, but not a lower percentage of gravel (0.81mm, 16% at BN and 0.71 mm, 11% at BS). Closest to the bulkhead there is a lower percentage of gravel at BN (7%) and about the same amounts at BS and C (10%) at 0 m (Table 3).

Recording of sediment movement in front of BN showed that there is more gravel visible on the flood tide when waves break just in front of the bulkhead, than is left on the beach in front of the bulkhead at low tide. In general, there are no gravel lag deposits left in front of the bulkheads after a tidal cycle. On June 14th, there were many gravel lag deposits to the south of BS, but none in front of the bulkhead during the ebb tide (Figure 20).

The MANOVA test statistics for control versus bulkheaded site reveal significant differences in sediment size. Examination of the individual analyses (ANOVAs) show that the bulkhead and control sites are differentiated by the amount of medium sand sizes, 0.23-0.35 mm. The Bonferroni test for variation among the means shows no significant difference in the amount of sediment in the coarsest fraction, 0.71-16 mm, between the sites. There is a difference between the control and bulkhead sites in sediment of 0.5 mm and 0.35 mm for C and BS. These tests are a more conservative comparison of the significance of differences between means than the F values and verify that the coarse sand and granules differentiate the control and bulkhead sites.

Figure 20 The lag deposit visible south of the south bulkhead.

Table 3 Mean grain size in the sand and granule fractions and percent gravel (>4 phi size sediment) relative to total sample at each site.

Site	Distance	9-Jun		14-Jun		16-Jun		20-Jun		22-Jun	
		Φ	%	Φ	%	Φ	%	Φ	%	Φ	%
Bulkhead North	0	0.27	6.7	0.76	20.4	0.80	1.9	0.55	5.3	0.60	0.0
	1	0.24	14.3	0.69	5.3	0.62	17.0	0.58	11.3	0.31	4.4
	2	0.21	26.3	-0.11	15.6	0.11	10.4	0.18	11.5	-0.05	8.7
	3	0.20	11.5	0.02	23.3	0.17	13.7	0.64	25.3	-0.13	15.4
	4	0.24	18.1	0.32	23.3	0.22	12.5	0.10	52.2	-0.08	38.5
Bulkhead South	0	0.19	27.4	0.80	10.1	1.28	0.0	0.68	7.2	0.17	4.6
	1	0.26	10.8	0.92	3.5	0.99	1.3	0.18	18.1	0.09	3.2
	2	0.41	12.5	0.44	9.6	0.61	12.1	0.32	8.0	0.21	0.4
	3	0.34	20.0	0.42	7.9	0.30	6.3	-0.04	37.2	-0.05	4.5
	4	0.18	47.3	0.27	10.6	0.42	11.4	0.42	29.3	-0.24	29.4
Control 1	0	0.53	1.8	0.32	18.4	0.13	6.0	-0.28	11.5	1.14	11.0
	1	0.13	4.1	0.17	8.2	-0.17	18.2	0.16	26.5		
	2	-0.04	9.0	0.02	12.4	0.08	11.5	-0.25	7.1		
	3	-0.36	11.2	0.10	17.9	-0.27	36.7	-0.35	6.1	0.46	27.6
	4			0.19	8.0	-0.44	23.8	-0.07	9.1	-0.11	25.1
Control 2	0	0.79	21.6	0.19	23.2	0.09	4.6	0.09	5.9	1.09	0.0
	1	-0.21	8.9	0.06	9.6	-0.23	14.2	0.31	22.1		
	2	-0.08	21.1	0.41	2.6	0.07	6.9	-0.29	19.2		
	3	-0.30	18.4	0.40	8.6	-0.25	22.7	-0.19	12.2	1.01	4.7
	4			-0.15	20.4	-0.17	28.9	-0.01	1.2	-0.16	47.6

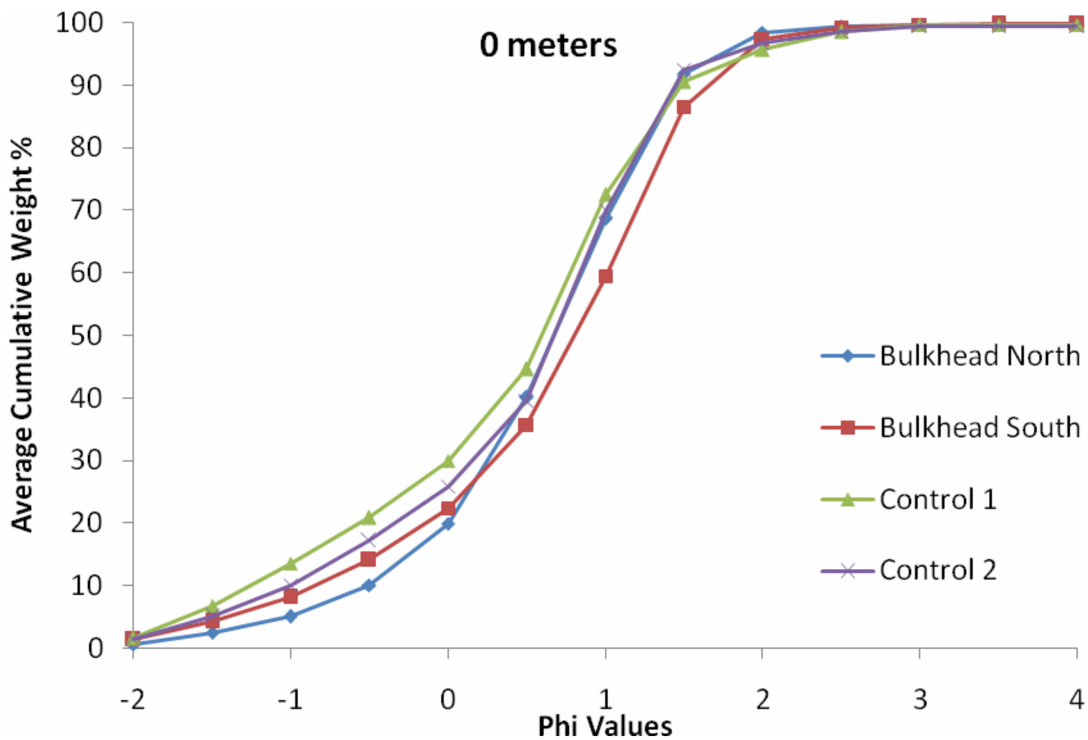
Table 4 Individual ANOVA F and p values for the size classes by control versus bulkhead, cross-shore location, and sample day. The overall column represents the ANOVA values based on beach type and cross-shore distance only.

Grain Size	Control vs Bulkhead		Cross-shore Dist		Sampling Day		Overall	
mm	F value	p value	F value	p value	F value	p value	F value	p value
4.00	1.28	0.70	8.6500	<0.01	1.24	0.30	2.11	0.05
2.83	1.14	0.34	9.8500	<0.01	0.63	0.64	2.52	0.02
2.00	0.82	0.48	4.4700	0.04	0.44	0.78	1.22	0.30
1.41	0.14	0.94	1.9600	0.16	0.34	0.85	0.58	0.77
1.00	0.21	0.89	0.4400	0.51	0.48	0.75	0.32	0.94
0.71	1.32	0.27	0.3700	0.55	1.38	0.25	0.72	0.66
0.50	0.38	0.77	17.8600	<0.01	6.13	<0.01	3.66	<0.01
0.35	4.65	<0.01	27.8800	<0.01	1.38	0.25	8.76	<0.01
0.25	10.68	<0.01	24.0700	0.03	0.35	0.84	9.07	<0.01
0.18	0.72	0.54	0.6300	0.43	1.27	0.29	0.53	0.81
0.13	0.18	0.91	0.7700	0.38	2.29	0.07	0.32	0.94
0.09	0.09	0.96	0.9700	0.33	3.37	0.01	0.37	0.92
0.06	0.23	0.87	0.4800	0.49	2.83	0.03	0.38	0.91

The principal factor in determining the proportion of sediment in most size classes is cross-shore distance (Table 4). Cross-shore distance influenced the amount of sediment in the mid-range sand classes between 0.25-0.5 mm and the granules and pebbles between 2.83-16 mm. F values also show that the significant differences in the proportion of sediment in each size class are due to cross-shore distance. The F value is a ratio of the amount of variance between the groups over the total variance within groups, so the larger the value, the more likely there are true differences between the groups. The largest F values are for the cross-shore distance for mid-range and coarse sediment sizes (Table 4).

Sample date is also an important factor in determining the grain size distributions. The MANOVA test statistics are all significant, but the individual ANOVAs show that the only individual significant size classes are 0.71 mm (coarse sand) and between 0.063 and 0.09 mm (very fine sand) (Table 4).The Bonferroni test for variation in grain size by day shows that there is no significant difference in the amount of sediment in each class for most days. Exceptions are, 0.71 mm (coarse sand), which separates days 2 and 3 from 5, and 0.06 mm (very fine sand), which separates day 5 from days 1 and 3. The amount of coarse sand (0.71 mm) differentiates most days, with fine sand a significant factor after the storm event (Table 4).

The partial correlation coefficients of proportion of grain size and site show that there is a significant positive correlation between the bulkhead sites; these correlations are especially strong 0 to 2 m from the bulkhead. Both bulkhead sites are weakly negatively correlated with the control samples. The control site samples are strongly correlated with each other. The correlation between bulkhead and control site is also apparent from the plots of average cumulative weight percent (Figure 21). The bulkhead sites have similar sediment distributions 1, 3, and 4 m from the structure. The control site samples appear to have similar grain size distributions at all distances. All sites have similar fine sediment distributions, with similar amounts of 0.06-0.25 mm sediment in the tails. Differences between sediment distributions at the sites are largest between 0.35-2.83 mm (medium sand to granules).


0 meters
Average Cumulative Weight %
Phi Values
100
90
80
70
60
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-2
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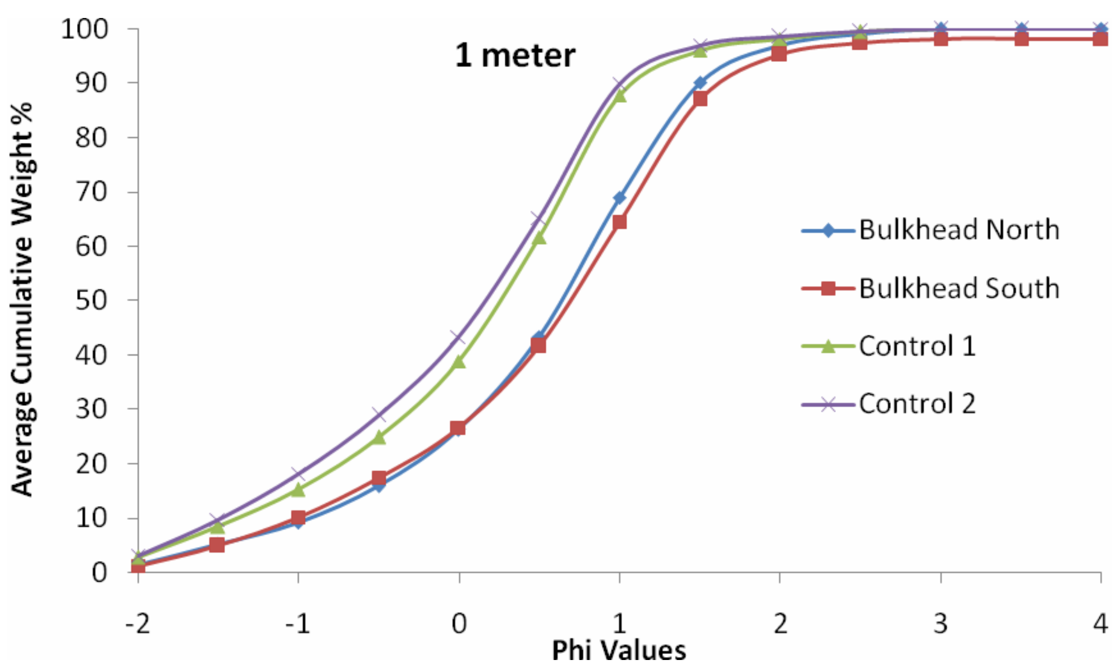
2
3
4
Bulkhead North
Bulkhead South
Control 1
Control 2


1 meter
Average Cumulative Weight %
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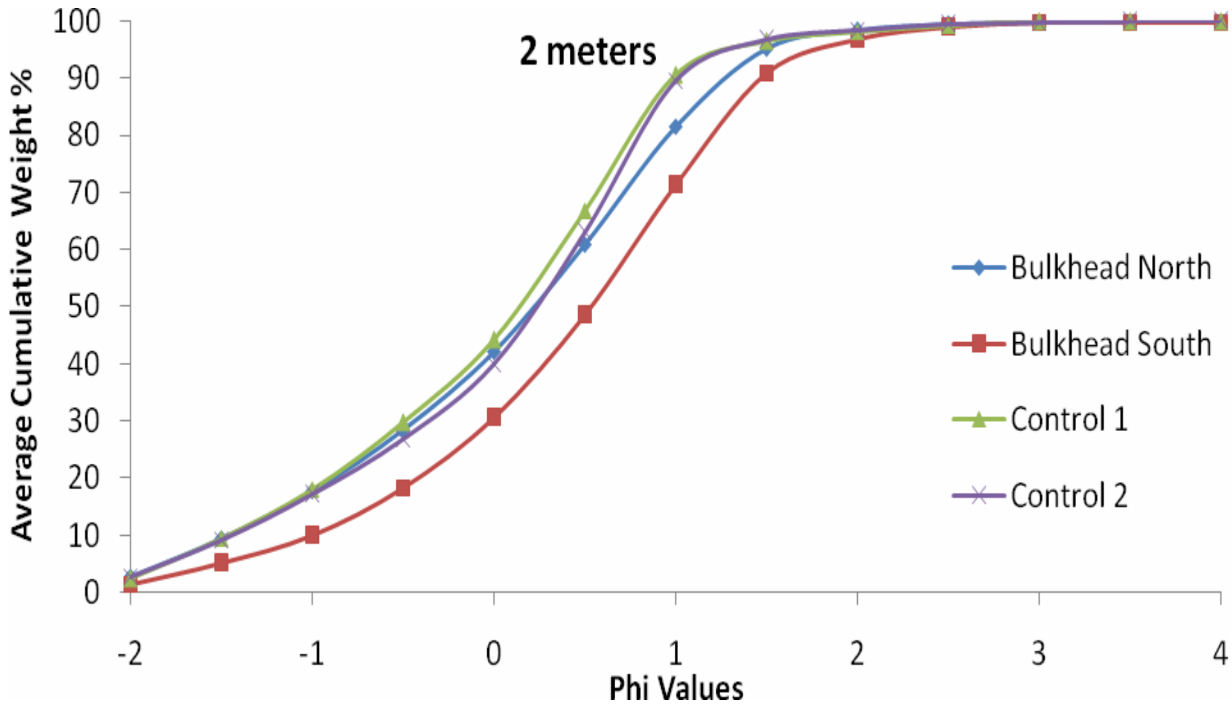
Bulkhead North
Bulkhead South
Control 1
Control 2


2 meters
Average Cumulative Weight %
Phi Values
Bulkhead North
Bulkhead South
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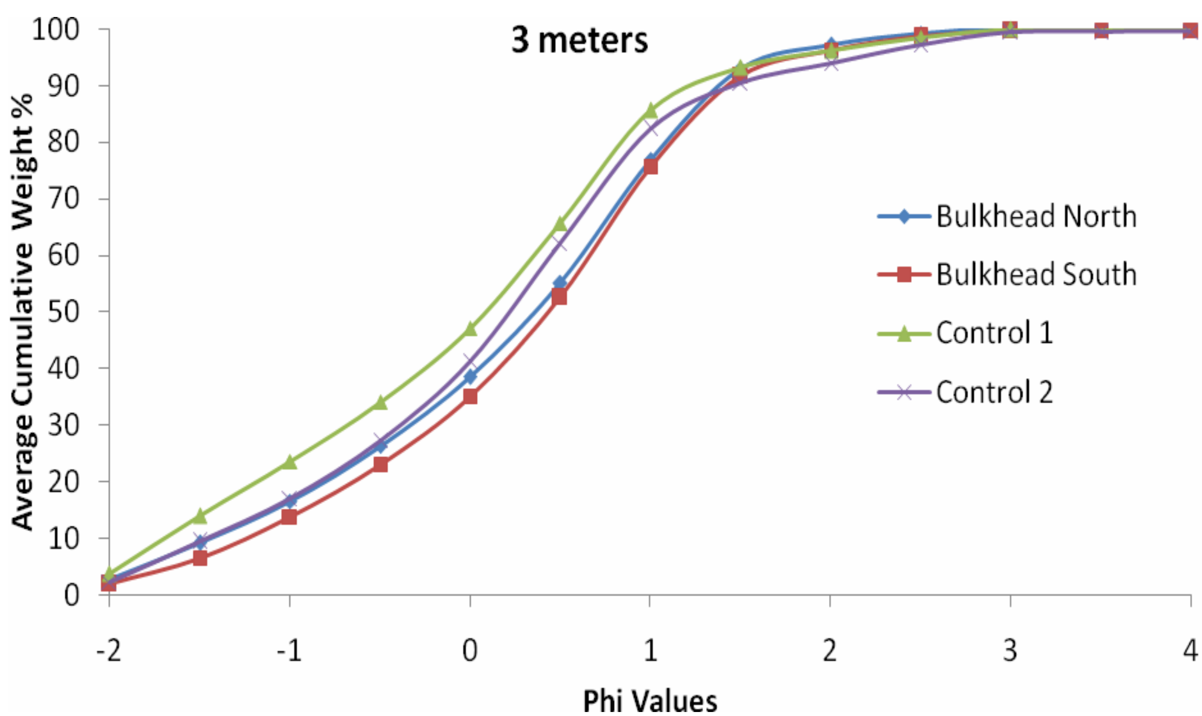
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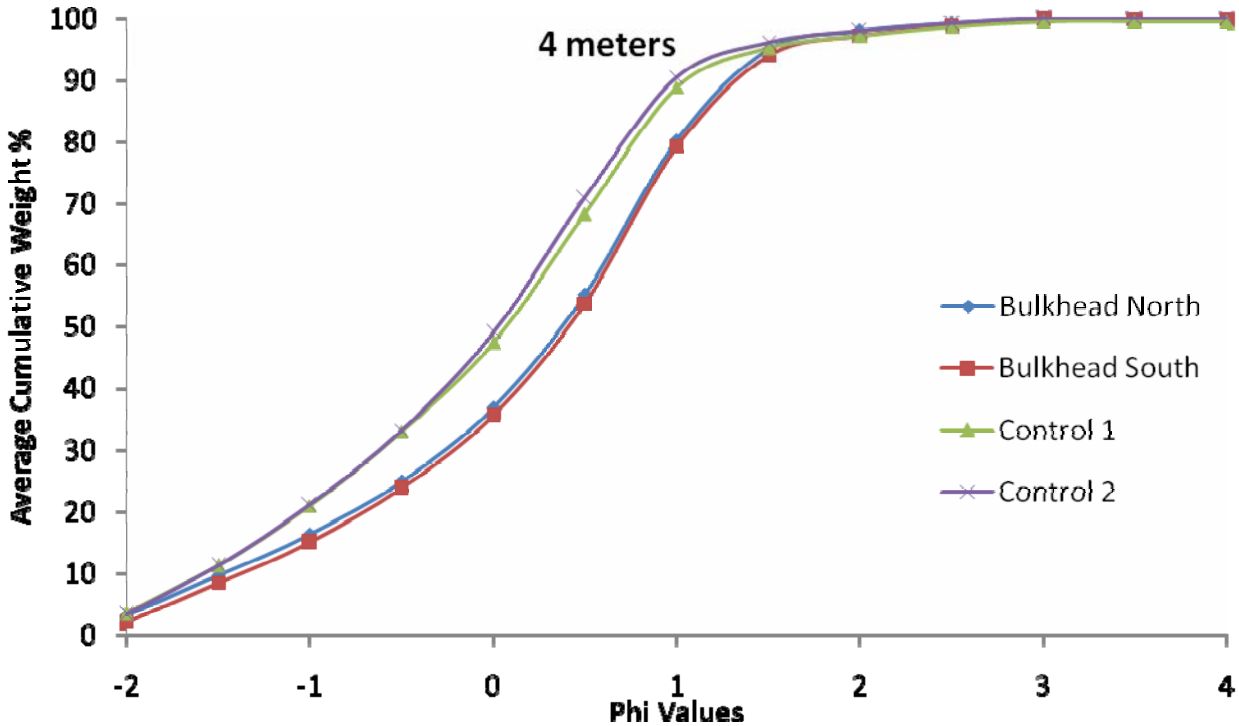

Figure 21 The plots of average cumulative weight percent for 0-4 m

DISCUSSION

Beach processes in front of bulkheads are altered when waves and swash contact the structure. Reflected wave and swash energies interfere with incident wave and swash processes, increasing the potential for sediment suspension. Movement of suspended sediment depends on the constructive or destructive incident and reflected energies resulting in net onshore or offshore transport or *in situ* mixing (Figure 22). The beaches in front of the two bulkheads are different from the control beach in several ways: they have increased topographic complexity with 3-4 steps in the profile, 2-3 times greater sediment mixing, and more frequent erosion/accretion reversals directly in front of the bulkhead (Figure 23). The sediment distribution is finer in the mixed layer in front of bulkheads.

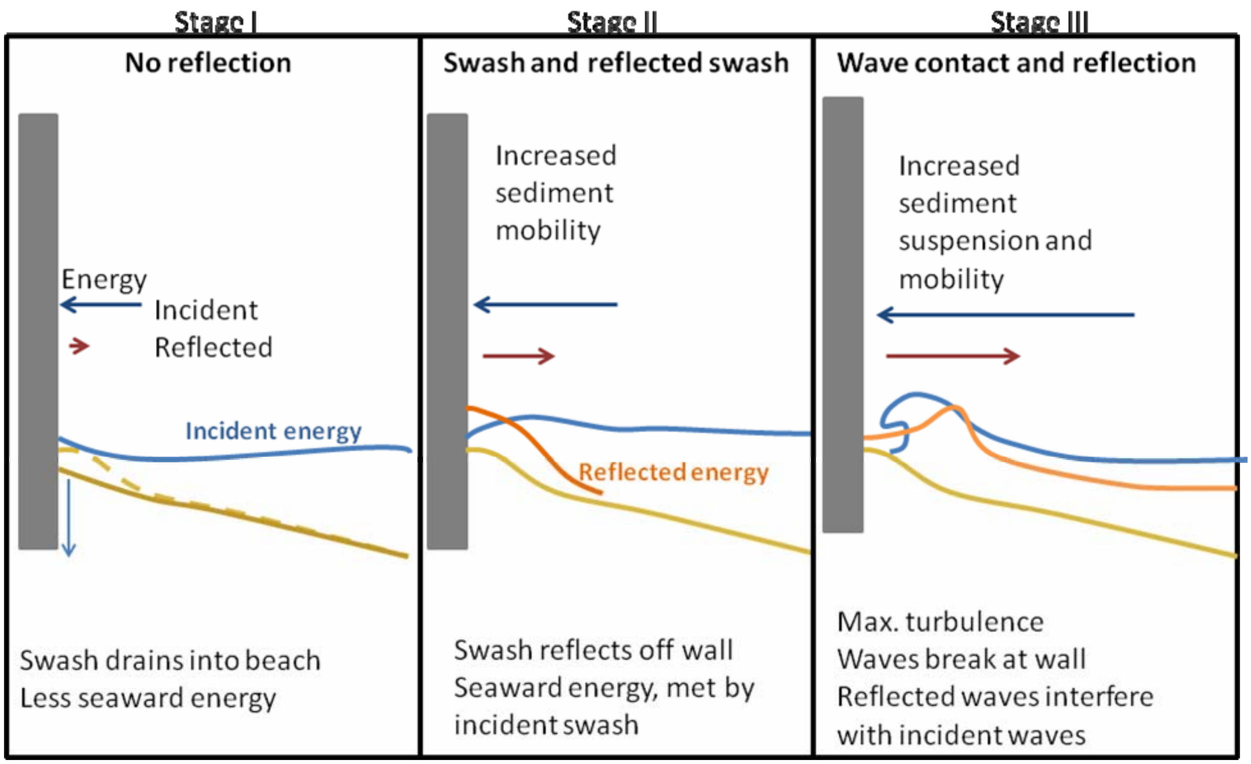

Figure 22 A conceptual model of swash and wave interactions with the bulkhead on the rising tide showing resultant incident and reflected energies.

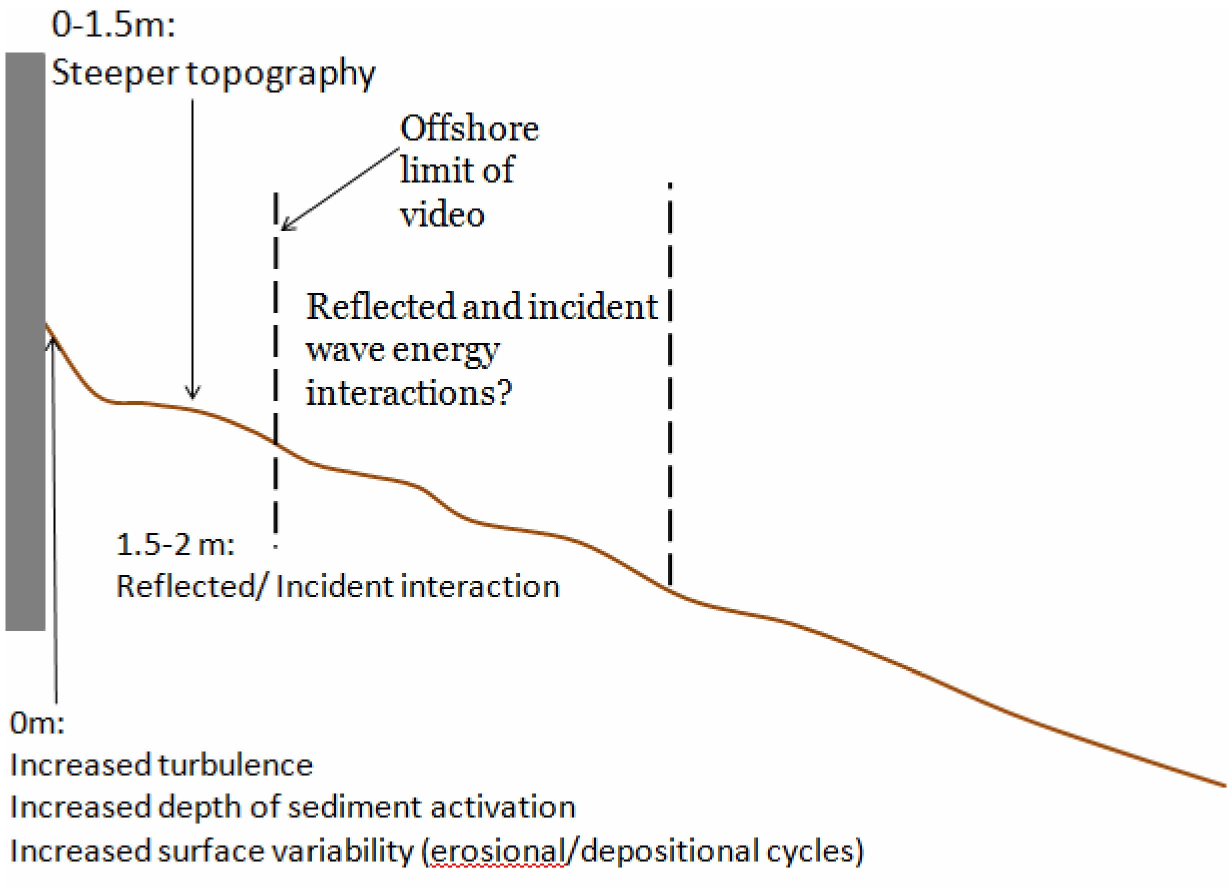

Figure 23 Diagram of spatial process and response variable alterations at the bulkheads.

Breaking Wave and Swash Characteristics

Truncation of the swash zone by the bulkhead decreases the swash amplitude on the rising tide. While the swash interaction with the wall dissipates some of the energy, the remainder is reflected as a seaward wave. Wave energies are highest near the time of high tide when the wave energy dissipation on the low tide terrace is a minimum (Nordstrom et al., 2006). Since the bulkheads intersect the shoreline below mean high water, they act as an artificial reflection point to the waves for a period of time. The reflected wave energies travels farthest late in the flood tide and the early in the ebb when the waves break within about 1 m or less from the bulkhead. At this distance the swash still has some of landward momentum when it reaches the bulkhead. This reflected wave energy meets the incident wave and in many cases slows and decreases the incident wave size.

The alterations to backwash depend on the bulkhead construction type. Reflected swash energies increase the velocity of the backwash in front of both bulkheads, but the reflected wave travels a greater distance and is more conspicuous in front of the planar bulkhead. The pilings and buttresses on BS break up reflected waves. The buttresses at BS also delay the infiltration of backwash into the beach by causing the sediment to become saturated sooner since the angled pilings (Figure 8) extend below the beach surface creating an impermeable surface that water must flow around. The buried pilings in this study act similar to the buried portions of rock revetments, which Plant and Griggs (1992) measured beach groundwater interactions in front of and found that they can reduce the permeability and porosity of the beach causing the beach water table elevation to rise more rapidly and to a greater level on the rising tide.

One reason the transport of sediment offshore by reflected waves may be unimportant in net surface change is because the sediment cannot travel far offshore. Reflected waves are only visible out to 2 to 3 m on most days, so sediment transported seaward will be returned to the location of the bulkhead during the swash uprush on the falling tide. When the reflected wave energy is reduced or eliminated, offshore sediment transport is unlikely. The incident wave oftentimes overrides the reflected wave. This process can dissipate reflected energy (Griggs and Tait, 1989). Cross-shore sediment transport is restricted in estuaries because short fetch distances result in a relatively low wave-system energy. Even the erosional higher-energy waves only transport sediment from the upper foreshore to the lower foreshore, creating a concave profile, from which the beach will recover to a linear profile with the onset of accretional conditions (MacDonald et al., 1994).

Topographic and Surface Variability

Generally the Delaware Bay beaches have low topographic diversity, since the swash, surf, and breaker zones are condensed into a narrow zone that rapidly migrates over the narrow active shoreface with the tides (Nordstrom and Jackson, 1992). Unlike oceanic beaches, estuarine beaches do not have a breaker bar, but may have a small swash bar (MacDonald et al., 1994). The control site in this study typifies an estuarine beach with low topographic variability, but the bulkhead sites have many more differences in cross-shore topography over short distances, appearing as step-like formations, and an over-steepened slope immediately in front of the bulkhead. The differences between the typical estuarine beach profile and those in front of the bulkheads suggest that the bulkheads alter the morphologic effect of waves, swash, and current, making the profile more variable. Kraus (1988) has described an "undulatory" appearance of oceanic beaches in front of bulkheads, which is an apt description of the bulkhead and enclave sites.

A steep portion of the beach at the control site, between 3-9 m (Figure 11), corresponds to the location of the largest sediment activation depths. The most conspicuous topographic feature is located at 9 m and appears as a step-like formation in the profile. The rapid change in slope and beach elevation will cause waves to break at this point, so the area above 9 m is most often in the turbulent breaker/swash zone, causing larger sediment activation depths. The slight concavity of the upper foreshore on the control site (0 to -5 m) that persists through the study may be attributed to horseshoe crab spawning. Spawning activity at about this location creates a concave profile at other sites (Jackson et al., 2005).

The beaches immediately in front of the bulkheads are steeper than at the equivalent elevation at the control site. Since the steepened portion is localized within 0.5-1.5 m from the bulkhead, some interaction of the waves and swash with the bulkhead likely causes this profile response. At both bulkheads a net accretion of sediment is never more than a few centimeters, but over time an accumulation of swash-derived sediment settling in front of the bulkheads would increase local steepness. The swash normally migrates up the shore, distributing sediment over the foreshore, but is unable to distribute the sediment over a wider area due to the truncation of the shore by the bulkhead, resulting in sediment accumulation. Increased sediment deposition in front of the bulkhead resulting in sediment mounding within 0.5 m of BS could explain the increased steepness. The buttressed bulkhead has a wider zone of over-steepening, 1.5 m, compared to 0.5 m at the planar bulkhead, which is likely due to differences in construction. The buttresses extend out almost 1 m in front of the bulkhead and break up the reflectance patterns, allowing sediment to settle a greater distance from the bulkhead.

The bulkheads protrude into the intertidal zone by as much as 8 m during spring tide, which means they are affecting long-shore processes as well as cross-shore processes. The south ends of the bulkheads act as traps for sediment transported to the north. The magnitude of the groin effect of bulkheads depends on the location of the bulkhead on the beach relative to the location and width of the longshore current (Weggel, 1988). Observations at BS show a conspicuous decrease in sand elevation in front of the wall from south to north (Figure 8). Some of the sediment trapped by the bulkhead appears to be transported to the front of the south end of the bulkhead, creating an area of higher relief and increasing the relief of the beach steps.

Studies have documented increased longshore current velocities in front of bulkheads (Pilkey and Neal, 1980). An increase in sediment entrainment by the longshore current is likely if the current is close to the bulkhead where there is an increase in turbulent energies. Over the low energy days the depths of sediment activation are increased, but the overall net change is small in front of the bulkheads. However, on the high energy day, sediment deposition occurred across the bulkhead profiles, except at 0 m. The increased turbulence at the bulkhead on this high energy day in combination with winds that could produce a strong longshore current may have prevented sediment accumulation in front of the bulkheads. The buttresses on BS are likely responsible for the accumulation that occurred, while the planar bulkhead, BN, had no structural components to reduce turbulence and sediment transport.

The net change at the sites usually takes one of two forms (1) parallel slope retreat; and (2) cross-shore sediment shifts between the upper and lower foreshore. The cross-shore shift in sediment at the bulkheads most frequently results in localized sediment erosion/accretion on one tidal cycle followed by the opposite trend (accretion/erosion) on the subsequent tidal cycle. This appears to represent differences in long-shore versus cross-shore dominance of sediment transport. Parallel slope change is the erosion or accretion of the entire cross-shore profile and normally occurs when the longshore current is unidirectional for a long period of time (Nordstrom and Jackson, 1992). On June 22nd there was a large parallel slope change at all sites, which was due to strong alongshore winds, creating strong longshore transport. The cross-shore erosion/accretion reversals are common when the wave energy changes between tidal cycles. There is erosion of the upper foreshore under high energy waves and accretion on the upper foreshore during calmer conditions (Nordstrom and Jackson, 1992). This process occurs on the estuarine beaches because the local wind conditions change throughout the day. The results from this study indicate that the wave energy shifts between tidal cycles have a greater effect on geomorphic processes at the bulkhead. The flashiness in daily surface change suggests that beaches seaward of bulkheads are much more sensitive to changes in wave forcing.

Sediment Activation Depth

The dominant factor in determining the location of the greatest sediment activation depth is wave height (Jackson and Nordstrom, 1993). Wave periodicity and grain size were not found to be significant on sandy estuarine beaches (Jackson and Nordstrom, 1993), although these variables were predicted to be positively correlated by King (1951). The location of maximum sediment activation corresponds to the area just landward of the location of breaking waves (Jackson and Nordstrom, 1993). In this study the greatest depths of sediment activation occurred directly in front of the bulkhead (0 m) and between 3 and 9 m on the control site. The activation depths in front of the bulkhead are large because of the increased turbulence due to the concentration of incident and reflected wave energy. The bulkhead reflects waves, so while the breaking waves will migrate up the shoreface with the tide on non-bulkheaded beaches, the waves are forced to reflect at the wall. Miles at al. (2001) reported that the sediment mixing depths were as much as three times greater seaward of bulkheads due to the turbulence from the interaction of incident and reflected waves and swash, along with the rising water levels with the tide. The activation depths are about 3 times greater at BS and over 4 times greater at BN than at the control directly seaward of the bulkhead. The activation depth at -1 m at ES is over 4 times greater than at the same elevation on the control. The increased sediment activation at ES is likely due to turbulence coming off the end of BS. Not only is the sediment activation increased in front of the bulkheads, but the daily variability in sediment activation is increased. While standard deviations in the enclave and at the control site are related to the magnitude of surface variability, which affects sediment activation, the magnitude of surface change is smaller in front of the bulkheads (Figure 13), but the daily profile response is flashier (Figure 14). The large sediment activation variability at the bulkheads is due to turbulent mixing, not large vertical surface variability.

The depth of sediment activation can be between 10-20% of significant breaker height on steep, reflective beaches (Masselink et al, 2007). Sediment activation depths at the Fortescue sites generally follow this rule with the exception of days with strong southeast winds, where sediment activation depths directly in front of the bulkheads exceed this and are 20-40% of the significant breaker heights. East (offshore) winds on June 9th, 10th and 13th produced activation depths that are smaller or fall within the 10-20% range in front of the bulkhead. The offshore winds probably inhibited the interactions of the swash with the bulkhead, limiting turbulence.

Sediment Characteristics

Sediment differences can either be due to the bulkhead affecting sediment characteristics or more regional differences in hydrodynamic processes or sediment sources. The statistics seem to support the hypothesis that the bulkheads affect sediment characteristics. Significant differences between the bulkhead and control sites in sediment between 0.25-0.35 mm imply that it is the central part of the sediment distribution, not the tails that differ. The coarser sediment distribution at the control site casts doubt on the hypothesis that the bulkheads cause a removal of fine-grained sediment. The coarser sediment could be attributed to the horseshoe crab spawning, which does not occur in front of the bulkheads. During this study there were at least four days where spawning was evident in the sediment activation records, including three of the five days cores were taken. On these three days, the control site exhibited coarser surface sediment than the bulkhead sites. Delaware Bay is one of the most active spawning grounds for horseshoe crabs, which spawn in the swash zone at high tide and bury the eggs 0.1-0.15 m below the surface (Botton et al., 1994). Horseshoe crabs increase the mean grain size of the mixed layer sediment by mixing more gravel into the surface layer during spawning and egg burial (Jackson et al., 2005). The horseshoe crabs spawn most heavily and frequently at the control site and avoid the bulkhead sites. The sediment characteristics at the control site on the 20^{th} (a day without noticeable spawning effects) could be influenced by the frequent prior spawning, since the sediment activation at the sample locations were small (>12 mm). On the 22^{nd}, the only day that the control site had a finer sediment distribution, there were storm conditions through the prior tidal cycle that would have prevented the horseshoe crabs from spawning on the beach and caused the sediment to be well-mixed, which increases the likelihood of finer mean sizes (Nordstrom and Jackson, 1992).

Another factor that could affect the sediment distribution at each site is the local shoreline orientation, which can significantly affect the amount and direction of sediment movement because transport is closely related to local wind direction (Jackson and Nordstrom, 1992). Since both beach site and day influence the amount of mid-range sized sediment, it seems likely that the sites are responding differently to events due to differences in shoreline orientation. This is also supported by the high correlations between the pairs of bulkhead and control site samples.

The bulkhead sites have similar sediment distributions to each other after each event, just as both control sample distributions are similar to each other.

Sediment distribution varies based on daily changes in the angle of the breakers and direction and strength of the longshore current, which also affects the source of sediment. On the last day of sampling, the finer sediment distribution caused by the high energy event differentiated the control and bulkhead sites. The greater proportion of finer sand at the control site in comparison to the bulkhead sites is what would be expected normally if the process alterations at the bulkheads were decreasing the amounts of fine sediment on seaward beaches.

The proportion of coarser sediment varies cross-shore on both bulkheaded and unbulkheaded beaches. The distribution varies because wave and swash energies decrease landward of the breaker zone. There is an increase in coarser sediment from the core taken at 0 m to 4 m at all sites. Even if the bulkheads cause some local change in sediment distribution, the grain size distribution still becomes coarser with distance offshore due to wave sorting processes.

One significant conclusion is that the differences in sediment distribution between the bulkhead and control sites appears in the mid-range sand to granules (0.18-2.83 mm), rather than the coarse or fine extremes. While each of the bulkhead sites has sediment characteristics distinct from the control, it is not apparent that this is due to processes occurring at the bulkhead. It is just as likely that the bulkhead sites, which are close in proximity to each other and are removed from the control sites, are influenced differently by changing wave and energy regimes or by variations in the level of biological activity, which alter local sediment characteristics in the mixed layer daily.

FUTURE STUDIES

Although this study of estuarine beaches revealed differences between bulkheaded and unbulkheaded sites, more process-response research can be done to address several issues that could not be addressed because the field deployment was primarily designed to address other issues related to transport of horseshoe crab eggs over a 14-day period in the summer:

- Spatial variability should be addressed in a follow-up study with control sites on both sides of bulkheads sampled to evaluate the effects of longshore sediment transport and sediment source characteristics. Identification of the apparent longshore transport effects on beach morphology including the increased step relief and the sloping along-shore beach surface at BS requires further investigation.

- Initial measurements suggest that alteration of wave and swash processes occurred within about 0-4 m of the bulkheads, but the location of steps out to 5 m at BS and 7 m at BN suggests that the bulkheads may change morphology farther offshore. An examination of the processes that result in the stepped profile at the bulkhead can be conducted by capturing a wider angle of reflected and incident energies with video.

- The differences in process and response alterations caused by different bulkhead construction types indicate that evaluation of alternative configurations may be useful in designing more compatible structures.

- The similarities between the bulkhead and enclave site in this study suggest that the effects of bulkheads extend to adjacent beaches. The significance of the size of an enclave between bulkheads should be tested to examine the magnitude of these end effects and what it means to processes occurring in the interior of the enclave.

CONCLUSION

The results from this study indicate that bulkheads can alter beach topography, sediment movement, and processes. There is an increase in topographic variability at the bulkhead sites, leading to a stepped cross-shore profile. Directly in front of the bulkheads, the increased swash, wave, and reflected energies that are concentrated at this location increase the sediment activation depth and the frequency of erosional/depositional cycles. While this did not lead to increased erosion of sediment through the study and even may have resulted in deposition, mobilizing greater amounts of sediment means that there is greater potential for transport under higher wave-energy conditions. Beaches in front of bulkheads are more likely to experience an onshore-offshore shift in sediment with tidal rise and fall. In general the bulkheads make the beaches more sensitive to changes in local forcing, causing greater tidal cycle variability in geomorphic response. Although amplification of wave and swash energies at the bulkhead may be responsible for altering the sediment characteristics of the mixed layer, it seems just as likely that varying shoreline orientation or levels of biological activity causes different distributions. The proportion of fine or coarse sediment does not vary significantly between sites.

The two bulkheads behave differently, most likely due to the differences in construction. Buttresses break up and dissipate reflected waves and swash leading to slightly smaller sediment activation depths. The beach in front of the buttressed bulkhead was steeper for a greater distance (1.5 m, compared to 0.5 m at the planar bulkhead). The microtopographic mound-like features formed between the buttresses contrast with the planar surface at bulkhead north. The drainage at the south bulkhead was affected by the buttresses, leading to slower drainage in front of the buttresses, which could contribute to the mounding of sediment between the buttresses and the increased relief of step-like features at the buttressed site.

The beach enclaves between bulkheaded segments are also affected by the bulkheads. Enclaves exhibit more complex topographic variability than the control site, similar to the profiles in front of the bulkheads. The enclave also has areas of increased depth of sediment activation, particularly close to the ends of the bulkhead, where the reflected energy increases turbulence. The effects of bulkheads appear to extend beyond the structures, but the sites monitored here were too close to evaluate the significance of distance.

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