ABSTRACT

TRANSPORT OF TERRIGENOUS SEDIMENT AND HORSESHOE CRAB EGGS IN THE SWASH ZONE OF AN ESTUARINE FORESHORE IN DELAWARE BAY, NEW JERSEY, USA

by
Sherestha Saini

Identification of processes responsible for egg exhumation and transport in the swash zone is paramount to conservation of species that use the intertidal foreshore. One example where the understanding of these processes is critical to egg exhumation, transport and deposition is in Delaware Bay, USA. Beaches in Delaware Bay provide foraging grounds to many shorebird species that migrate thousands of miles from Central and South America to feed on nutrient rich horseshoe crab eggs during their peak spawning season. Eggs laid at depth by horseshoe crabs are exhumed and transported by bioturbation, wave and swash processes and made available to foraging shorebirds. The objectives of this dissertation are to: (1) compare differences in the significance of wave and swash processes to horseshoe crab egg exhumation and transport on the mid - foreshore relative to the upper foreshore in the absence of spawning; (2) compare how horseshoe crab eggs are mobilized relative to sediment; and (3) evaluate the processes responsible for textural changes of sediment in transport. The study was conducted on a steep, predominantly sandy foreshore on the New Jersey shoreline of Delaware Bay.

Instrumented wave (height and period) and swash (depth, duration, velocity, width) measurements were gathered on October 12 and October 14, 2007 during spring tidal conditions. Dyed horseshoe crab eggs and sediment were injected at a location on the mid-foreshore that were influenced by wave breaking and swash flows and at a location on the upper foreshore that was influenced by swash flows alone. Total load

traps were used to measure textural changes in sediment and quantities of egg and sediment tracer transported over individual swash events during the rising, high and falling tide.

Sediment on the foreshore comprised medium to coarse sands with a gravel fraction of granules and pebbles. The proportion of gravel within the foreshore prior to trapping was low. An increase in the percent gravel transported was observed in the swash approaching the time of high water. Results suggest that as the energy under incident waves increase with tidal rise, the quantities of gravel mined out from the bed also increase and are incorporated into the beach step. Plunging waves breaking over the step suspend gravel and transport it up the foreshore in the swash. The lag in the rate of step migration relative to migration of the breaker zone during the falling tide increases the likelihood of mining gravel from the step and transporting it downslope in the backwash.

Results from the tracer experiments reveal that wave breaking is the primary mechanism that accounts for the greater quantities of sediment and eggs trapped from the mid-foreshore in the uprush relative to the backwash despite offshore directed flows during the tidal cycle when wave heights ranged from 0.43-0.64 m. Low quantities of eggs and sediment entrained from the upper foreshore are a function of the decreasing swash depths and flow velocities approaching the uprush limit. Waves did not activate sediment on the mid-foreshore to depths where crabs would generally lay eggs and subsequent spawning would be required to make these eggs available to shorebirds. Data reveal that higher wave heights ranging from 0.65-1.1 m representing storm conditions resulted in accretion across the foreshore, and no eggs were released from the mid or upper foreshore.

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To my parents Parmila and Amar Singh Saini.
Their believing in me taught me how to believe myself.

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CHAPTER 1

INTRODUCTION

1.1 Statement of Purpose

The swash zone is characterized by low water depths, high flow velocities and high sediment transport rates (Masselink and Russell, 2005). Hydrodynamics and sediment transport in the swash zone are important for geomorphic and biologic reasons. First, the swash zone plays an important role in the erosion and accretion of the beachface. Fluid behavior in the swash zone influences the cross-shore sediment transport rate and whether sediment will remain on the beachface or be transported offshore (Butt et al., 2005; Masselink and Puleo, 2006). Second, swash processes contribute to beach recovery after storm erosion (Elfrink and Baldock, 2002). Third, a significant part of the longshore sediment transport occurs in the swash zone (Bodge and Dean, 1987; Nielsen, 1992). Fourth, inclusion of swash run-up dynamics into numerical models improves the engineering design of coastal structures (Kobayashi, 1999). Fifth, rapidly reversing swash motions carry oxygen and organic material to interstitial fauna (McIntyre et al., 1970), deliver food to macrofauna buried in the sand (Lastra et al., 2002), displace macrophytic wrack (vegetative litter) landward (Thornton and Jackson, 1998) and transports eggs, larvae and juveniles of faunal communities across the foreshore slope (Nordstrom et al., 2006).

Several species such as the California grunion (*Leuresthes tenuis)* (Clark, 1925; Walker 1952), Atlantic horseshoe crab (*Limulus polyphemus)* (Shuster and Botton, 1985), Atlantic silverside (*Menidia menidia)* (Conover and Kynard, 1984), the mummichog (*Fundulus heteroclitus)* (Taylor et al., 1977) and the Japanese puffer fish (*Takifugu* *niphobles)* (Yamahira, 1996) live in the aquatic environment, but use the interstitial environment of the foreshore of beaches to lay their eggs. These species bury their eggs to depths ranging from the top few centimeters (Yamahira, 1996) to 20 cm (Walker, 1952; Brockmann, 1990) in the foreshore, where they are kept warm and moist and undergo further development (Brady and Schrading, 1983; Griem and Martin, 2000) or are exhumed to the beach surface and transported by wave breaking and wave-induced currents.

The exhumation, dispersal and subsequent deposition of eggs and larvae of many species have important implications for the population viability of animals that feed on them. For instance, Rice (2006) observed that the numbers of eggs containing live embryos of the surf smelt (*Hypomesus pretiosus)* on an armored beach with no terrestrial shoreline vegetation were approximately half that of an unarmored, naturally vegetated beach in Puget Sound. These fish are a key food resource for threatened and endangered groups of populations of Puget Sound salmon, and maintenance of their stocks has been identified as high priority for salmon recovery (Bargmann, 1998). Another example of the effect of egg movement on the population dynamics and abundance of species is observed in the relationship between Atlantic horseshoe crabs and many species of western hemisphere shorebirds that migrate thousands of kilometers from Central and South America to the Arctic (Baker et al, 2004; Morrison et al., 2004). These migratory shorebirds make a stopover every spring in Delaware Bay to feed on nutrition rich horseshoe crabs eggs (Walls et al., 2002). Failure to consume sufficient quantities of eggs could hinder the ability of these birds to accumulate energy in order to complete their migration successfully, and thus affect their nesting success and long-term population viability (Baker et al., 2004; Haramis et al., 2007). Thus understanding the processes responsible for egg exhumation, transport and deposition is important to developing conservation strategies for species that use the intertidal foreshore and to other organisms whose life cycles maybe associated with them.

The two primary mechanisms responsible for exhumation of eggs from the intertidal zone include bioturbation and physical processes within the wave breaking and swash zones. Bioturbation, or burrowing of organisms into the substrate, disturbs sediment, disaggregates eggs and exhumes eggs to the surface of the foreshore (Kraeuter and Fegley, 1994). However, the importance of bioturbation to egg exhumation is dependant on the density of organisms burrowing on the foreshore (Smith, 2007) and the depth to which previous eggs have been laid. In the absence of bioturbation, eggs will remain buried and undergo development until wave and swash processes exhume them to the surface of the foreshore. Hydrodynamic processes within wave breaking and swash zones that influence egg exhumation and transport when bioturbation is low or absent have not been fully assessed in past studies.

Cross-shore exhumation, transport and deposition of eggs buried in the foreshore has been attributed to the tide (Botton et al., 1988; Yamahira, 1996; Martin et al., 2004). Species that spawn in the intertidal zone synchronize spawning activities with tidal and lunar cycles (Botton et al., 1998, Martin and Swiderski, 2001). Most species emerge from the bay or ocean and move onshore during or a few hours after semi-lunar high tides. Females dig into the sand first to release their eggs, while males on the surface surround them to fertilize the eggs (Martin and Swiderski, 2001). These temporal patterns of lunar or tidal spawning will influence spatial patterns of egg burial and subsequent exhumation cross the foreshore. For example, eggs of the grunion (*Leuresthes tenuis)* and the puffer (*Takifugu niphobles)* laid during semi-lunar high tides complete development and remain buried above the mean high tide line until turbulent, high energy waves associated with subsequent spring tides exhume the larvae and currents transport them offshore (Moffat and Thomspon, 1978, Yamahira, 1997, Griem and Martin, 2000). These results supported the findings of Rudloe (1979), Ehlinger and Tankersley (2003) and Botton and Loveland (2003) who observed peaks in larval abundance when localized storms with strong onshore winds coincided with high tide, producing rough surf zone conditions.

Egg exhumation and transport in the intertidal zone has been identified to be influenced primarily by “mixing” or activation of sediment by waves (Walker, 1952; Yamahira, 1996) and swash processes (Nordstrom et al., 2006). However, physical explanations of characteristics of flows that may influence reworking, transport and/or reburial of eggs and sediment buried at different locations across the foreshore have not been identified in past studies. For example, while studies (Walker, 1952; Yamahira, 1996) have identified that high wave heights associated with spring tides will erode sediment and exhume eggs that were buried by fauna during spawning, the influence of cross-shore or longshore dominant flows in the swash subsequent to wave breaking on egg transport and deposition are still unknown. In addition, high wave events can create differing erosional and accretional conditions on the foreshore depending on the direction of dominant wave approach (Nordstrom, 1980; Nordstrom and Jackson, 1992), but the implications foreshore response may have on the fate of exhumed eggs and larvae is still unclear.

Since eggs become well mixed with sediment when activated by wave and swash flows, it can be assumed that hydrodynamic forces transport egg and sediment across the foreshore in a similar manner. Previous research has shown that maximum sediment transport occurs in the wave breaking and swash zones (Komar, 1991; Beach et al., 1992). Investigations on sediment transport have been mostly conducted on exposed ocean beaches, and have revealed that transport is influenced by wave characteristics (Elfrink and Baldock, 2002), beach slope (Miles et al., 2006), flow velocities in the swash (Masselink and Hughes, 1998), shear stresses at the bed (Hughes et al. 1997; Masselink and Hughes, 1998) conditions in the surf (Masselink and Puleo, 2006), turbulence (Puleo et al., 2000), infiltration-exfiltration effects associated with the bed (Turner and Masselink, 1998; Butt et al., 2001) and textural properties of the sediment (Elfrink and Baldock, 2002).

The importance of understanding key hydrodynamic processes in the swash zone responsible for entraining eggs and sediment becomes more critical on estuarine beaches because they provide significance ecological value as spawning, nesting, and foraging areas for several organisms like meiofauna (Spalding and Jackson, 2001), horseshoe crabs (Smith et al., 2002), and shorebirds (Botton et al., 2003, Karpanty et al., 2011). Beaches in sheltered estuarine environments are generally located where there is a sediment supply and waves energy capable of reworking the sediment. The foreshores of sandy estuarine beaches are relatively steep (6 to 9°) with a narrow backshore (< 20 m) and a relatively flat low tide terrace (Nordstrom, 1992, Fenster et al., 2006) (Figure 1.1). Dominant waves on most estuarine beaches are locally generated with heights ranging from 0.15 to 0.50 m and periods of 2.0 to 5.0 s (Nordstrom, 1992). On estuarine beaches with an appreciable tidal range relative to wave height, the foreshore will be reworked by both the swash zone and the breaker zone under low and moderate wave energies during rise and fall of the tide. Sediment that forms estuarine beaches may be predominantly sand with a smaller gravel fraction (Nordstrom, 1977, Kennedy, 2002, Freire et al., 2007), mixed sand and gravel (Curtiss et al., 2009) or predominantly gravel (Isla and Bujalesky, 2004). The gravel fraction (according to the Wentworth scale) may consist predominantly of granules and pebbles (Nordstrom and Jackson, 1993) or pebbles and cobbles (Curtiss et al., 2009). The upper foreshore of estuarine beaches is dominated by swash processes and is comprised predominantly of medium to coarse sands (0.48-0.70 mm). The mid-foreshore, where reworking of sediment by wave activation is greatest, has predominantly coarse sands (approximately 0.90 mm). Since foreshores of estuarine beaches are steep, the surf zone width is usually insufficient to allow complete dissipation of incident wave energy (Short, 1999; Nordstrom et al., 2006) and plunging waves are converted directly to swash (Nordstrom, 1992). (Figure 1.1)

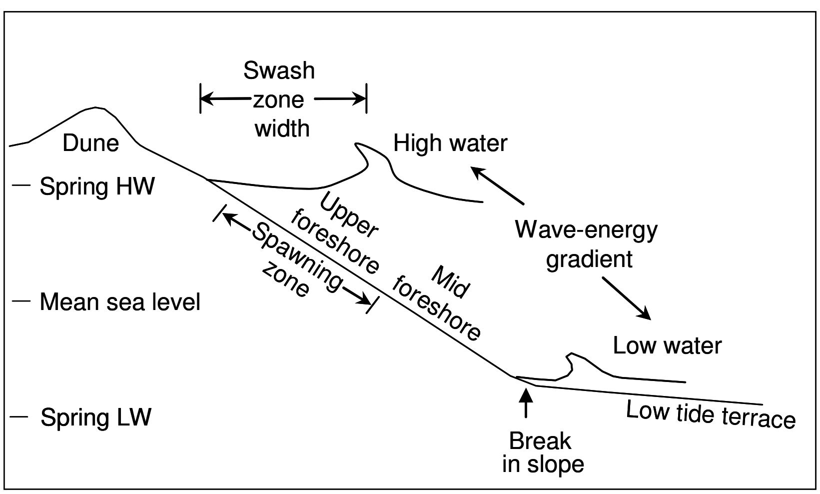


Figure 1.1 Estuarine beach foreshore.
Source : Nordstrom et al., 2006.

Under constant wind speed and direction, swash energies are lowest at low tide when waves break on the broad, flat, shallow low tide terrace and highest at high tide, when wave energy dissipation is minimized (Nordstrom et al., 2006). Consequently, breaking waves and the swash uprush and backwash become the entrainment and transporting mechanism for sediment and biogenic material present on the foreshore of estuarine beaches (Nordstrom et al., 2006).

This dissertation analyzes the morphological and sedimentological changes across the foreshore of a steep, estuarine beach in Delaware Bay in response to process conditions within the wave breaking and swash zones and examines their influence on horseshoe crab egg and sediment entrainment and transport.

1.2 Background

One example where the understanding of wave breaking and swash zone processes is critical to understanding egg exhumation, transport and deposition is in Delaware Bay, USA. The largest concentration of horseshoe crabs in the world arrives in May and June each year to spawn on sandy beaches in the estuary Delaware Bay (Pierce et al., 2000) (Figure 1.2).

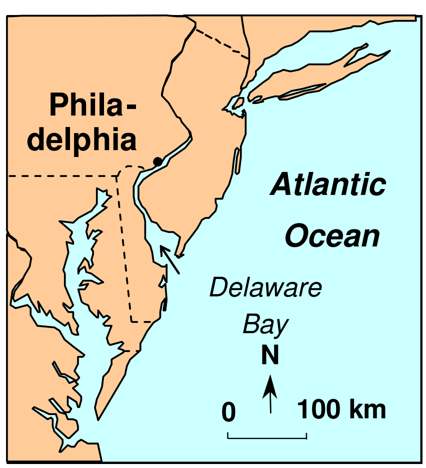


Figure 1.2 Map showing location of Delaware Bay.

During the spring horseshoe crab spawning period, many shorebirds migrate thousands of miles to feed on nutrient rich eggs of these crabs. Each spawning female crab in Delaware Bay may lay egg clusters with numbers varying from 2,524 to 16,835 across the foreshore (Weber and Carter, 2009). Botton et al. (1994) observed that horseshoe crab egg clusters are initially deposited by female crabs 15-20 cm deep into the foreshore on the New Jersey side of Delaware Bay. Weber and Carter (2009) reported egg clusters buried to depths ranging from 3.5-25.5 cm, with an average depth to center of 15.5 ± 3.5 cm SD across the foreshores of four beaches on the western shoreline of Delaware Bay. The depth to which egg clusters are laid is a function of the female's body size and depth to which she can burrow into foreshore sediments (Shuster and Sekiguchi, 2003). During each spawning tide, more sets of females burrow into the same part of the beach to depths of previously laid clusters disaggregating them and mixing them within sediment (Kraeuter and Fegley, 1994). Dissociated eggs and sediment activated by waves move upward toward the beach surface, where they eventually come within the reach of foraging shorebirds (Pooler et al. 2003). Jackson et al. (2005) reported that bioturbation at locations of the foreshore where maximum horseshoe spawning occurs, combined with low wave action (wave heights < 0.08 m), can increase depths to which sediments are activated (Jackson et al. 2005). These depths are greater than those to which sediments would be activated in the absence of spawning. Smith (2007) reported that as many 20% of clusters buried in the mid-foreshore region maybe disturbed, even at low spawning densities.

The literature provides conflicting information on when shorebird foraging is greatest following horseshoe crab spawning on foreshores in Delaware Bay. Burger et al.

(1997) reported foraging activity during all stages of the tidal cycle, but numbers during rising tide were greater than falling and low tide. Botton et al. (1994) observed the largest flock sizes of shorebirds at high tide, but differences in numbers of birds foraging during the high, mid-tide and low tide were not significantly different. Most shorebirds generally fed within the swash zone (Botton et al., 1994), but Ruddy Turnstones *Arenaria interpres* and Sanderlings *Calidris alba* fed on dry sand just above the swash zone (Nordstrom et al., 2006). Karpanty et al. (2011) observed increased Red Knot foraging behavior on the falling tide than at low tide whereas Ruddy Turnstones and Sanderlings foraged for an equal proportion of time during all stages of the tide.

Delaware Bay's sandy beaches are subject to erosion and shorefront development that negatively affect their habitat value (Jackson et al., 2002). Harvesting over the last decades of the 20^{th} century (Kreamer and Michels, 2009), sea level rise (Galbraith et al., 2005) and the restricted availability of suitable spawning habitats (Botton et al., 1988) have put the horseshoe crab populations under stress. Populations of shorebirds, especially the Red Knot (*Calidris canutus rufa)* are also under stress and have been declining consistently for the past several decades (Baker et al., 2004). Their numbers at the prime wintering site in southern South America (Bahia Lomas) fell by approximately 50%, from 45300 in 2000 to 25000 in 2002-2003 (Morrison et al., 2004). This decline has been attributed to reductions in their food resource, the eggs of the horseshoe crab (Niles et al., 2008). Since these eggs are of vital importance to the stability of populations of these shorebirds, it becomes imperative to understand (i) the processes responsible for egg exhumation by waves and swash; (ii) whether there are differences in rates of exhumation and transport of eggs that maybe buried at different locations on the foreshore, and (iii) what proportion of eggs maybe available for shorebird foraging at different stages of a tidal cycle from specific locations on the foreshore.

1.3 Objectives

The objectives of this dissertation are to: (1) compare differences in the significance of wave and swash processes to horseshoe crab egg exhumation and transport on the mid-foreshore relative to the upper foreshore in the absence of spawning; (2) compare how horseshoe crab eggs are mobilized relative to sediment; and (3) evaluate the processes responsible for textural changes of sediment in transport.

The first two objectives were accomplished by gathering data so that comparisons could be made between quantities of horseshoe crab eggs and sediment exhumed and transported from a location on the foreshore influenced by both wave and swash processes and quantities from a location that was influenced by swash processes alone over a tidal cycle. It is important to analyze the morphological responses at different locations on the foreshore because wave and swash processes rework sediment to different depths depending on the time any given region is influenced by these processes. Wave and swash processes on estuarine beaches cause high degrees of sediment mobility with varying rates of erosion and accretion across the foreshore during individual swash events as the tide rises and falls. These changes across the foreshore will influence quantities of eggs and sediment that are reworked and mobilized to the surface of the beach as well as quantities of eggs that maybe available on the foreshore for shorebird foraging with rise and fall of the tide. Steps to accomplish the first two objectives involved (a) deploying horseshoe crab egg and sediment tracer simultaneously at two locations across the foreshore where exhumation and transport is due to both the swash and wave breaking and swash processes alone; (b) measurement of the quantities of egg and sediment tracer in transport by deploying traps in the swash; and (c) evaluating the differences between swash characteristics in the uprush and backwash, which will ultimately decide whether egg and sediment tracer transport occurs in an onshore or offshore direction. Data on time averaged flow velocities, depths, durations and widths were compared during different stages of the tide (rising, high and falling tide) to evaluate the relative contributions of these processes to egg and sediment entrainment and transport in the swash.

The third objective was accomplished by analyzing the textural properties of sediment in transport during individual swash events. Steps involved (a) gathering trap samples of sediment in transport in the uprush and backwash; (b) evaluating changes in grain sizes in the uprush and backwash (c) comparing changes in grain sizes in the swash over different stages of the tidal cycle; and (d) understanding mechanisms responsible for changes in grain sizes over individual uprush and backwash events. Variables identified to explain changes in textural properties included individual uprush and backwash velocities, depths, durations and widths. Surface samples from the lower and upper foreshore were also gathered to evaluate what sizes of sediment were mobilized over the tidal cycle. Shear stresses in the uprush and backwash were calculated to assess whether flows were competent to mobilize the sand and gravel fractions in samples.

1.4 Research Contribution

This doctoral research is expected to make several contributions. Results from this research will improve knowledge of the physical processes that determine exhumation and transport of horseshoe crab egg and sediment from two locations (the mid and upper foreshore) on an estuarine foreshore that are influenced by different morphodynamic and hydrodynamic conditions at different stages of the tidal cycle. The mid and upper foreshore locations are dynamic sub-environments and differ in terms of the amount of wave energy delivered to the foreshore, rates of sediment transport and textural characteristics of the sediment. Therefore, spatial and temporal differences in physical processes need to be assessed and correlated with quantities of eggs and sediment exhumed and transported from those locations.

Insight will be provided to the process conditions in the swash that sustain the link between populations of horseshoe crabs and migratory shorebirds that are both under stress due to alteration of estuarine beach habitat. Knowledge of the quantities of eggs that are exhumed due to wave activation and those that are entrained due to swash processes alone under different weather-mediated wave energy conditions in the absence of spawning, will enhance models of shorebird population fitness that are dependant on available nutritional sources. In addition, knowledge of the quantities of eggs that remain buried under different weather-mediated wave energy conditions across the foreshore will help provide insight to horseshoe crab habitat use, early life history survival including egg development, and long term population viability. Depending on the wave energy and angle of wave approach, plunging waves and swash processes may erode and decrease the depth of sediment deposited over buried eggs, or deposit more sediment over buried eggs burying them deeper under the surface of the foreshore making them unavailable to foraging shorebirds. Results from this research will provide the quantitative contribution of wave and swash processes to egg exhumation and reburial relative to those of beach sediment.

Third, this research will highlight processes in the swash responsible for the textural properties of sediment found on the surface of an estuarine beach. Low energy estuarine beaches are sensitive to small changes in tidal range and wave energy that cause significant sedimentological changes across the foreshore. While several studies have investigated differences in the volume of sediment transported in the swash and related these differences to swash characteristics, few have investigated the differences in the textural properties of sediment in transport. Understanding these processes is especially important in mixed sediment estuarine and low energy beaches because they lack surf zones and foreshore reworking is dominated by swash uprush and backwash. Changes in the textural properties of foreshore sediment can alter habitats for fauna that utilize estuarine beaches so it becomes important to understand how wind, wave and swash conditions change sediment characteristics.

1.5 Dissertation Structure

This dissertation consists of five chapters in total. Chapter 2 provides an overview of the rationale behind the proposed research, the discussion of a conceptual model based on findings of previous investigations on horseshoe crab egg and sediment transport; and research hypotheses. Chapter 3 identifies the field experiments, laboratory and data analysis involved to test each of the hypotheses. The first section in Chapter 4 provides a description of the wind and wave characteristics prevailing on the days of monitoring, and morphological changes across the foreshore. The second section presents the textural properties of sediment in transport during the rising, high and falling stages of the tide during a moderate energy storm event and identifies key processes responsible for the mobilization and transport of sediment. The third section reports results of a tracer experiment to assess the quantities of horseshoe crab eggs and sediment in transport in the swash and provide process explanations responsible for entrainment and transport. Chapter 5 discusses the findings in relation to what is currently known about horseshoe crab egg and sediment exhumation and transport.

CHAPTER 2

LITERATURE REVIEW

2.1 Importance of Egg Exhumation and Transport

Horseshoe crabs are locally abundant for short periods of time in late spring and early summer (Botton et al., 1994; Smith et al., 2002) and concentrate on sheltered, coarse-grained, well-drained sandy beaches that are conducive to spawning and egg incubation. Horseshoe crab spawning surveys report crab spawning from Woodland Beach to Cape Henlopen on the Delaware shoreline of Delaware Bay and from Sea Breeze to Cape May on the New Jersey shoreline of Delaware Bay (Smith et al., 2002b, c).(Figure 2.1)

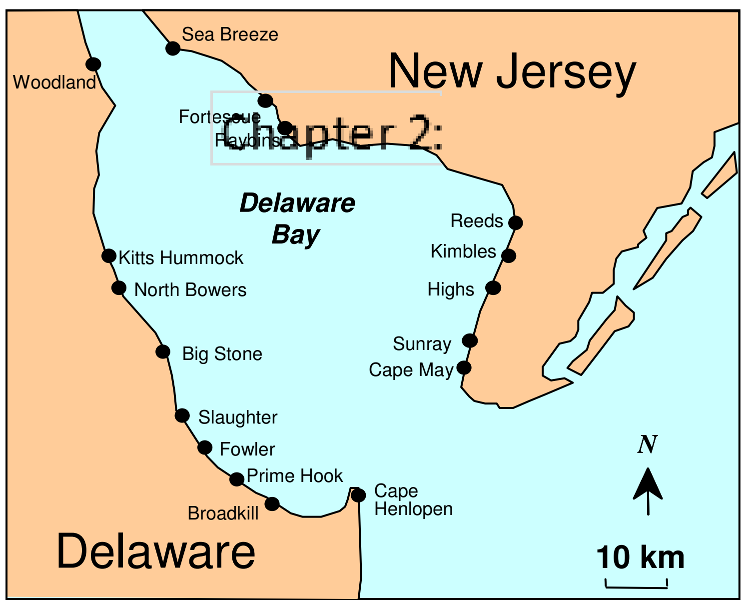


Figure 2.1 Map of Delaware Bay beaches where horseshoe spawning has been reported.

Eggs laid by females are extremely sticky (Brown and Clapper, 1981) and stick to one another as well as to the sediment (Rudloe, 1979). The potential for the vertical movement of these eggs to the sand surface depends on factors such as wave energy, sediment grain size, beach morphology, and frequency of nest disturbance by crabs (Smith, 2007). Waves on estuarine beaches are generally low in height (< 0.25m) and short in period (3-4 seconds) resulting in low depths of activation (Jackson et al., 2002; Jackson et al., 2005). Under low wave energy conditions (<0.25 m significant wave heights), depths of activation will be less than 0.03 m and exhumation of eggs will be confined to the top few centimeters of the foreshore (Jackson et al., 2002). It is in the top 0.05 m of the foreshore where horseshoe crabs eggs are generally available to shorebirds for feeding (Botton et al., 1994). According to Kraeuter and Fegley (1994), burrowing horseshoe crabs can disturb sediment on tidal flats to depths of 0.11 m. Jackson et al. (2005) reported maximum sediment activation depths of 0.103 m where spawning occurred on the upper foreshore of a sandy estuarine beach. In the absence of spawning crabs, the depth of the bottom sediment layer that is affected by hydrodynamic processes over a tidal cycle, known as the depth of sediment activation, will ultimately be responsible for the exhumation of eggs from the sand matrix (Jackson et al., 2002).

Smith (2007) provided a simulation study to quantify horseshoe crab density-dependant nest disturbance on a typical beach in Delaware Bay during a spring tidal cycle. He observed that nest disturbance during peak spawning increased approximately linearly as spawning density increased from one half to approximately twice the 2004 crab densities. When the density of spawning crabs was increased further, nest disturbance reached asymptotic levels. A minimum of roughly 5-9% of these disturbed eggs would be exhumed to the surface (i.e., 0-5 cm) through various processes and be available for consumption by most shorebirds.

Horseshoe crab eggs are laid in masses and are not uniform in size or shape, but do tend to be ovoid, slightly flattened, and thinner (from top to bottom) than wide. As these eggs develop, they become more turgid and rounded (Weber and Carter, 2009). They behave as passive, negatively buoyant particles once they enter the water column (Botton et al., 1994) and like the eggs of other beach spawning species, attach to the substrate by some form of adhesion so that they are not transported too far from where they are laid on the beach or transported in an offshore direction (Martin et al., 2001). Previously laid egg clusters may break into several smaller aggregations of eggs, or ‘‘clusterlets”, and further into individual eggs (Pooler et al., 2003). Sediment containing clusterlets and dissociated eggs are activated by waves, moved vertically upward towards the beach surface, entrained within the flow and deposited on the bed. Cross-shore and longshore currents in the swash exhume and transport these eggs until they settle near beach obstructions or get trapped in the vegetative litter (Nordstrom et al., 2006) and these areas become important foraging areas for shorebirds (Botton et al., 1994). Understanding the link between physical processes (tides, waves, current velocity, sediment grain size, beach morphology) and biological responses (egg densities within sediment matrix, egg exhumation and transport) is therefore, critical to the conservation and management of horseshoe crabs and shorebirds in their environment.

Waves and currents play an important role in the erosion, deposition or activation of sediment in the beach matrix which control quantities of eggs that may remain buried in deeper sediment or be mobilized to the surface in the absence of bioturbation by horseshoe crab spawning. Dominant winds in Delaware Bay are from the northwest and blow onshore with the greatest velocity over a short fetch distance (maximum of 48 km)

(Jackson, 1999). Significant wave heights of 0.50-0.60 m associated with onshore wind speeds of 12 m s^{-1} or more are required in order to disturb sediment and eggs that maybe buried to depths of up to 0.15 m (Jackson and Nordstrom, 1993). However, high wave events can create differing erosional and accretional conditions on the foreshore depending on the direction of dominant winds during that event (Figure 2.2). Erosion of the upper foreshore and deposition on the lower foreshore with little change on the low tide terrace typically occurs when shoreline orientation is near perpendicular to dominant high velocity winds generating waves approaching normal to the shoreline (Figure 2.2, Type A). During post-storm recovery, sediment is transported up the foreshore resulting in restoration of the previous foreshore slope (Nordstrom, 1980; Nordstrom and Jackson, 1992). When shoreline orientation is at an angle to approaching winds, waves also approach at an angle, erosion occurs across most of the foreshore and changes are less conspicuous (Figure 2.2, Type B). Alongshore wind conditions cause prolonged periods of unidirectional wave approach and vertical landward displacement of the entire foreshore profile while the profile slope is maintained. These patterns of change across the foreshore in response to varying wind and wave regimes may either make eggs available to shorebirds following exhumation by erosional events (Castro and Myers, 1993), or bury them under sediment deposited during accretionary events where they undergo development into larvae at a temperature dependant rate (Weber and Carter, 2009). It is important to note that burial of eggs may potentially affect egg survival at different beach elevations (Penn and Brockmann, 1994; Jackson et al., 2008). Eggs buried on the upper foreshore are more likely to desiccate because sediment at that location are warmer and have less moisture because of less potential of recharge by swash infiltration. Burial of eggs beneath sediments on the mid-foreshore creates an environment that is more conducive to egg development because of the presence of optimal moisture, interstitial oxygen and temperature. Textural properties of sediment at the mid and upper foreshore also extend an influence on egg development by controlling the amount of moisture sediment grains can hold and the rate of drainage once the tide recedes (Jackson et al., 2008). Conditions on the mid-foreshore of estuarine beaches promote egg development but this is also the region where activation by waves is greatest at high water (Sherman et al., 1994) and eggs are likely to be exhumed especially during storm events.

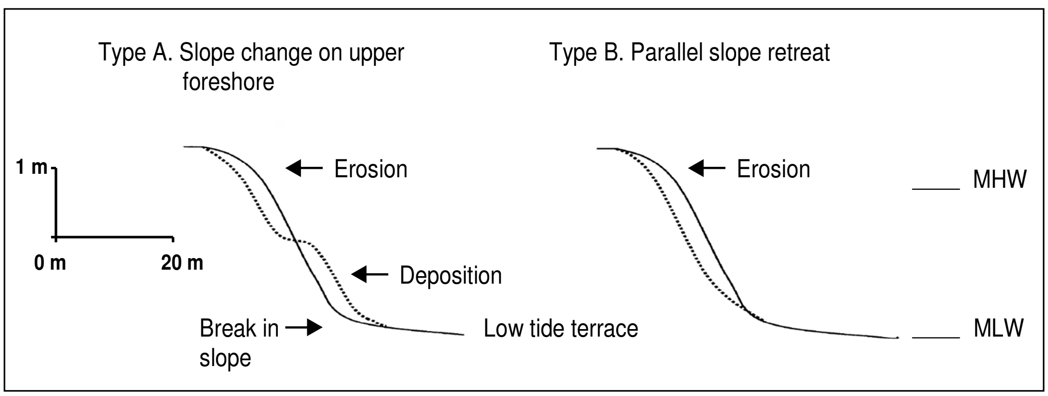


Figure 2.2 Morphological change on the foreshore of a sandy beach in response to high energy waves. MHW and MLW are mean high water and mean low water. Source: (Nordstrom and Jackson, 1992).

Delaware Bay experienced a decline in spawning population of horseshoe crabs in the early 1990's due to peaks in harvesting of the species (Swan et al., 1996; Shuster, 1996; ASMFC, 1999), but recent assessments indicate that relative abundance of crabs has stabilized since 2000 and is showing signs of recovery. A technical report compiled by the Atlantic States Marine Fisheries Commission established that female spawning activity in Delaware Bay has been stable over the past nine years and both male and female adults were experiencing a positive population growth (ASMFC, 2008). Smith et al. (2009) provide a recent review of assessments of *Limulus* populations in Delaware Bay. They reported a high degree of correlation (r =0.77 for females, r = 0.94 for males) between estimates of relative abundance of adults based on data gathered through offshore trawl surveys (Hata, 2008) and spawning surveys (Michels et al., 2008) between the years 2002-2007. Hata (2008) observed an increase in the numbers of juveniles, adult males and adult females since 2003 and also reported increased recruitment to the population owing to the greater numbers of smaller size classes caught by the trawl gear. Smith et al. (2009) also observed expanding size distributions amongst 9,075 juvenile horseshoe crabs captured in a tagging study in Delaware Bay from 2003 - 2005.

While adaptive management strategies since the late 1990's have contributed to an increase in horseshoe crab abundance in Delaware Bay (Smith et al., 2009), numbers of wintering Red Knots (*Calidris canutus rufa)* continue to decline (Baker et al., 2004, Morrison et al., 2004). Greater crab abundance within Delaware Bay alone does not imply that egg numbers will be sufficient to arrest the decline in Red Knot numbers. The timing of horseshoe crab spawning relative to shorebird refueling also plays a very important role in ensuring that Red Knots and other shorebirds are able to gain mass for their departure from the Delaware Bay stopover area. Data gathered by McGowan et al. (2011) suggest the probability that a bird arriving at Delaware Bay weighing less than 180 g will become a heavy bird (weighing more than 180g) was positively related to estimated female crab abundance on spawning beaches during the second half of May when peak horseshoe crab spawning is observed. Total horseshoe crab spawning numbers during this period did not show any statistical correlation with Red Knots' gain in body mass. Any gain in mass by Red Knots during the early periods of the spawning season (between early to late May) was also not attributed to spawning crabs suggesting that horseshoe crab spawning and shorebird foraging needs to match temporally in order for shorebirds to successfully complete their long distance migration to the Arctic breeding grounds.

Heavy spawning events are often delayed if the water temperature falls below 15 ºC (Smith and Michels, 2006) or if there is increased wave activity due to the occurrence of storms (Smith et al., 2011). Also, habitats of both horseshoe crab and migratory shorebird populations are threatened by shoreline development and erosion. According to Botton et al. (1988), only 10 percent of the New Jersey shoreline provides optimal habitat for spawning horseshoe crabs. Shuster and Botton (1985) reported that the increased number of jetties and residential development may have been a contributing factor in the decline of numbers of horseshoe crabs in Delaware Bay between 1871 and 1981. High rates of erosion may result in the modification, deterioration or loss of suitable spawning beaches for horseshoe crabs (Jackson et al., 2002). For example, highly eroding beaches may expose peat outcrops which create anaerobic conditions within sediment reducing horseshoe crab egg survivability. Crabs detect the hydrogen sulfide or low oxygen condition in such areas and avoid spawning on these beaches (Botton et al., 1988). Global warming and subsequent sea level rise could further exacerbate horseshoe crab spawning and shorebird foraging habitat (Cooper et al., 2008). In order for all migratory shorebirds to meet their energy requirements during their three week stopover in Delaware Bay, a large number of horseshoe crab eggs are required. Castro and Myers (1993) estimated that at least 1,820,000 female horseshoe crabs would be required to produce approximately 539 metric tons of eggs sufficient for shorebirds if they fed exclusively on horseshoe crab eggs and not on any other food items. The actual number of horseshoe crab eggs consumed by shorebirds is likely fewer than this estimate, requiring a smaller number of horseshoe crabs to produce the actual amount consumed by migratory birds. Botton et al. (1994) estimated that an average of 44,000 eggs per square meter would be required to sustain the entire shorebird population in the Delaware Bay. Since horseshoe crab egg availability is critical to meeting the energy needs of shorebirds over a narrow window of time every spring (Smith et al., 2011) and the probability that an increased frequency of mismatched migrations of the two species would result in decreased recruitment of shorebird populations (Durant et al., 2005), the understanding of physical processes in relation to egg exhumation and transport needs more attention.

2.2 Processes Responsible for Sediment Transport in the Swash Zone

Understanding the hydrodynamic forces operating within the swash zone is important to determine the mechanisms by which horseshoe crab eggs are made available to migratory shorebirds. Natural sediment (biogenic and terrigenous) generally consists of a mixture of different grain sizes with correspondingly different settling velocities. Intuitively, for a given flow velocity, we would expect that finer sediment would have a greater tendency to go into suspension than coarser fractions (Nielsen, 1992; Raudkivi 1998). Even though horseshoe crab egg and foreshore sediments are subject to the same hydrodynamic forces in the swash and breakers, their rates of transport are expected to be different due to differences in their physical properties. Horseshoe crab eggs are less dense (0.65 gm ml^{-1}) compared to the density of the sediment (quartz sand density = 2.65 gm cc^{-1}) they deposit their eggs in. Once in the water column, eggs will tend to stay in suspension longer than sediment. Being denser than horseshoe crab eggs, sediment particles will sink faster and be deposited on the foreshore when water levels drop in the swash lens.

Sediment on estuarine beaches is mostly comprised of medium to coarse sand and a gravel fraction consisting predominantly of granules and pebbles (Nordstrom & Jackson, 1993). Gravel is a key diagnostic feature on predominantly sandy estuarine beaches, and its presence and distribution are important for the interpretation of palaeo-deposits (Nordstrom & Jackson, 1993) and for the assessment of the viability of habitat for biota that utilize the estuarine foreshore (Wieser, 1959; Rice, 2006; Jackson et al., 2008; Dethier et al., 2010). Previous investigations of the transport of gravel on estuarine beaches identified the importance of wave height and tidal elevation to the net position (horizontal and vertical) of gravel on the foreshore. The stage of the tide determines the width of the foreshore that will be reworked by waves, the wave energy delivered to different locations across the foreshore and the locations where sediment can be entrained. Field observations reveal that concentration of gravel on the surface increases with decreasing elevation across the foreshore and is a function of the tide and wave energy gradient (Nordstrom & Jackson, 1993; Curtiss et al., 2009). After low and moderate wave energy events on sandy beaches with a gravel fraction (Figure 2.3), the foreshore is characterized by a gravel band at the upper limit of swash, a lack of gravel across the upper foreshore above mean tide level, and a high concentration of gravel on the lower foreshore down to the break in slope, that represents the contact between the foreshore and the low tide terrace (Nordstrom & Jackson, 1993; Curtiss et al., 2009). During high wave energy events, the foreshore undergoes cut and fill, the sediment is well-mixed, and there is a reduction in the amount of gravel remaining on the surface at the time of low tide, except in the band of gravel at the upper limit of swash (Nordstrom & Jackson, 1993).

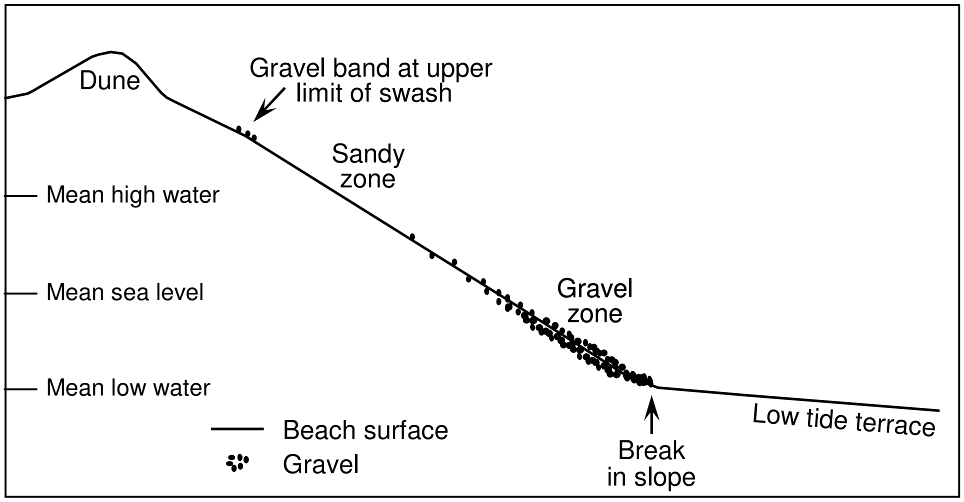


Figure 2.3 Profile of an estuarine beach identifying sand and gravel concentrations across the foreshore.
Source: Saini et al. (2011) In press.

Transport of sediment by fluid generally occurs as bed load or suspended load, depending on the size of the particles and strength of the flow (van Rijn, 1984). When flow speeds exceed the critical value for initiation of motion of a particle on the bed, sediment moves as bedload transport. In this mode of transport, grains roll, slide and saltate along the bed. Bed load is the dominant mode of transport when flow rates are low and/or grain sizes are large. According to Soulsby (1997), coarse sands and gravel are usually transported as bed load. If flows are strong and they exceed the threshold of suspension, bedload transport will still occur but the quantity of sand sized sediment carried as suspended load will exceed the quantity transported as bed load. However, it is difficult to accurately estimate bedload and suspended load separately in field experiments because of sampling difficulties. Extremely sensitive devices are required to be deployed in sufficient depths of water in order to measure bedload and suspended load effectively. Therefore, total load representing a sum total of bedload and suspended load is used to represent quantities of sediment transported in the swash uprush and backwash. Hughes et al. (1997) observed that sediment transport on steep beaches occurred as sheet flow, i.e. several layers of the bed were mobilized as bed load and suspended load throughout the uprush. Therefore, it is assumed that horseshoe crab egg and sediment transport is dominated by sheet flow conditions in the swash zone of steep estuarine beaches.

The most routinely used model to predict sediment transport in the nearshore zone is based on the energetics model developed by Bagnold (1963). The basic principle behind this model is that the energy expended by a fluid moving on a sediment bed is transferred into energy that generates shear stress between sediment particles and mobilizes and transports sediment grains along the bed. As this stress increases, grains roll over each other and are in continuous contact with the bed. This model works if the sediment transported is predominantly entrained by locally generated shear stresses in swash flows. The applicability of this model in the swash zone decreases if larger quantities of sediment are entrained by bore collapse and subsequently advected into the swash zone

Sediment transport rates in the uprush and backwash on steep sand beaches have been related to many inter-related processes. These processes include cross shore velocity asymmetries (Ivamy and Kench, 2006), shear stresses at the bed (Hughes et al., 1997; Masselink and Hughes, 1998), cross-shore morphology as a function of beachface slope and textural properties of the sediment. A description of each of these factors is provided below.

Cross-shore Velocity Asymmetries

Previous studies have reported that the attributes of the swash uprush and backwash are not identical. Mean onshore flow velocities during the uprush are generally higher and of short duration compared to the backwash (Masselink and Hughes, 1998, Hughes et al., 2007). As a result, the mean cross-shore velocities are directed offshore (Masselink and Russell, 2006). Peak uprush velocities may either be similar (Puleo et al., 2003) or slightly higher than peak backwash velocities (Hughes and Baldock, 2005). The velocity of a swash uprush is at a maximum near the start and velocity of a backwash is at a maximum at the end. Water depths are relatively greater in the uprush than in the backwash (Hughes et al., 1997). These differences between the swash uprush and backwash make them behave like two separate systems (Kirk, 1970).

After wave breaking, flows in the shallow water of the swash become increasingly asymmetrical and the statistical distribution of the recorded instantaneous velocity data points become skewed. Thus, the mean cross-shore velocity by itself is not sufficient to explain sediment transport in the swash zone. Therefore, a higher order velocity moment of the cross-shore flow, referred to as the skewness (u_{sk}) is used to determine the cross-shore velocity asymmetry in the swash, and thus the direction of net sediment transport (Masselink and Russell, 2006). The skewness gives information about the asymmetry of the statistical distribution of the data points in the cross-shore velocity time series. A skewness value greater than 0 indicates that the velocity is skewed onshore (i.e. onshore velocities are higher, with short duration, while offshore velocities are lower, with longer duration). The inverse holds true if the skewness value is less than zero. It is important to note that the significance of skewness in explaining cross-shore sediment transport increases when sediment entrainment and transport is predominantly induced by local shear stresses during wave uprush and backwash, and to a lesser extent by bore collapse seaward of the swash zone.

Ivamy and Kench (2006) related data on uprush and backwash sediment transport to cross shore velocity asymmetries gathered during low energy conditions on a mixed sand and gravel beach following a storm event. They observed that energy under breaking waves modulated by the tidal stage was critical in entraining sand and gravel present on the lower foreshore. However, onshore swash velocity asymmetries were responsible for transporting the entrained sediment to the upper beach. Recently, Blenkinsopp et al. (2010) developed a method to measure simultaneous bed level changes and depth averaged cross shore flow velocity data during swash events and were able to demonstrate that swash velocities are more negatively skewed (offshore directed) than observed in previous investigations. Negative skewness values may have significant effects on the results of energetic calculations made over a swash cycle (e.g., by using Bagnold's energetics model), leading to increased estimation of predicted offshore sediment transport.

Masselink and Russell (2006) compared shoreline changes by the swash on a flat dissipative ocean beach relative to a steep intermediate ocean beach. They observed that cross shore flows were dominated by offshore directed mean flows, especially on the steeper beach. However, profile measurements reported accretion on the upper part of both beaches, indicating that net sediment transport was onshore. Their data demonstrated that application of energetics-based sediment transport models to the cross-shore velocity time series in the swash would have predicted offshore sediment transport with erosive conditions on the upper part of the beach. They attributed failure of the energetics model using cross shore flow asymmetry data in predicting onshore sediment transport to factors such as enhanced bed shear stresses in the uprush which could be attributed to flow acceleration, bore turbulence or infiltration effects. Advection of bore-entrained sediment into the swash zone is also another reason highlighting the fact that flow asymmetry data cannot be used alone to explain onshore sediment transport. Jackson et al. (2004) reported that the sediment transported in the early part of the uprush right after wave breaking is inherited in part by turbulence generated during bore collapse seaward of the lower swash zone. Jensen et al. (2010) were able to isolate individual bores from pressure transducers deployed in the lower swash and observed an increase in suspended sediment loads entrained at the bore front which is delivered to the mid and upper regions of the swash.

Shear Stresses in the Uprush and Backwash

Sediment transport within the swash also occurs due to turbulence arising from local shear stresses generated at the bed during swash uprush and backwash. Direct measurements of shear stress in the swash are difficult to obtain and therefore most sediment transport model rely on velocity measurements to calculate the shear stress at the bed.

Conley and Griffin (2004) used a hot film anemometer deployed flush with the bed to measure bed shear stresses in the field, and observed a rapid rise and gradual decline in bed shear stress during uprush, and a more symmetric rise and fall of shear stresses during the backwash. Peak uprush shear stress was also observed to be nearly twice that of the peak backwash shear stress. Many studies have found that the friction coefficient in the uprush is significantly larger than in the backwash (Cox et al. 1998; Cox and Hobensack, 2001; Conley and Griffin, 2004), and therefore for a given velocity, bed shear stresses in the uprush would be higher than those in the backwash (Masselink and Puleo, 2006). Enhanced shear stresses during the uprush have been attributed to several processes including bore turbulence (Puleo et al., 2000), in/exfiltration effects (Conley and Inman, 1994; Turner and Masselink, 1998), and flow acceleration (Nielsen, 2002; Puleo et al., 2003). Puleo et al. (2000) measured suspended sediment concentrations and velocities within three locations across the swash zone of a steep sandy beach during high tide. They reported maximum suspended sediment concentrations in the leading edge of the swash following bore collapse. Their instruments detected a decrease in suspended sediment concentrations right after initial inundation by the swash. They could not determine whether the decrease was attributed to sediment being advected with the leading edge of the uprush or if sediments were simply settling down in the water column. The velocities behind the leading uprush edge were quite large, but no new sediment appeared to be entrained while the uprush was in motion suggesting that bore generated turbulence acting on the bed near the start of the uprush played a more important role in suspending and transporting sediment onshore than in situ bed shear stresses in the uprush alone. Furthermore, they observed a direct correlation between the energy dissipated and resulting suspended sediment concentrations in the vicinity of the bore. Suspended sediment concentrations were observed to gradually increase in the backwash with highest suspension at the very end of the flow associated with maximum backwash velocity.

Turner and Masselink (1998) used field measurements to include the effects of seepage flow on the bed shear stress. They compared swash zone sediment transport in the presences of infiltration/ exfiltration relative to a case of no flow through the bed. They calculated that infiltration effects increased bed shear stresses in the uprush and led to a greater than 40% enhancement of the transport potential in onshore flows. Due to exfiltration, backwash flows were observed to undergo a 10% reduction in their sediment transport potential. They concluded that the effects of seepage forces and enhanced bed shear stresses in the swash on a saturated beachface increased net onshore sediment transport.

Swash Processes as a Function of Beach Slope

The beach slope exerts a direct control on sediment transport processes in the swash, and consequent morphological changes on the foreshore. Duncan (1964) reported that beaches with low slopes generally had wide swash zones and those with steep slopes had narrow swash zones. When the beach slope is small, incoming waves break gradually over greater widths, producing a well developed surf zone in which wave heights decrease progressively while moving onshore. When the beachface is steeper, the width of the surf zone maybe small or negligible, and waves break by plunging. Therefore, for small slopes, shear stress generated by swash flows is the primary mechanism for sediment transport. For steeper slopes, other transport mechanisms such as wave breaking may play a greater role in transporting sediment (Larson et al., 2004).

According to Hardisty (1986), the beachface is in dynamic equilibrium with swash motions when the quantities of sediment transported onshore by the uprush is equal to that transported seaward by the backwash, and the associated equilibrium gradient represents the balance between onshore swash asymmetry and the downslope component of gravity (Hardisty, 1986). However, beachface gradients can be modified with variation in the mean grain sizes in transport across the foreshore. Coarser grain sizes are associated with steeper beach slopes and finer grain sizes have flatter beach slopes (Bascom, 1959). When sediment on the beach is relatively coarse ($D_{50} > 1$ mm), swash infiltration plays an important role in sediment transport processes (Grant, 1948; Quick, 1991). Water percolates into the bed comprising coarse grains and resulting backwash flows are weaker. Onshore sediment transport is enhanced, resulting in a steepening of the beachface until a gradient is attained where onshore forces due to swash asymmetry are balanced by gravitational forces. On beaches comprising sediment with median grain sizes less than 1 mm, suspended sediment transport is the dominating mechanism controlling sediment transport. In this case, the beachface gradually becomes flatter as finer sediment causes less percolation, and therefore less sediment transport in the swash.

Indirect effects of the beachface gradient on sediment transport in the swash were discussed by Masselink and Puleo (2006). The beach gradient at the bottom of the swash zone plays an important role in controlling the type of breaker generated and thus determines the amount of turbulence and suspended sediment advected into the swash zone at the start of the uprush. For spilling and surging-type breakers, the onshore swash asymmetry derived from the wave breaking process maybe limited since wave energy is released more gradually as waves move onshore. However, plunging breakers allow increased energy dissipation and associated turbulence with onshore swash asymmetry greatly favoring uprush sediment transport, hence promoting the development of a steep gradient.

The flattening and steepening of the beachface also cause an increase and decrease in swash period, respectively that affect swash processes and sediment transport (Masselink and Puleo, 2006). If the duration of a swash cycle is less than the incident wave period, swashes are uninterrupted and are believed to promote offshore sediment transport and flattening of the beachface. If the duration of a swash cycle is greater than the incident wave period, interactions between swash cycles occur and onshore sediment transport is promoted with associated profile steepening. Holland and Puleo (2001) used innovative video measurements on a sandy foreshore to assess morphological response following a storm and reported that their foreshore adjusted to wave and swash conditions in a way that it minimized differences between swash duration and the incident wave period.

2.3 Conceptual Model of Egg Exhumation and Transport

A conceptual model based on the findings of previous investigations on swash zone sediment transport that is applicable to transport of horseshoe crab eggs and sediment (coarse sand and granules) on a steep estuarine beach is as follows. Most of what is known about swash zone hydrodynamics and sediment transport is based on field investigations carried out on exposed ocean beaches (Elfrink and Baldock, 2002;

Masselink and Puleo, 2006), not on estuarine beaches. The foreshore of estuarine beaches are typically steep and comprise sediments that are relatively coarser than those found on ocean beaches. Wave and swash energies are delivered across a narrow and more concentrated zone because plunging waves are directly converted to the swash without passing through a surf zone that is characteristic of many ocean beaches. The contribution of plunging waves to sediment entrainment is thus expected to be greater than the contribution of bed shear stresses generated locally in uprush and backwash flows. The importance of wave breaking as the dominant mechanism of sediment entrainment on steep beaches relative to shear stress has also been reported by other investigations (Hughes et al., 1997; Puleo et al., 2000; Butt et al., 2004). Therefore, the key hypotheses to be tested in order to explain horseshoe crab egg and sediment transport on steep estuarine beaches are as follows:

a) During the rising and falling stages of the tide, greater quantities of egg and sediment will be exhumed in the lower swash zone due to wave breaking than quantities entrained by locally generated shear stresses in the upper swash landward of wave breaking.

b) During the high water still stand, greater quantities of egg and sediment will be entrained in the swash due to locally generated shear stresses than exhumation by wave breaking.

2.4 Conceptual Model of Textural Changes of Sediment Transported in the Swash

A conceptual model based on previous findings of processes that control sediment transport in the swash zone when winds blow directly onshore and moderate energy wave conditions prevail is as follows. During the early part of the rising tide, the energy under the peak of the incident waves will be low because offshore water levels are low, and resulting velocities of the uprush and backwash will also be low. Swash widths determined, in part, by the wave height and period, will be short compared to other tidal stages. Waves breaking at the location of the break in slope will generate swash events with upper swash limit at the location of the lower foreshore. Sediment transported will be moderately well sorted and comprised predominantly of sand and a small percentage of granules and pebbles that are entrained from the surface of the lower foreshore by local shear stresses during the uprush and backwash. The potential for entrainment of larger pebble clasts by locally generated shear stresses is expected to be low during the early part of the rising tide. As the tide continues to rise, offshore water depths and wave energies will increase and an increasing proportion of gravel to sand will be transported in the swash as plunging waves breaking on the lower foreshore suspend and deliver gravel into the swash zone.

Since breaking wave heights and energy dissipation are greatest at high tide, increasing quantities of granules and pebbles relative to the sand fraction will be suspended and delivered into the swash. Sorting of sediment during high tide is expected to be poor indicating an increase in the range of sediment sizes transported. Swash widths and velocities are expected to be greatest relative to other stages of the tide. The potential for uprush and backwash flows to entrain the coarser fractions present on the foreshore will also be high during high water still stand. Coarser fractions that are entrained by the largest uprush excursions will be stranded at the upper limit of swash and will not be recaptured in the subsequent swash events.

The falling tide will be characterized by low wave heights and the associated energies under the peaks of incident waves will begin to decline. Granules and pebbles deposited on the upper foreshore will become entrained in backwashes and progressively move downslope. Quantities of granules and pebbles transported during the falling tide will be similar to those transported during the rising tide.

The shape of the granule and pebble fraction will also play an important role in determining transport over the tidal cycle (Orford, 1975; Ciavola and Castiglione, 2009). If the shape of the coarse fraction is more discoidal, the likelihood of particles to be suspended in the uprush and deposited at the upper limit of the uprush will be high. If granules and pebbles are well rounded, they will tend to roll down more easily in the backwash by the force of gravity and be deposited on the lower foreshore. Hypothesis to be tested in support of this model are:

a) The percentage of granules and pebbles in transport over the tidal cycle will be lowest during the initial stages of the rising tide and latter stages of the falling tide when wave energies are lower relative to other stages of the tide.

b) The percentage of granules and pebbles in transport over the tidal cycle will be greatest during high water when wave and swash energies are at a maximum.

CHAPTER 3

METHODS

3.1 Overview

The methods presented here address the three main objectives of this study including: (1) the significance of wave and swash processes to horseshoe crab egg exhumation and transport in the absence of spawning; (2) comparison of how horseshoe crab eggs are mobilized relative to beach sediment; and (3) evaluation of the processes responsible for textural changes of beach sediment in transport in the swash zone on a steep estuarine foreshore during a moderate energy storm event. The first two objectives were accomplished by deploying egg and sediment tracer at two locations (mid and upper foreshore) on two separate days, and measuring the quantities of tracer in transport by using total load streamer traps in the uprush and backwash over individual swash cycles. Tracer injection sites were exhumed after the fall of the tide to identify quantities of egg and sediment tracer that was mobilized due to wave and swash processes. The third objective was accomplished by analyzing sediment characteristics (mean size, sorting and skewness) of total load of sediment trapped over a tidal cycle. Characteristics of the swash uprush and backwash were gathered on the foreshore from mid-rising tide to mid-falling tide by deploying instruments including pressure transducers and electromagnetic current meters in the swash zone to identify processes responsible for entrainment and transport of eggs, sediment tracer and total load.

3.2 Field Site

The field investigation was conducted on the foreshore of a small transgressive barrier located on the west facing shoreline of Delaware Bay, New Jersey (Figure 3.1). Delaware Bay is a micro tidal estuary; tides are semi-diurnal with a mean range of 1.6 m and spring range of 1.9 m (NOAA, 2007a). The site, located 15 km north of the mouth of the estuary in the community of Green Creek, New Jersey, was chosen because it has been observed to support the highest numbers of spawning horseshoe crabs along the New Jersey shoreline in past spawning seasons (Shuster and Botton, 1985; ASFMC, 2005). Horseshoe crabs prefer to spawn on beaches that are dominated by coarse sandy sediment (Botton et al., 1988), like those present at the field site. Also, the site is present in the middle region of Delaware Bay, where salinity levels are optimal for spawning and ocean generated wave energy is limited (Smith et al. 2002).

Wind speed, direction, and duration determine the height and periodicity of waves generated in estuaries; thus beach morphology is tied to local wind conditions (Jackson, 1995). Beach processes are generally dominated by locally generated waves of low height (< 0.25 m) and short period (2.5 sec) associated with winds blowing from the northwest during nonstorm events (Jackson et al., 2002; Jackson et al., 2005). However, the passage of low pressure centers can bring strong northwesterly or northeasterly winds that can create storm conditions (wind speeds greater than 8 m s^{-1}) and cycles of erosion and accretion at the field site (Jackson, 1995). Plunging waves break on the foreshore and are converted directly into swash without passing through a surf zone. The foreshore is approximately 12 m wide with a 6° slope, and a flat (< 0.5 º) low tide terrace (Jackson et al. 2005). Sediment is predominantly quartz and feldspar medium to coarse sands with a conspicuous gravel fraction of granules and pebbles (Nordstrom and Jackson, 1993).

Figure 3.1 Map showing location of Delaware Bay (A), the field site (B) and photograph of the field site (C).

3.3 Field procedures

Field data were collected during spring tides, one day after the new moon on October 12, 2007 and three days after the new moon on October 14, 2007 from mid rising to mid falling tide. The cross-shore limits of investigations on both days extend from a baseline on the dune crest to 4 m bayward of the break in slope separating the foreshore from the low tide terrace (Figure 3.3). The procedures involved to fulfill the objectives of this dissertation are described below:

3.3.1 Trapping Experiments

In order to assess egg and sediment exhumation and transport due to wave and swash processes, experiments were performed by injecting tracer into two locations on the foreshore on October 12 and October 14, 2007. A mid-foreshore location was chosen for tracer injection so that both swash processes and wave breaking would influence the exhumation and transport of tracer over the tidal cycle. An upper foreshore location was selected, above the expected position of wave breaking at high tide, so that exhumation and transport processes could be related to swash processes alone. It is difficult to ascertain the exact location of the maximum landward extent of wave breaking and that of the upper limit of the swash before monitoring, thus a best estimate of these two locations was made by identifying the spring tidal wrack elevation. The spring tidal wrack elevation is defined as the location on the foreshore where accumulation of vegetative litter takes place during the highest tides of the month during new and full moon.

Sediment collected from the dry foreshore was washed, dried and coated with fluorescent paint. Eggs, harvested during the spring spawning season and frozen, were thawed, mixed in a pail filled with a solution of bay water and commercial food coloring, and then left overnight for color to set in. Sediment and eggs placed at depth in the mid and upper foreshore on October 12 were dyed orange and blue, respectively. In order to avoid data contamination and for ease of counting tracer after trapping, sediment and egg tracer placed at depth in the mid and upper foreshore on October 14 were dyed green and red, respectively. Approximately nine kilograms of the dyed sediment and 400,000 dyed horseshoe crab eggs were well mixed and injected into both plots in the foreshore.

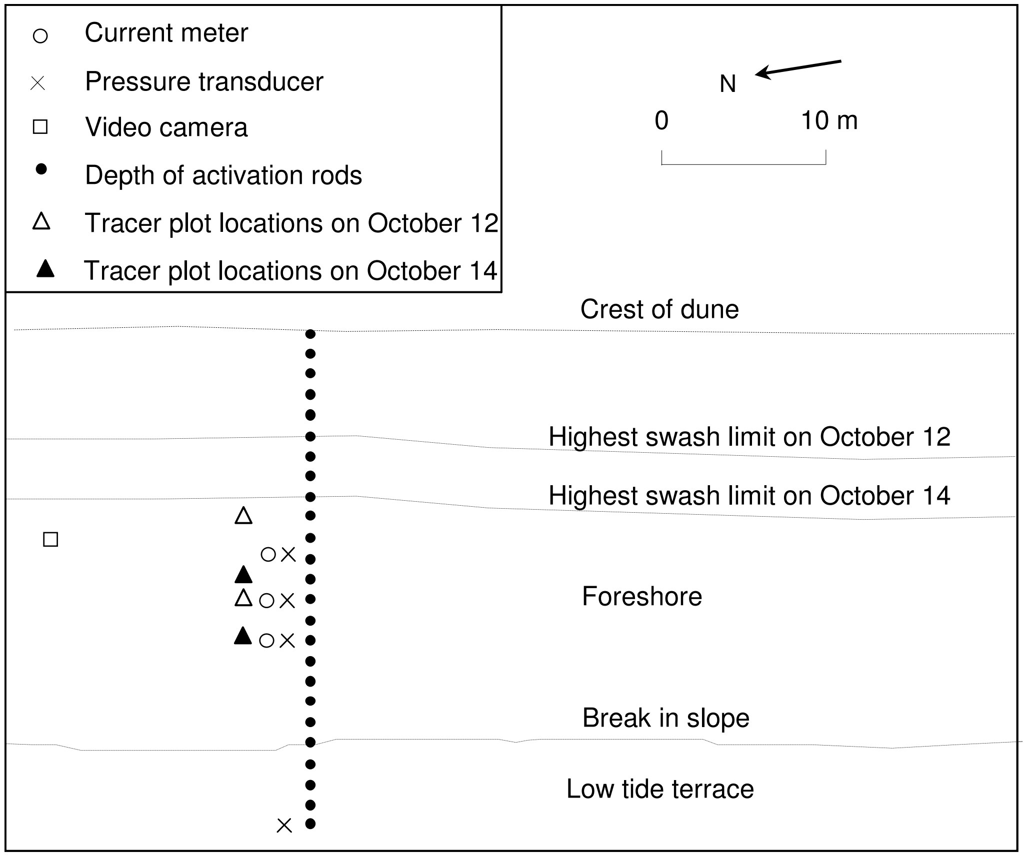


Figure 3.3 Field deployment showing location of instruments, tracer plots and upper swash limit on October 12 and October 14, 2007.

On October 12 tracer was injected within a plot 0.10 m deep, 0.75 m long and 0.12 m wide located 13m from the dune crest on the mid-foreshore and within a plot 0.10 m deep, 0.75 m long and 0.12 m wide that was located 9 m from the dune crest on the upper foreshore. On October 14, tracer was injected within a plot 0.08 m deep, 0.5 m long and 0.175 m wide located 15m from the dune crest on the mid-foreshore and within a plot 0.08 m deep, 0.72 m long and 0.16 m wide located 12m from the dune crest on the upper foreshore (Figure 3.3).

Quantities of eggs and sediment tracer as well as the total sediment load transported in the swash were measured by deploying streamer traps in the swash from mid rising tide to mid falling tide on both days. Streamer traps are hydraulically efficient and have been used to provide reliable estimates of sediment flux in the surf and swash zones (Kraus and Dean, 1987; Masselink and Hughes, 1998; Wang et al., 1998). The advantages and limitations of streamer traps relative to alternative techniques for estimating sediment transport are discussed in Wang et al. (1998). The mean error of this kind of trap is calculated as 10%, with a standard deviation of 9%, based on differences in trap weights of side-by-side duplicate measurements (Edwards, 1997). The traps used in this study have a 0.1 m wide, 0.8 m high opening enabling sampling of the entire water column in the swash.

A single swash event is comprised of an uprush and backwash. The uprush begins right after wave breaking and ends at its upper landward limit. The backwash begins slightly before the uprush travels to its uppermost landward limit and ends upon the arrival of the next uprush. Traps were held perpendicular to swash flow and deployed just prior to arrival of the uprush and subsequent backwash. Trapping began as soon as the first swash came into contact with the mid-foreshore tracer plot, continued until both mid and upper foreshore tracer plots were inundated by the swash, and ended after the upper limit of swash fell just below the mid-foreshore tracer plot. Trap samples were typically taken about once every two minutes, but the interval between sampling was longer if instrument rigs were being moved to the mid or upper foreshore location or instrument probes that became buried in the sand were being adjusted to an appropriate position above the bed. An attempt was made to gather trap samples at the mid swash position in order to ensure that measurements of tracer and total load represented transport primarily due to swash flows, and were not influenced to a great degree by turbulence due to wave breaking. However, variation in heights of individual waves breaking on the foreshore cause differences in the widths of swash events, making it difficult to anticipate the actual position of mid-swash in advance of wave breaking. A total of 55 and 110 swash events were gathered over the mid-rising tide, high water still stand and mid-falling tide to ensure comparative samples on October 12 and October 14, 2007, respectively. Egg tracer, sediment tracer and total sediment load in each trap were washed into a bucket of water; the water was decanted and wet sediment was transferred into Ziploc bags for further analysis. Tracer plots were excavated following trapping at low tide by slicing vertically through the beach matrix. This was done in order to identify the depths to which sediment had been activated, to ascertain the proportion of buried tracer that remained in the foreshore and to assess the thickness of the accretion lens (if any) on top of the tracer plots.

3.3.2 Deployment of Instruments

Characteristics of waves and those of the swash uprush and backwash were gathered on the foreshore from mid-rising tide to mid-falling tide on both days. Flow velocities in the swash were measured with two mini electro-magnetic current meters (Valeport 802) with a 3.2 cm discus sensor deployed 30 mm above the bed. Water depth in the swash was measured with two mini-pressure transducers (Druck PDCR1830) co-located with the current meters but deployed flush with the bed (Figure 3.4). The instruments were adjusted over the tidal cycle to maintain their elevations relative to the bed. These four instruments were initially deployed 13 and 15 m from the crest of the dune (Figure 3.3). The lower pressure transducer and current meter were relocated 4 m landward (11 m from the dune crest) on the rising tide and 4 m seaward (15 m from the dune crest) on the falling tide to maintain their relative position in the swash. A video camera was placed on the mid-foreshore, oriented perpendicular to the shore, and used to provide data on the upper limit of wave uprush and backwash, location of wave breaking, duration of uprush and backwash and width and type of swash events (single or multiple). Data on non-breaking wave characteristics and bay water levels were gathered using a pressure transducer located on the low tide terrace 4 m offshore of the break in slope. All instruments were hardwired to a data logger and sampled at 8 hz over the tidal cycle.

A total of 50 and 110 time series of swash velocities and water depths of each trapping cycle were generated from the wave and current data for October 12 and October 14, 2007 respectively. Analysis of swash records proceeded in a number of steps. The pressure transducer data and current meter data were sampled at a rate of 8 Hz (0.125 s) during the two tidal cycles when monitoring occurred. Data from the datalogger were extracted and converted from comma separated value (csv) form to be further converted into usable data sets with the Campbell Scientific datalogger support software, PC208W v3.01. The support software extracted the raw data as a single file which was separated into wave and current components. Data extracted from this single file in hourly blocks was converted into a format that could be manipulated in spreadsheet form. Times of swash cycles recorded by the video camera were synced with times of wave and swash data stored in the dataloggers. Off-set values that were ascertained by testing the current meters in still water before sampling were applied to the raw data before processing.

Time series data on cross shore velocities and water depths were partitioned into individual swash events and separated into onshore and offshore components of flow. As described by Masselink and Hughes (1998), swash velocity measurements were analyzed such that : (a) the start point of the swash uprush recorded by the flow meter coincides with the time that the leading edge of the swash uprush passes the instrument; (b) the time of the point of peak uprush should be one time step after the uprush start; (c) the peak uprush velocity should be similar to the velocity of the leading edge when the swash front passes the flow meter and (d) the flow velocity should stop recording data when the landward edge of the retreating swash move past the flow meter. The beginning and end of each velocity time series were identified when mean depth was <0.03 m (the lowest depth that can be recorded by the instrument).

Figure 3.4 Photograph of the instruments deployed in the swash during rising tide on October 14, 2007.

3.3.3 Topographic Change and Depth of Activation

Topographic change of the foreshore was measured using 1.5 m long, 10 mm diameter steel rods emplaced across the foreshore at 1 m intervals from the crest of the dune to the low tide terrace (Figure 3.3). A loose fitting washer was placed over each rod, and net change (top of rod to beach surface) and depth of activation (top of rod to washer) were measured to 0.5 mm during daylight low tide before and after monitoring according to the procedure described in Greenwood and Hale (1980). Washers were exhumed and relocated to the surface after each measurement. These rods enable measurement of changes of the sand surface to within 0.5 mm. Measurements of profile elevation were made by surveying the top and bottom of each rod using a stadia rod and transit and tied to a common datum. The position of the step was identified twice each during the rise, high and falling tide by physically locating the step and estimating the cross-shore position of the top of the step relative to the survey rods on October 14, 2007. The position of the step was monitored because it represented the zone of interaction between the breaking waves and the backwash of the swash and the location of greatest turbulence. The location of the step provides information on the likelihood of delivery of gravel to the swash with tidal rise and fall. Two bulk sediment samples were gathered to a depth of 0.10 m at 13 and 15 m from the dune crest to identify characteristics of the beach prior to performing trapping experiments on October 12, 2007.

3.4 Variables

The following section describes variables that were analyzed in order to relate wave and swash characteristics to (a) horseshoe crab egg and sediment tracer exhumed and transported on October 12 and October 14, 2007; and (b) textural changes of sediment trapped across the foreshore over the tidal cycle on October 14, 2007.

3.4.1 Tidal Stage

Tidal stage determines the width of the foreshore that will be reworked, the distribution of wave energy across the foreshore and the location where sediment and eggs can be entrained. The stage of the tidal cycle (rise, high, fall) and height of the tide was determined by averaging five minute pressure transducer data gathered on the low tide terrace (Figure 3.3)

3.4.2 Wind Speed and Direction

Wind speed and direction provide information on the potential for wave generation and the heights of locally generated waves. Fastest six minute wind speeds and six minute modal directions gathered from the Brandywine Shoal Light meteorological station in Delaware Bay were used to determine conditions at the field site.

Table 3.1 Variable identification and method of determination.

Variable	Method of Determination
Offshore water depth (m)	Five-minute average of pressure transducer data on the low tide terrace gathered during the tidal cycle
Wind speed (m s^{-1}) and direction (°)	Fastest six minute wind speeds and six minute modal directions were gathered from the Brandywine Shoal Light meteorological station
Wave height (m) and period (s)	Significant wave height determined from the equation $H_s = 4\eta\sigma$ using 17.1-minute time series of the pressure transducer data gathered on the low tide terrace over the tidal cycle. Wave period determined by spectral analysis of the 17.1 minute time series of the pressure transducer data gathered on the low tide terrace over the tidal cycle.
Swash duration (s)	Video records were used to assess start and stop times of uprush and backwash events.
Swash velocity (m/s)	Cross shore and longshore velocity time series data gathered from current meters located in the mid and upper swash over the tidal cycle.
Bed shear stress (N m^{-2})	Calculated using the quadratic friction formula $\tau = ½\rho\ f\ u^2$.
Swash depth (m)	Averaging of pressure transducer data in the uprush and backwash on the mid and upper foreshore over the tidal cycle.
Swash width (m)	Location of start and end of the uprush, and start and end of the backwash from video records.
Skewness of cross-shore flows	$u_{sk} = \langle u^3 \rangle / \langle u^2 \rangle^{1.5}$ for skewness.
Uprush backwash interaction	Location of interaction on foreshore estimated from video records.
Fall velocity (m s^{-1}) of horseshoe crab eggs	Length and duration of fall of egg in settling tube
Fall velocity (m s^{-1}) of sediment	Equations proposed by Hallermeier (1981)
Quantities of total load trapped in the swash (kg m^{-1})	Weighed on scale after drying.
Quantities of egg tracer trapped in the swash	Direct counts by hand in each sample trapped in the uprush and backwash.
Quantities of sediment tracer trapped in the swash	Counts using clicker counter device under UV lamp in a dark room.
Textural properties of sediment (mm, phi)	Sediments washed, dried and sieved to 0.25 ϕ intervals.
Net change (m)	Subtracting the surface elevation measured at each depth of activation rod at low tide after trapping with the surface elevation measured at the previous low tide
Depth of activation (m)	Subtracting the depth of the buried washer at low tide after trapping with the surface elevation measured at the previous low tide
Beach profile	Difference between the elevation of the top of each depth of activation rod and the elevation of the datum was calculated and this value was added to each subsequent elevation measurement across the foreshore in order to tie each profile measurement to the common datum.

3.4.3 Wave Height and Period

Significant wave heights, defined as the mean of the highest one-third of all the waves in the record, were determined from $H_s = 4\eta\sigma$, where $\eta\sigma$ is the standard deviation of the water surface elevation record. Wave heights were calculated from 17.1-min time series of the pressure transducer data recorded on the low tide terrace. Wave height at breaking on the foreshore was determined from the procedure of Goda (1970) using data from the pressure transducer on the low tide terrace.

Spectral analysis was used to determine the peak wave period for each of the 17.1 minute records. The Matlab signal processing toolbox was used to split the frequency range of 8192 points into 512 bins with 50% overlapping. A spectrum of each segment was computed by detrending (subtracting the means or the best-fit line) the time series so that fluctuations in the time series could be analyzed. The resulting spectrum generated by Matlab provides the distribution of the spectral energy against the wave frequency or amplitude. The peak wave period is identified as the period corresponding to the frequency band with the maximum value of spectral density in the non-directional wave spectrum.

3.4.4 Swash Characteristics

The following variables were assessed to describe swash characteristics over the tidal cycle.

Swash Duration

Durations of the uprush and backwash for each swash event were measured from video records in order to determine whether total sediment load transported was more likely to be transported onshore or offshore. Durations were also important to assess whether the time taken for a typical swash event to complete was greater or lesser than wave period, and whether the uprush or backwash events were likely to interact with a breaking wave. A typical uprush start time occurred right after wave breaking and ended at the uppermost location of the uprush excursion. A backwash start time was indicated by observing when the flows reversed on the foreshore and end time occurred at the arrival of the next wave.

Swash Velocity

Cross shore and longshore velocity time series data was used to determine mean and maximum velocities of the uprushes and backwashes in each trapping cycle. Velocities in the uprush and backwash were calculated for each swash event to provide data on the potential for different sediment sizes to be entrained. Mean velocities were calculated to provide information on the mean sizes in transport during an uprush or backwash event whereas the maximum flow velocities were calculated to provide an estimate of the largest particles that will be transported in the uprush and backwash.

Bed Shear Stress

Bed shear stress and critical shear stress were calculated for uprush and backwash during individual swash events to assess the potential for entrainment of the sand and gravel population. Bed shear stresses (τ) in the uprush and backwash were calculated based on the quadratic friction formula

$$\tau = ½\rho \, f \, u^2 \tag{3.1}$$

where ρ = density of bay water (998.36 kg m^{-3}) , u is the fluid velocity and f is a friction coefficient calculated using Swart's (1974) formulation

$$f = \exp \left[5.213 \left(\frac{2.5 \, D_{50}}{\hat{a}} \right)^{0.194} - 5.977\right] \tag{3.2}$$

where â is the peak wave orbital excursion given by = T û/ 2Π, T is the wave period and û is the peak flow velocity. Critical shear stresses were calculated based on the methods of Soulsby (1997). The critical bed shear stress is calculated by the formula

$$\tau_{cr} = (\theta_{cr}) * g \, (\rho_{s-} \rho) \, d \tag{3.3}$$

and the threshold Shields parameter θ_{cr} was calculated using the formula

$$\theta_{cr} = \frac{0.30}{1 + 1.2 \, D_*} + 0.055 \left[1- \exp (- 0.020 \, D_*) \right] \tag{3.4}$$

where D_* = the dimensionless grain size given by

$$D_* = \left[\frac{g \, (s - 1)}{v^2} \right]^{1/3} d \tag{3.5}$$

where g is the acceleration due to gravity = 9.81 m s^{-1}, s = ρ_s/ρ is the ratio of the grain density to the bay water density, d is the grain diameter and v is the kinematic viscosity of bay water. Since the bed is sloping, gravity provides a component of force on sediment grains that may increase the critical shear stress required from the flow during the uprush and decrease the critical shear stress in the backwash flow. In order to account for the slope, a modified critical shear stress is calculated for the uprush by

$$\frac{\tau_{\beta cr}}{\tau_{cr}} = \frac{\sin(\phi_i + \beta)}{\sin \phi_i} \tag{3.6}$$

and for the backwash by

$$\frac{\tau_{\beta cr}}{\tau_{cr}} = \frac{\sin(\phi_i - \beta)}{\sin \phi_i} \tag{3.7}$$

where (ϕ_i is the friction angle of the sediment (ϕ_i = 32.2 degrees), β is the beach angle (β = 6 degrees). The ratio τ/τ_{cr} was calculated to compare the potential for sediment transport by uprush and backwash flows.

Swash Depth

Water depths in each of the uprush and backwashes lens were determined by averaging water surface elevation for each of the swash events from the pressure transducer data. Swash depths provide an estimate of the heights to which the sediment particles were entrained and suspended due to flows.

Swash Width

Maximum runup location and widths of uprush and backwash were determined for each swash trapping cycle from video records that helped determine the area over which sand and gravel had been entrained and transported on the foreshore.

Skewness of Cross-shore Flows

The skewness was estimated to assess the degree of asymmetry in swash flows. The cross-shore velocity time series was used to calculate the skewness using the equation

$$u_{sk} = \langle u^3 \rangle / \langle u^2 \rangle^{1.5} \qquad (3.8)$$

where $\langle u \rangle$ is the mean flow velocity and the brackets denote time-averaging (Masselink and Russell, 2006).

Uprush-Backwash Interaction

Video records and depth of activation rods placed across the foreshore at 1m intervals adjacent to the tracer plots were used as markers to determine the location on the profile where an uprush met the backwash of a preceding swash cycle. Interaction of successive swash events may enhance sediment suspension in the swash, contributing to gravel movement.

3.4.5 Fall Velocity of Horseshoe Crab Eggs and Sediment

The fall velocity of horseshoe crab eggs of size 1.6 mm was determined by using a settling tube. The fall velocity of sediment of size 2 mm (transition from sand to granules) in baywater was calculated according to the equations proposed by Hallermeier (1981). In order to calculate the fall velocity, the grain buoyancy (A) needs to be calculated using the equation:

$$A = \frac{\rho_s - \rho \; g \; M_d^3}{\rho \; \upsilon^2} \qquad (3.9)$$

where ρ_s = sediment density, ρ= fluid density, υ= fluid kinematic viscosity, and M_d is the median grain size diameter.

The fall velocity was thus calculated using the quation

$$V_f = = \frac{\left[\frac{\rho_s - \rho \, g \, M^3_d}{\rho}\right]^{0.7} M_d^{\;1.1}}{6 \, \upsilon^{0.4}} \qquad (3.10)$$

Comparison of the fall velocity of eggs and sediment in swash flows provides information on the likelihood that eggs or sediment will remain in suspension and be transported onshore or offshore.

3.4.6 Quantities of Total Load Trapped in the Swash

Total load of sediment trapped in streamer traps were weighed after air drying to obtain dry weights. Dry weights were converted to immersed weights to represent total load trapped in the uprush and backwash per m^{-1} of horizontal beach width. Total load data transported over each swash event provides an estimate of the net direction of sediment transport and helps ascertain whether different areas of the foreshore underwent erosion or accretion.

3.4.7 Quantities of Tracer Trapped in the Swash

Material in traps was spread on a fine mesh screen and counts of eggs transported from the mid and upper foreshore tracer plots were made by hand. Counts of eggs trapped in each of the uprush and backwashes were converted to weights trapped in the uprush and backwash per m^{-1} of horizontal beach width.

In order to assess quantities of sediment tracer trapped in the uprush and backwash, total load samples were air dried and then transferred on to a cardboard sheet with a dark background. Direct counts of sediment tracer (orange and green tracer from the mid-foreshore tracer plot and blue and pink tracer from the upper foreshore tracer plot) were made using a clicker counter device under an ultraviolet lamp in a dark room. Counts of sediment tracer were converted to immersed weights to represent total sediment tracer trapped in the uprush and backwash per m^{-1} of horizontal beach width.

3.4.8 Textural Properties of Sediment

Surface sediment samples and those trapped at different stages of the tide were subjected to grain size analysis. Samples were washed to remove organic material, dried in an oven, weighed to the nearest 0.001 g and sieved at 0.25 ϕ intervals. The sediment from -4 ϕ through 2 ϕ was hand-sieved and weighed at 0.25 ϕ intervals. A sonic sifter separator was set for 2 minute intervals to sieve sediment between -1.5 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. Gravel is considered any sediment that is equal to or larger than -2 ϕ; granules fall between -2 and -1 ϕ, while sand is between -1 and 4 ϕ (Table 3.1). Sieved sediment from each size fraction was weighed and recorded to the nearest 0.001 g. Mean, sorting, skewness and kurtosis were calculated using inclusive method of moments (Krumbein and Pettijohn, 1938). Roundness and sphericity of the gravel fraction of all trap samples were estimated visually using Powers (1953) criteria.

3.4.9 Net Change and Depth of Activation

Change in elevation across the foreshore was determined by subtracting the surface elevation measured at each rod after trapping with the surface elevation measured at the previous low tide, so that positive values indicate accretion and negative values indicate erosion. The depths of sediment activation were calculated by subtracting the depths of the buried washer with surface elevation recorded at the low tide of the previous day.

3.4.10 Beach Profile

The difference between the elevation of the top of each rod and the elevation of the datum was calculated and this value was added to each subsequent elevation measurement in order to tie each profile measurement to the common datum. Variability on the beach profile was compared before and after trapping to determine amount and location of topographic change.

3.5 Data Analysis

<u>Analysis to Explain Textural Changes Occurring on the Foreshore on October 14, 2007</u>

A total of 25 sets of uprush and backwash samples of the 110 sets gathered on October 14 were analyzed to represent conditions when both traps were successfully placed at the mid-swash location. Total load representing both bed and suspended sediment trapped during each swash cycle represents instantaneous transport of material. Analysis of the hydrodynamic conditions and sediment characteristics in traps over different stages of the tidal cycle provide insight to the processes responsible for mobilization of sediment from the upper and mid-foreshore in the uprush and backwash. Since total load in the traps represent material that has been transported instantaneously over individual swash events, swash characteristics during the uprush and backwash of individual events were used to explain changes in the availability of sand and gravel across the foreshore over the tidal cycle. The paired two sample t-test was used to determine significant differences in uprush and backwash flow characteristics. The two sample t-test was used to test for differences in the percent gravel trapped during the rising versus falling tide for both the uprush and backwash samples. Bed shear stress and critical shear stress were calculated for uprush and backwash during individual swash events to assess the potential for entrainment of the gravel population using the procedure of Soulsby and Whitehouse (1997) and modified for a sloping bed as presented in Soulsby (1997).

Analysis to Explain Tracer Exhumation and Transport

Data from trapping experiments were analyzed to test if (a) wave breaking and processes in the lower swash zone at the location of the mid-foreshore tracer plot exhumed and transported greater number of eggs during rising and falling stages of the tide, and (b) quantities entrained during high water in the swash from the upper foreshore tracer location were greater than those entrained by wave breaking. Egg and sediment tracer trapped in each of the uprush and backwash of individual swash events may consist of material that has either been (a) locally entrained by flows while the traps are being deployed during sampling, or (b) reworked by prior swash events, or both (a) and (b). Therefore, tracer trapped during sampling cannot be related to instantaneous wave and swash parameters. Since samples were gathered every 2-10 minutes, it becomes important to understand complex processes associated with waves and swash occurring between the sampling periods that also contribute equally to exhumation and transport of tracer over time periods longer than individual swash events. Therefore, characteristics of the swash (velocities, duration, depths, shear stresses and skewness) were averaged over five minute time intervals. Five minute averages of swash characteristics in the uprush and backwash were calculated by following a series of steps. After applying necessary calibration values and offsets, any spurious data points and flow velocity measurements that registered a reading in water depths less than 0.041 m were eliminated. This was done because the instruments only recorded valid measurements in water depths of 0.041 m. The five minute cross-shore velocity records were then separated into positive and negative flow velocity measurements representing onshore and offshore components of the flow respectively. Five minute longshore velocity records were averaged to provide an estimate of the strength of flows moving along the shoreline in the direction of dominant winds. A positive value represented flows that were moving northward whereas a negative value represented flows that were moving southward. Mean depths were calculated by averaging the pressure transducer records obtained concurrent to five minute cross-shore velocity records. Skewness values were calculated from mean cross-shore flows averaged over five minutes. Durations and widths were estimated by averaging 5-minute data gathered from the video records.

Time averaged swash characteristics were compared over the rising, high and falling stages of the tide to describe exhumation and transport of egg and sediment tracer. A Wilcoxon signed rank test was used to compare differences in swash characteristics as well as quantities of egg tracer trapped in the uprush relative to the backwash over different stages of the tidal cycle. Multiple regression analysis was performed on the time averaged cross-shore and longshore velocity data from the two current meters in the swash zone and the sediment and egg tracer trapped over the tidal cycle to determine statistically significant relationships between characteristics of the uprush and backwash and quantities of tracer.

CHAPTER 4

RESULTS

4.1 Overview

The results of the field investigations performed on October 12, 2007 and October 14, 2007 are presented in this chapter. Section 4.2 discusses the wind and wave characteristics that influenced swash processes over the two tidal cycles when trapping occurred. The associated changes in the elevation of the foreshore and depths to which sediment were activated across the foreshore are also discussed. Section 4.3 discusses the characteristics of sediment in transport across the foreshore spanning mid-rising to mid-falling tide on October 14. Conditions in the swash that distinguish transport of the gravel fraction relative to the sand fraction are provided. Section 4.4 describes the timing and quantities of horseshoe crab egg and sediment tracer exhumation from two locations in the foreshore over two tidal cycles and relates them to wave and swash processes.

4.2 Wind and Wave Characteristics

Figures 4.1 and 4.2 presents wind data recorded every six minutes over the tidal cycle on October 12, 2007 (A) and October 14, 2007 (B) at Brandywine Shoal Light's meteorological station in Delaware Bay (NOAA, 2007). On October 12, dominant winds approached the field site in an alongshore direction from the northwest during all stages of the tidal cycle. Wind speeds were high (16 ms^{-1}) and did not vary over the tidal cycle (Figure 4.1).

Wind data from the meteorological station at Brandywine Shoal Light reveal that storm conditions prevailed from noon on October 11 until the end of monitoring on

October 12. Winds approached perpendicular to the shoreline (from the west) during monitoring on October 14. Wind speeds recorded over the tidal cycle ranged from 5 ms^{-1} to 7 ms^{-1} (Figure 4.2).

The change in wave height and period and magnitude and distribution of wave energy over the tidal cycle on October 12 and October 14, 2007 is presented in Figures 4.3 and 4.3. Highest significant wave heights on the low tide terrace on October 12 were 0.77 m during high tide with peak wave periods of 4.8 s. Calculated breaking wave heights on October 12 were 0.65 m when the first of the 55 sets of samples were gathered (07:44), reached 1.11 m at high water and decreased to 0.43 m when the final samples were gathered (12:17).

Significant wave heights on the low tide terrace on October 14 ranged from 0.30-0.47 m over the tidal cycle, and peak wave period was 3.4 s during high tide. On October 14, calculated breaking wave heights on the foreshore were 0.49 m when the first of the 110 sets of samples were gathered (08:55), reached 0.64 m at high water and decreased to 0.43 m when the final samples were gathered (13:24). Data reveal that energy is concentrated at the incident frequency for waves generated by local winds in the estuary on both days (Figures 4.3 and 4.4). Long period waves are absent from the water surface elevation records, suggesting that locally generated waves were the primary source of energy influencing sediment transport processes.

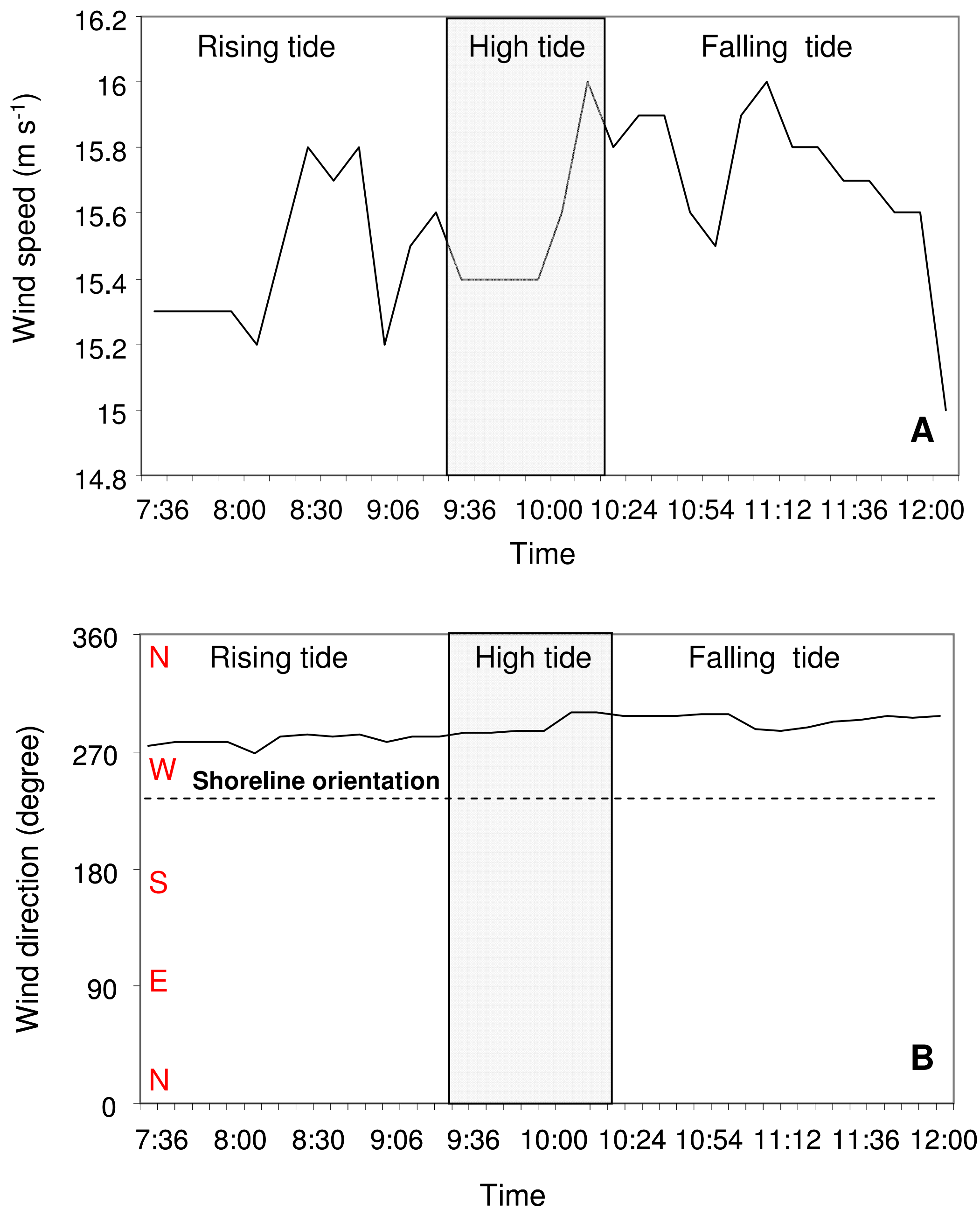


Figure 4.1 Data on wind direction (A) and wind speed (B) recorded every six minutes over the tidal cycle on October 12, 2007 at Brandywine Shoal Light's weather station.

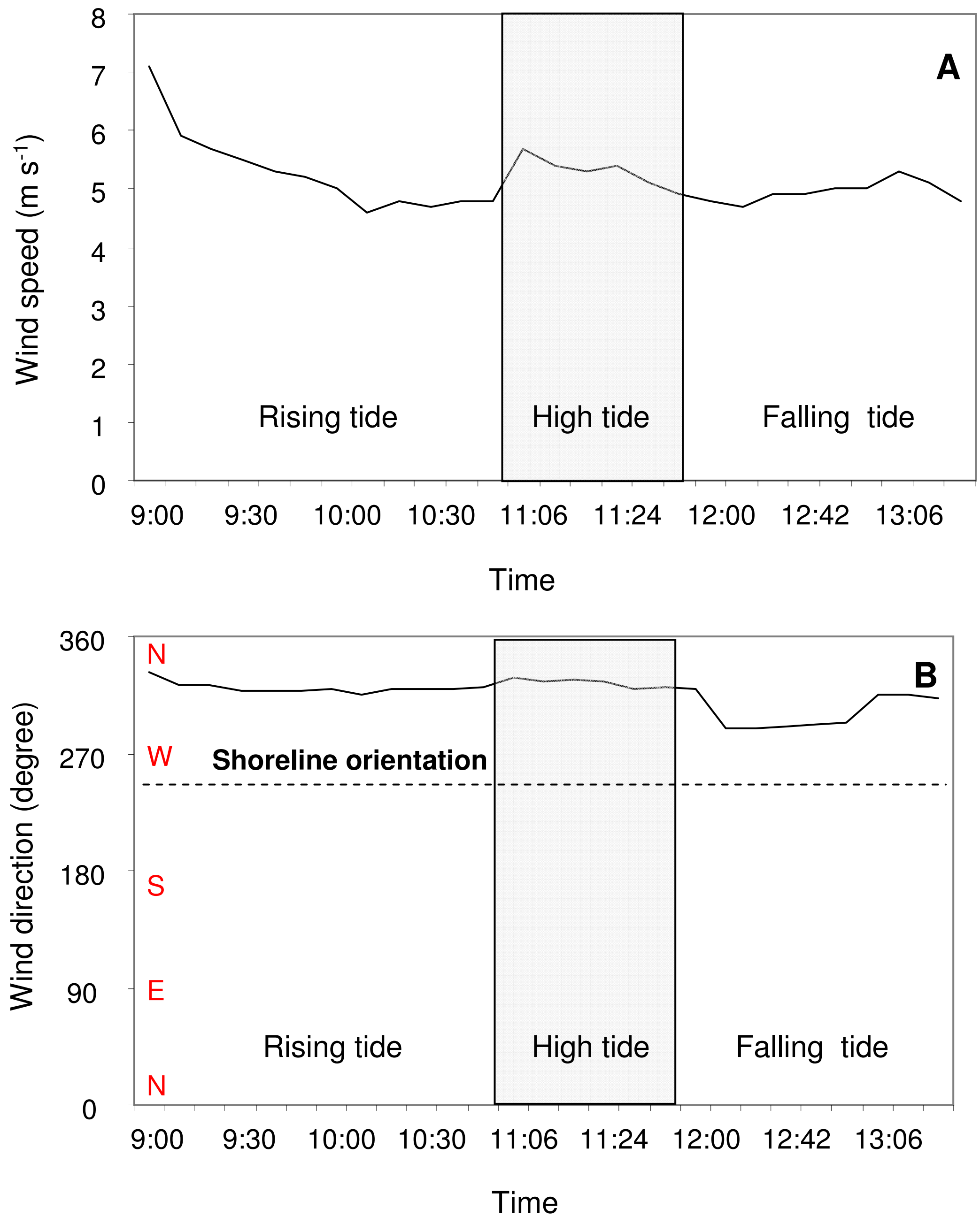


Figure 4.2 Data on wind direction (A) and wind speed (B) recorded every six minutes over the tidal cycle on October 14, 2007 at Brandywine Shoal Light's weather station.

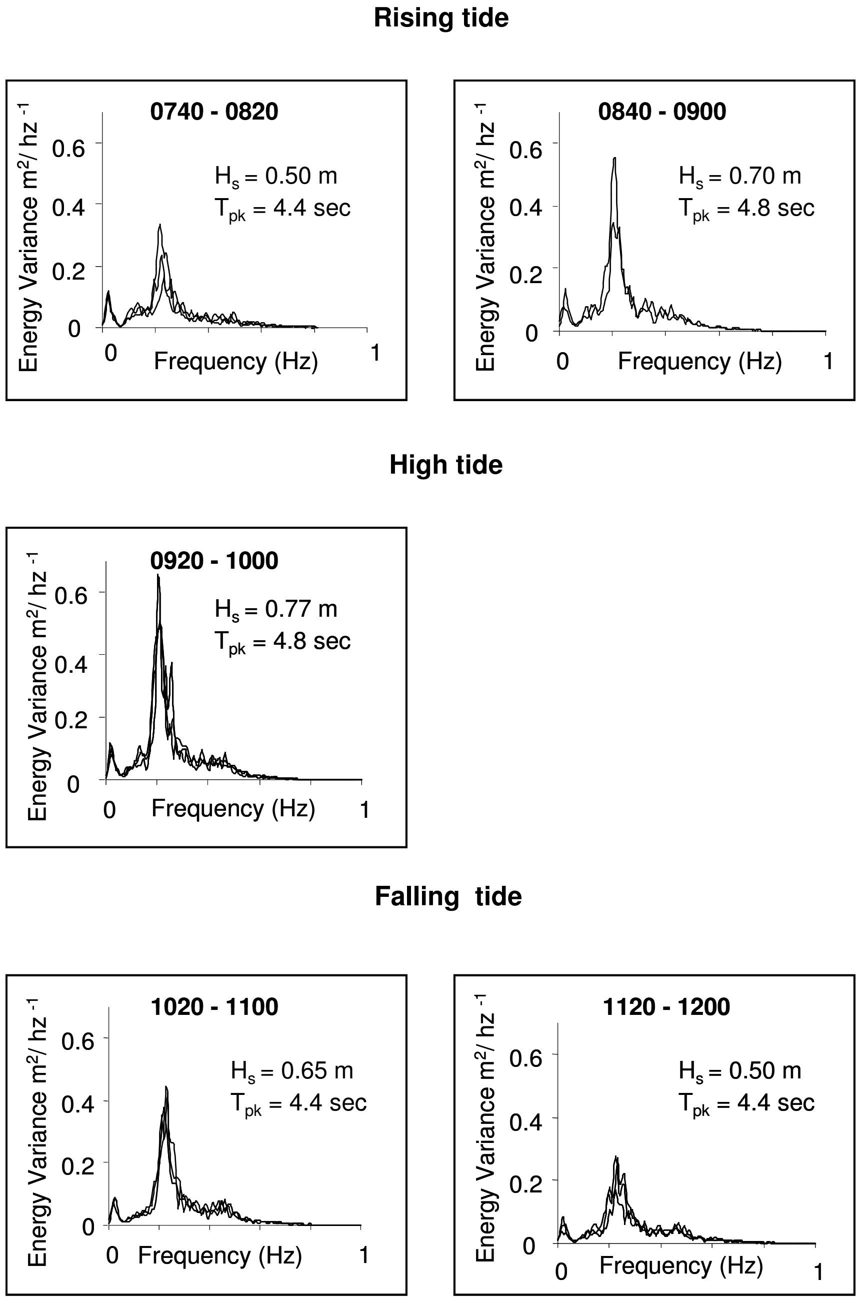


Figure 4.3 Energy spectra, significant wave height and peak period during rising, high and falling tide from data gathered on the low tide terrace on October 12, 2007.

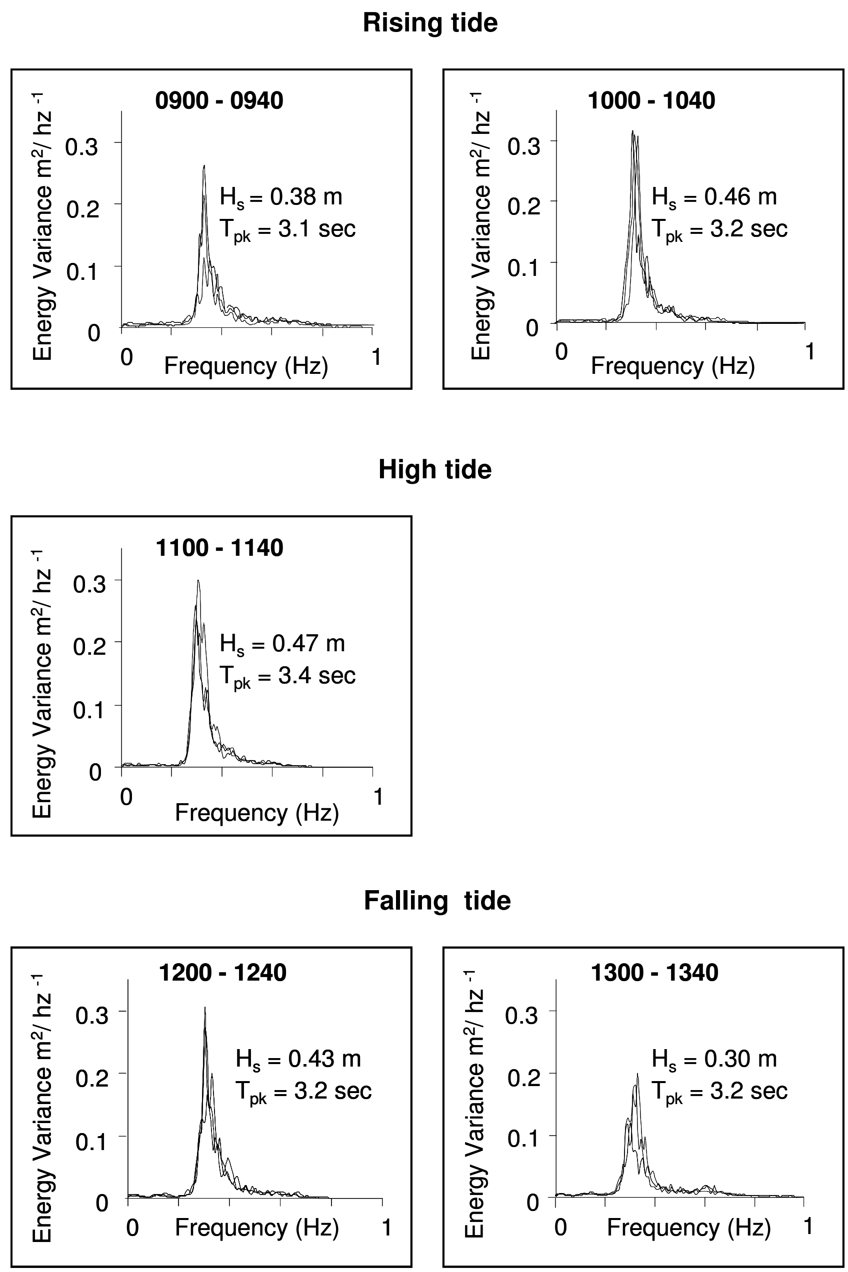


Figure 4.4 Energy spectra, significant wave height and peak period during rising, high and falling tide from data gathered on the low tide terrace on October 14, 2007.

Foreshore Conditions

This section describes topographic variability across the foreshore on October 12 and October 14, 2007 measured at low tide before and after sampling. Knowledge of regions across the foreshore that underwent erosion or accretion reveals the potential for horseshoe crab egs and sediment tracer to be exhumed over the tidal cycle Depth of sediment activation on October 12 (Figure 4.5) reveals that sediment was reworked to a depth of 0.11 m between 18 to 19 m from the dune crest in the region of wave breaking. Similar depths of activation were observed at a location 15 m from the dune crest when waves reworked sediment at this location during mid-rising tide and mid-falling tide. These values of depth of sediment disturbance are typically observed when significant wave heights exceed 0.5 to 0.6 m and onshore wind speeds are greater than 12 m s^{-1} (Jackson and Nordstrom, 1993).

In comparison, the region of the foreshore influenced by swash processes alone (6 to 13 m from the dune crest was reworked to depths less than 0.018 m. Minimal (< 0.014 m) to no net change occurred in the region of the foreshore 15 to 20 m from the dune crest where greatest depths of activation occurred over the tidal cycle. Significant accretion (0.04 to 0.06 m) occurred on the foreshore 7 to 12 m from the dune crest by swash processes alone over the tidal cycle. Deposition (0.03 to 0.04 m) occurred bayward of the break in slope. The region where the mid-foreshore tracer plot was located underwent minimal depths of reworking (0.018m) by wave breaking during high water, and approximately 0.03 m of accretion occurred over the tidal cycle. The upper foreshore tracer plot location has minimal (< 1 mm) depths of activation even though it was activated by swash process for longer periods of time during trapping compared to the mid-foreshore tracer plot that was reworked by wave breaking during the latter part of the rising and falling tide. The upper foreshore tracer plot was buried under an accretionary layer of sediment approximately 0.056 m in height (Figure 4.5).

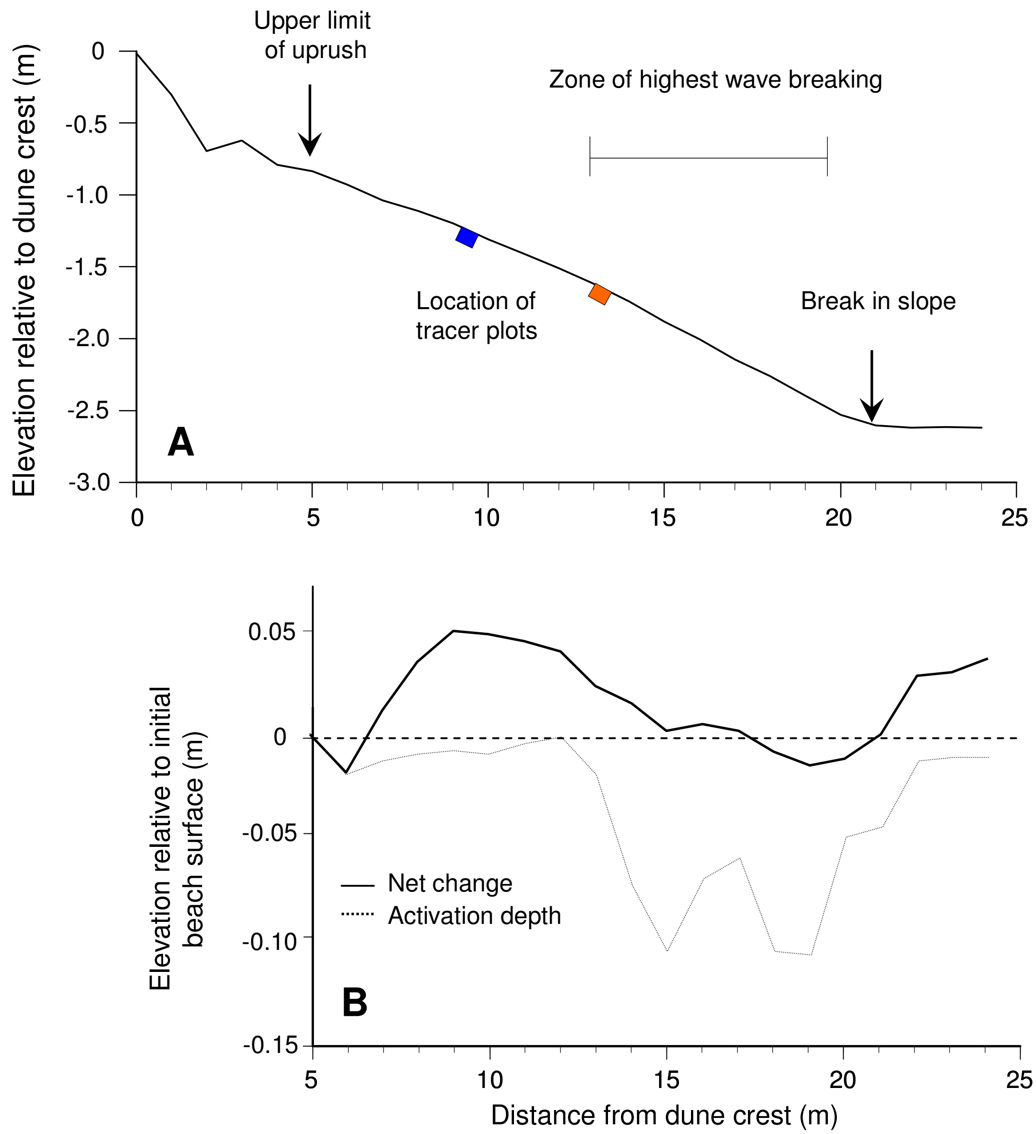


Figure 4.5 Profile showing position of the upper limit of swash, zone of highest wave breaking and location of tracer plots (A), and the depth of sediment activation and net change in surface elevation after trapping on October 12, 2007 (B).

Data from October 14, 2007 reveal that greatest depths of activation (0.067 to 0.092 m) occurred between 14 and 18 m from the dune crest in the region of wave breaking during sampling (Figure 4.6). Sediment at the location of the mid-foreshore plot (15 m from the dune crest) was reworked up to 0.05 m, meaning that egg and sediment tracer up to this depth had the potential to be exhumed or reburied by waves. In contrast, waves breaking 1 to 2 m bayward of the upper foreshore plot at high water had relatively high depths of activation (0.068 m). Sediment at the location of the upper foreshore tracer plot (12 m from the dune crest) were reworked to lower depths (0.013 m) by swash processes only. The mid-foreshore location has greater depths of activation values because this region was influenced by wave breaking on both the rise and fall of the tide for longer periods of time whereas the upper foreshore location was influenced by swash flows only from mid-rising to mid-falling stages of the tide. Minimal (<0.02 m) to no net change in surface elevation was observed across the foreshore. The greatest net change in the region where sediment activation depths were great (17 m from the dune crest) was < 0.015 m.

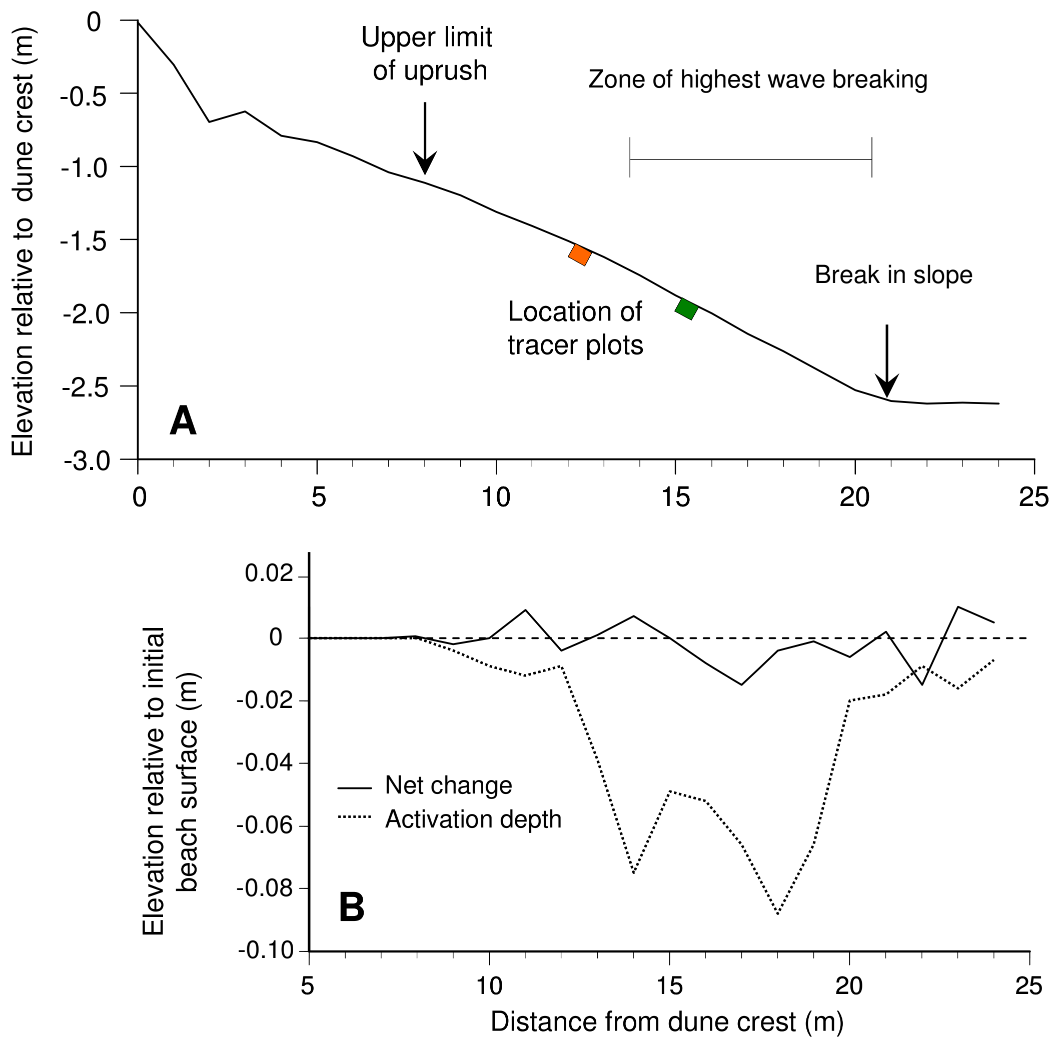


Figure 4.6 Profile showing position of the upper limit of swash, zone of highest wave breaking and location of tracer plots (A), and the depth of sediment activation and net change in surface elevation after trapping on October 14, 2007 (B).

4.3 Characteristics of Sediment in Transport in the Swash Zone

The focus of this section is on the changes in textural properties of sediment in the uprush and backwash of individual swash events over a tidal cycle and how these changes relate to tidal stage, wave characteristics, and velocities in the swash zone. A total of 25 sets of uprush and backwash samples of the 110 sets gathered on October 14, 2007 were used in this analysis to represent conditions when both traps were successfully placed at the mid-swash location (Figure 4.7). A process explanation of conditions in the swash that distinguishes transport of the gravel fraction relative to the sand fraction, with implications for the cross shore grading of sediment on the foreshore is also provided.

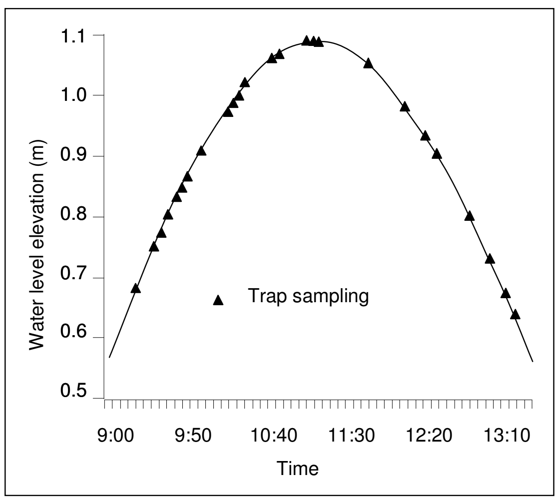


Figure 4.7 Trap sampling times during the tidal cycle on October 14, 2007.

4.3.1 Swash Characteristics

This section describes swash flow characteristics that were responsible for changes in textural properties of individual swash events over the rising, high and falling stages of the tidal cycle.

Time series data of individual swash events reveal that onshore flows increased almost instantaneously from zero to its maximum velocity after the arrival of the leading edge of the swash lens and subsequently decreased to zero for the remainder of the uprush. During the backwash, velocities of flows moving offshore increased steadily from zero to its maximum towards the end of the backwash and dropped rapidly to zero as the water levels decreased at the end of the swash event. Figure 4.8 summarizes properties of flow in the uprush and backwash during each of the 25 swash events. Maximum flow velocities ranged from 0.14 to 1.51 m s^{-1} in the uprush and 0.25 to 1.39 m s^{-1} in the backwash. Maximum and mean backwash velocities were generally greater than the uprush for individual swash events. Uprush depths were significantly greater than those in the backwash during all stages of the tide (t =7.36, df = 23, p = 0). Uprush duration ranged from 1.0 to 2.8 s; backwash duration ranged from 1.79 to 4.1 s. A paired t test revealed that uprush duration was significantly shorter than backwash duration (t = -6.59, df= 23, p = 0). Swash duration was greater than wave period, resulting in interaction of the backwash of a previous swash event with the subsequent uprush. Interaction occurred at the base of the swash for all but one of the swash events monitored and could have accounted for the lower mean uprush velocities.

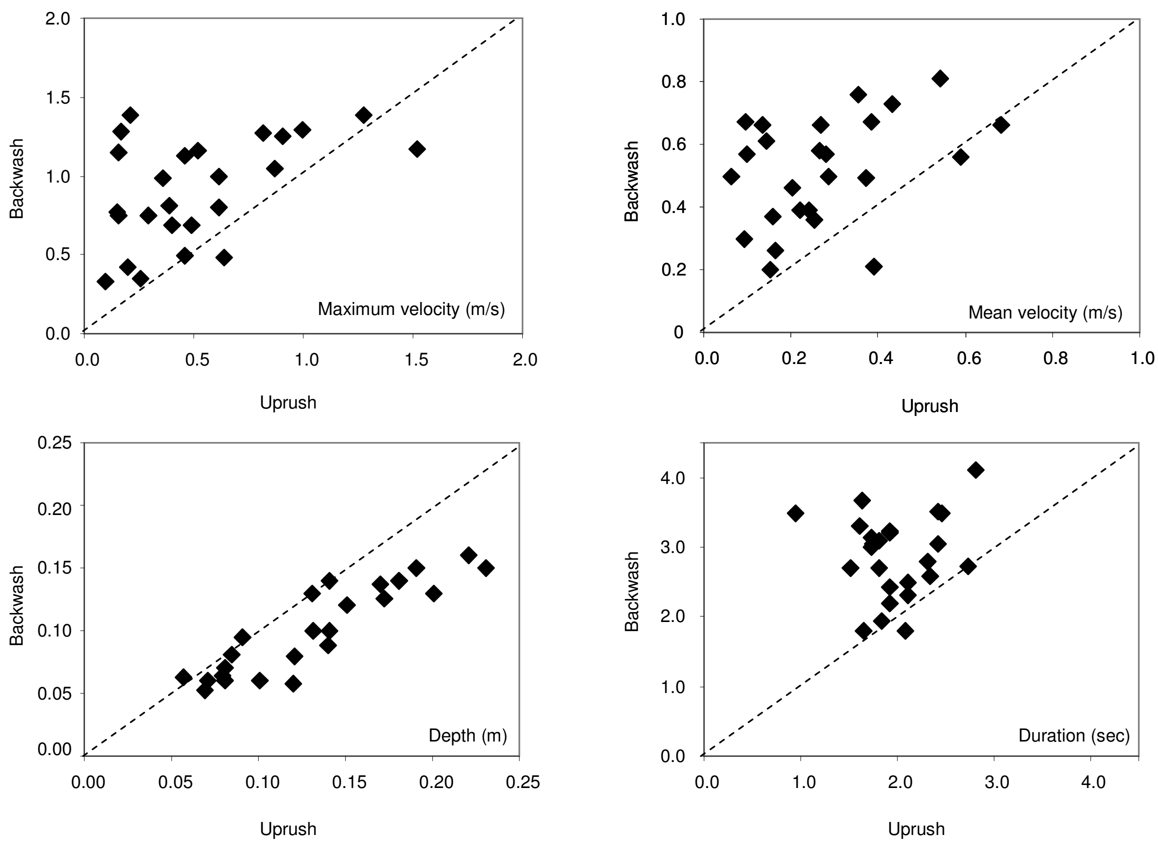


Figure 4.8 Maximum and mean cross-shore velocity, mean depth and duration in the uprush and backwash for twenty-five swash events on October 14, 2007.

4.3.2 Position of Beach Step

The location of the beach step relative to wave breaking was noted in order to provide an explanation for textural changes in sediment trapped during sampling over the tidal cycle on October 14, 2007. The beach step was 3 m landward of the break in slope at 10:00 and migrated 0.7 m landward by 10:37 (Figure 4.9). The step remained about 4.5 m landward of the break in slope during the relative still stand around high tide (from 11:09 to 11:53). The step moved bayward during falling tide and was 3.5 m landward of the break in slope at 12:35 and 3.0 m landward at 1249. Migration of the breakers down the foreshore was faster than step migration during falling tide, with breakers moving 1.1 m from 12:35 to 12:49 while the step moved 0.5 m.

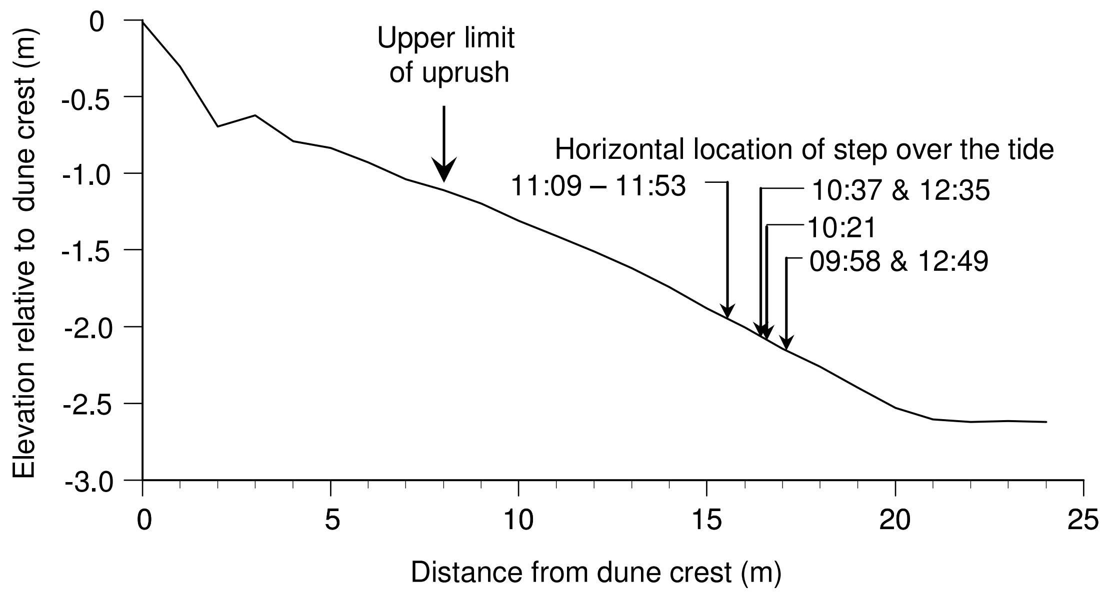


Figure 4.9 Profile showing position of beach step over the tidal cycle on October 14, 2007.

4.3.3 Characteristics of Sediment Trapped in the Swash Zone

Textural properties of sediment trapped during 25 individual swash events spanning mid-rising to mid-falling tide are presented in this section.

The two foreshore sediment samples taken to a depth of 0.10 m prior to trapping represent the sediment mobilized from these locations and trapped during different stages of the tidal cycle. These samples had a mean grain size of 0.77ϕ (0.59 mm), a sorting value of 1.07 ϕ and a gravel fraction of 7.5%. The foreshore was reworked by high energy waves prior to trapping and foreshore sediment was well mixed, with little gravel conspicuous on the surface (Figure 4.10).

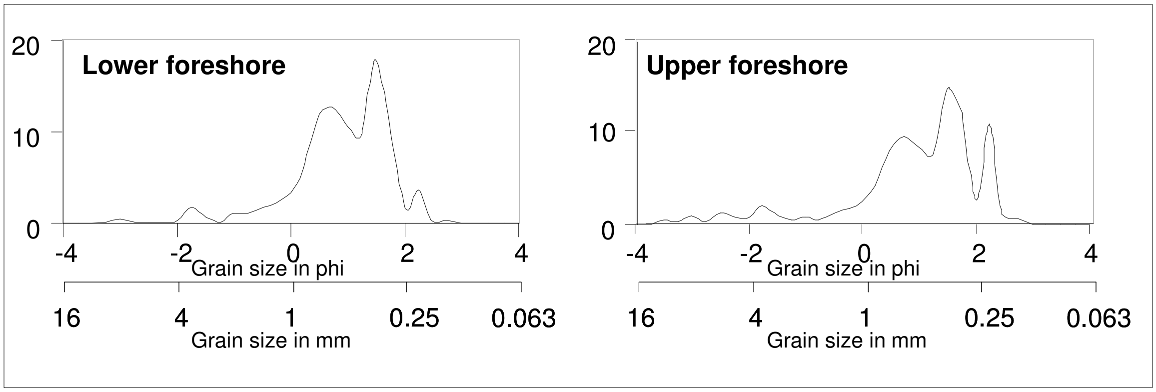


Figure 4.10 Frequency distribution plots of sediment sizes taken to a depth of 0.10 m on the lower and upper foreshore prior to trapping on October 14, 2007.

Sediment trapped in the uprush and backwash comprised medium to coarse sands with a gravel fraction of granules and pebbles (Figs. 4.11-4.12 and Table 4.1). Granules and pebbles trapped in the uprush and backwash were observed to have a rounded to well rounded modal shape with low sphericity. Mean size of sediment trapped in the uprush and backwash samples became coarser and more poorly sorted over the monitoring period due to an increase in percent gravel (Table 4.1).

During rising tide (09:16 to 10:27), the average percent gravel in the uprush and backwash was similar (11 and 13%). The percent gravel in the uprush decreased to 9 % and increased in the backwash to 18% when the swash zone was located on the upper foreshore (11:04 to 11:10). When the swash zone was located on the mid-foreshore on the falling tide (12:34 to 13:12) the average percent gravel in the backwash (30%) was greater than in the uprush (24%). The difference in percent gravel trapped in the uprush during the rising tide compared to the falling tide was significant ($t = -3.06$, $df = 9$, $p = 0.014$) and the difference in percent gravel trapped in the backwash during the rising tide compared to the falling tide was significant ($t = -3.25$, $df = 7$, $p = 0.014$).

Table 4.1 Characteristics of Sediment Trapped in the Uprush and Backwash over Individual Swash Events during Rise, High and Fall of the tide on October 14, 2007

		Uprush samples						Backwash samples					
Tide	Time	Mean (ϕ)	(mm)	Sorting (ϕ)	Skewness	Kurtosis	Gravel (%)	Mean (ϕ)	(mm)	Sorting (ϕ)	Skewness	Kurtosis	Gravel (%)
Rise	9:16	0.336	0.792	0.397	-0.537	6.069	0.6	-0.307	1.237	0.823	-0.989	3.789	17.9
	9:29	0.066	0.955	0.870	-1.572	6.565	9.2	-0.110	1.079	0.842	-1.490	5.594	12.8
	9:33	-0.136	1.099	0.730	-1.250	5.447	10.8	-0.288	1.221	0.883	-1.420	5.129	17.0
	9:34	-0.280	1.214	0.833	-0.735	3.587	18.2	-0.219	1.164	0.934	-0.865	3.928	17.1
	9:37	0.013	0.991	0.805	-1.161	5.472	9.9	0.117	0.922	0.909	-1.162	5.116	10.3
	9:39	-0.148	1.108	0.926	-1.079	4.097	16.1	-0.063	1.045	0.961	-0.791	3.79	15.6
	9:46	0.194	0.874	0.773	-1.527	7.107	7.4	-0.085	1.061	0.872	-0.876	3.988	14.2
	10:09	0.055	0.963	0.880	-1.504	5.933	11.2	0.430	0.742	0.781	-1.345	6.831	5.3
	10:11	0.196	0.873	0.756	-1.267	5.625	7.6	0.172	0.888	0.966	-1.190	4.373	12.3
	10:13	0.188	0.878	0.810	-1.748	7.077	7.8	0.389	0.764	0.742	-0.866	4.701	6.0
	10:17	-0.335	1.261	1.017	-0.739	2.869	25.4	0.035	0.976	1.012	-2.143	8.057	10.4
	10:27	0.029	0.980	0.729	-1.329	6.85	7.3	-0.261	1.198	0.686	-0.504	4.322	12.4
	10:38	-0.420	1.338	1.085	-0.848	3.206	25.9	0.314	0.804	0.576	-0.830	5.915	3.0
	10:46	-0.412	1.331	1.005	-0.860	3.318	24.8	-0.219	1.164	0.994	-1.087	3.712	19.6
High	11:04	-0.200	1.149	0.852	-1.184	4.449	15.4	-0.521	1.435	1.182	-0.486	2.371	33.0
	11:06	0.139	0.908	0.651	-1.202	7.068	5.3	-0.166	1.122	0.809	-1.101	4.75	12.9
	11:10	0.048	0.967	0.785	-1.794	7.949	7.8	0.125	0.917	0.786	-0.992	5.049	8.4
Fall	11:45	-1.029	2.041	1.120	-0.221	2.42	49.8	-0.163	1.120	0.810	-0.886	3.963	14.9
	12:02	-0.936	1.913	0.998	-0.252	2.375	46.1	-0.330	1.257	1.060	-0.683	2.573	26.1
	12:29	-0.715	1.641	1.023	-0.717	3.021	33.7	-0.849	1.801	1.247	-0.173	1.967	44.9
	12:34	-1.012	2.017	1.175	-0.343	2.064	45.8	-1.313	2.485	1.392	-0.058	1.902	57.4
	12:50	-0.184	1.136	0.886	-1.421	4.816	15.5	-0.201	1.149	0.959	-1.167	3.764	18.6
	13:01	-0.516	1.430	0.993	-0.864	3.107	27.2	-0.427	1.344	0.949	-0.868	3.139	24.9
	13:08	-0.317	1.246	1.057	-0.963	3.334	22.2	-0.392	1.312	1.229	-1.060	3.579	26.2
	13:12	0.088	0.941	0.715	-1.816	7.454	7.7	-0.289	1.222	0.99	-1.005	3.24	22.4

Source: Saini et al. (2011), in press.

The frequency distributions of sediment sizes trapped over individual swash events (Figures 4.11-4.12) reveal the increasing gravel fraction in the uprush and backwash over time. The distributions for swash events during the rising and high tide (Figures 4.11-4.12) reveal a primary mode in the coarse sand fraction (0 to 1.0 ϕ) (0.5 to 1.0 mm) and a pronounced tail in the gravel fraction (-1.0 to -4.0 ϕ) (2.0 to 16.0 mm) in both the uprush and backwash. Sediment during the rising and high tide are moderately to moderately well sorted. Distribution curves in both the uprush and backwash are mostly negatively skewed meaning that the mean grain sizes are coarser than the median values. Grain size distributions are predominantly leptokurtic implying that the central part of the distribution (sand fraction) is well sorted compared to the tail ends of the distribution (gravel fraction) (Table 4.1).

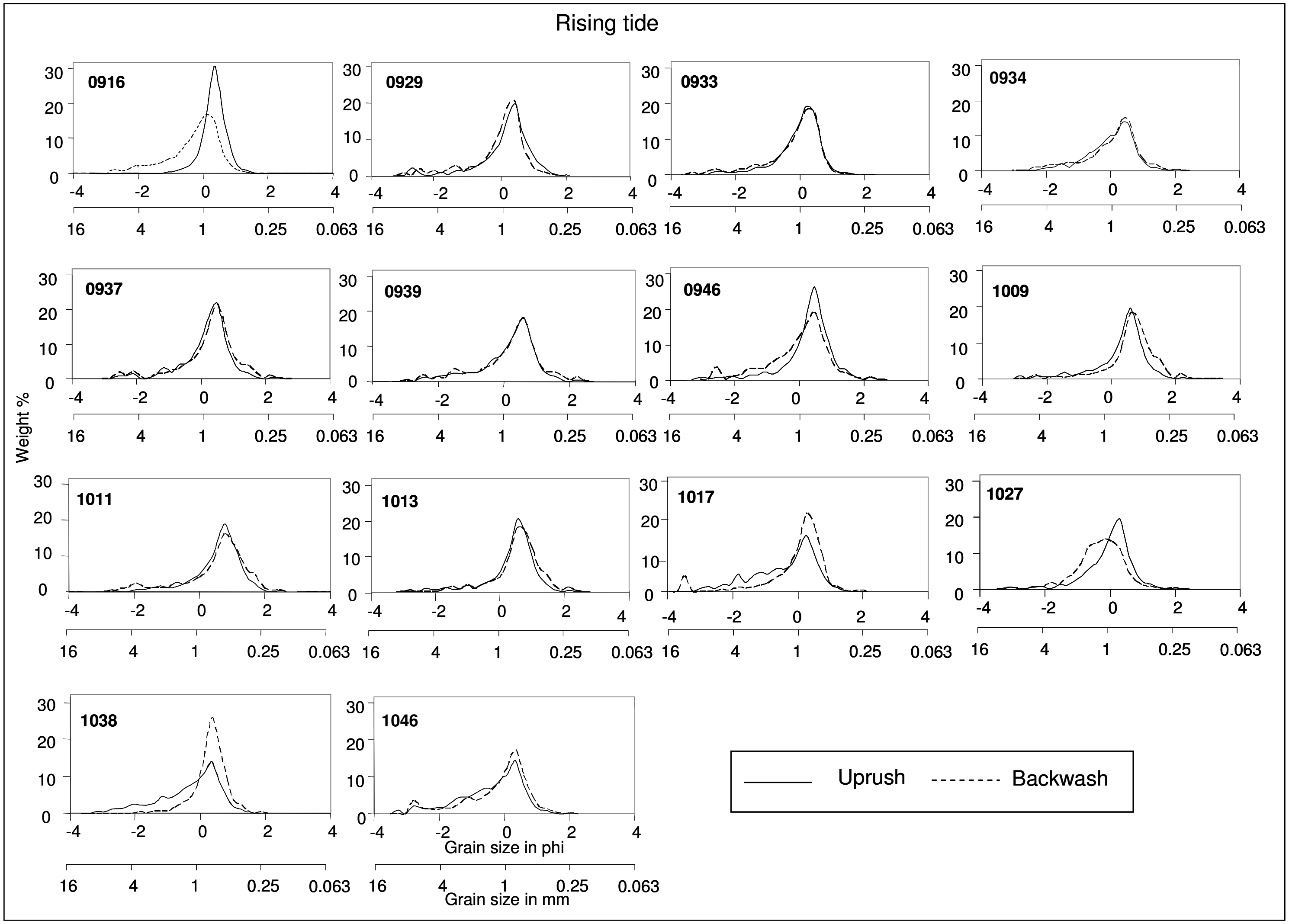


Figure 4.11 Frequency distribution plots of sediment size trapped in the uprush and backwash during rising tide on October 14, 2007.

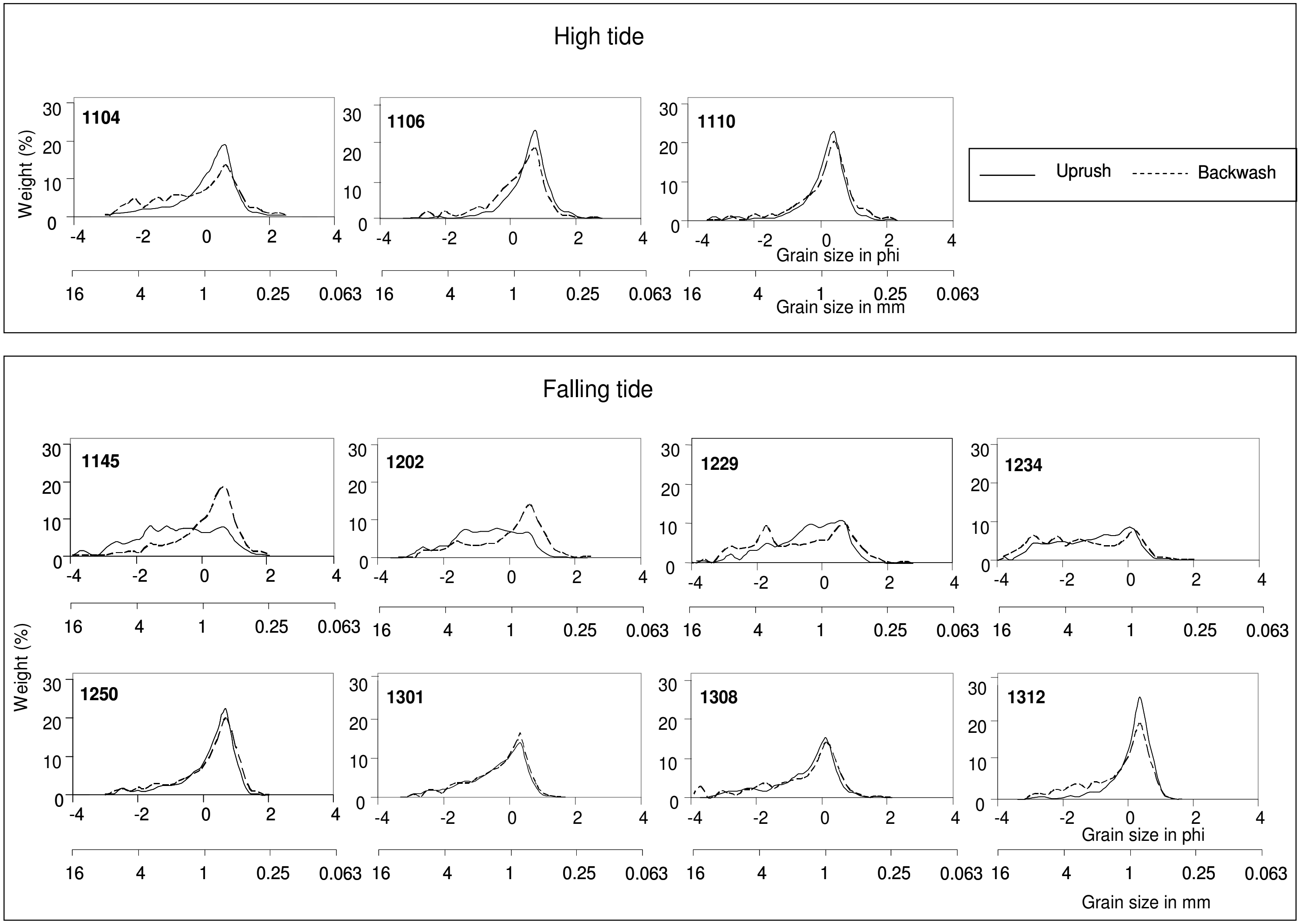


Figure **4.12** Frequency distribution plots of sediment size trapped in the uprush and backwash during high and falling tide on October 14, 2007.

During the early stages of the falling tide (11:45 to 12:34) sediment size distributions in the uprush and backwash are mesokurtic to platykurtic and poorly sorted (Figure 4.12). Weakly developed modes are observed in (1) the coarse sand fraction (2), the granule fraction, and (3) the pebble fraction. Data reveal an increase in the proportion of gravel trapped in both uprush and backwash during the early stages of the falling tide relative to the rise and high tide swash events (Table 4.1). This increase in gravel occurred around the time when breaker migration down the beach was faster than step migration. From 12:50 to 13:12, sediment in the uprush and backwash are moderately sorted, coarse sand. Modal peaks are once again observable in the sand fraction. Grain size distributions become more negatively skewed with either mesokurtic or leptokurtic curves.

The potential for swash velocities to move the gravel population was revealed by comparison of the calculated critical shear stress with the measured bed shear stress in the uprush and backwash of each swash event at the transition from granules to pebbles using maximum velocity (Table 4.2), a bed slope of 6° and sediment size of 4 mm. Maximum velocity was used because it provides an estimate of the greatest likelihood that the smallest pebbles will be moved. The calculated critical shear stress was 2.21 N m^{-2} in the uprush and 4.03 N m^{-2} in the backwash. Pebbles were trapped in all but one uprush (09:16) and two backwashes (10:13 and 10:38) (Figure 4.11). Bed shear stresses did not exceed critical threshold values for seven swash uprushes (09:29, 10:17, 10:27, 10:46, 11:06, 12:50, 13:12) and one backwash (13:12) when pebbles were trapped (Table 4.2).

Table 4.2 Bed Shear Stresses in the Uprush and Backwash of the Individual Swash Events. Critical Shear Stress for a 4 mm Size Grain is 2.21 Nm^{-2} in the Uprush and 4.03 Nm^{-2} in the Backwash.

Time	Uprush samples		Backwash samples	
	Bed shear stress (τ) ($N\ m^{-2}$)	τ / τ_{cr}	Bed shear stress (τ) ($N\ m^{-2}$)	τ / τ_{cr}
9:16	0.91	0.41	7.08	1.76
9:29	0.91	0.41	10.01	2.48
9:33	28.03	12.68	18.88	4.68
9:34	4.54	2.06	14.85	3.68
9:37	2.44	1.10	8.32	2.06
9:39	5.45	2.46	15.31	3.80
9:46	3.43	1.55	14.40	3.57
10:09	3.57	1.61	10.80	2.68
10:11	3.70	1.67	8.50	2.11
10:13	7.08	3.20	10.60	2.63
10:17	1.00	0.45	9.62	2.39
10:27	1.11	0.50	21.69	5.38
10:38	10.80	4.89	21.43	5.32
10:46	1.00	0.45	18.39	4.56
11:04	12.03	5.44	16.00	3.97
11:06	1.46	0.66	24.64	6.11
11:10	21.47	9.71	24.37	6.04
11:45	12.66	5.73	20.91	5.19
12:02	4.99	2.26	7.78	1.93
12:29	7.43	3.36	4.99	1.24
12:34	7.08	3.20	14.63	3.63
12:50	1.37	0.62	4.11	1.02
13:01	12.45	5.63	15.08	3.74
13:08	4.54	2.06	5.14	1.27
13:12	1.98	0.90	3.17	0.79

4.4 Exhumation and Transport of Egg Tracer, Sediment Tracer and Total Load by Wave and Swash Processes

This section presents data of five minute time averaged quantities of horseshoe crab egg tracer, sediment tracer and total load trapped from the mid and upper foreshore in the uprush and backwash over the rising, high and falling tide on October 12 and October 14, 2007. Time averaged quantities of eggs are presented as kg per m^{-1} of horizontal beach width whereas sediment tracer and total load are represented as the immersed weights kg per m^{-1} of horizontal beach width. Five minute time averaged swash characteristics that are responsible for differences in the rates of entrainment and transport of eggs and sediment tracer are also identified. Data are divided into rising, high and falling stages of the tide to assess when eggs entrained and transported in the swash were available in greatest quantities for foraging shorebirds. Also, tidal elevation determined where the breaker and swash zones were located at different stages of the tide. Therefore, it became necessary to analyze tracer exhumation and transport relative to stage of the tide.

4.4.1 Spatial and Temporal Trends in Quantities of Eggs, Sediment Tracer and Total Load Trapped on October 12, 2007

Depth of activation measured adjacent to the mid-foreshore tracer plot location after monitoring at low tide revealed that approximately 22.5% of the tracer buried at this location was removed by wave and swash processes (Figure 4.5). Depth of activation measured adjacent to the upper foreshore plot location revealed that only 5% of the egg and sediment tracer buried at this location had the potential to be entrained by swash processes. None of the eggs buried in the mid and upper foreshore tracer plots were trapped over the tidal cycle. Approximately, 11 grams of the 2 kg of sediment tracer (orange tracer) exhumed from the mid-foreshore tracer plot was trapped in the uprush and backwash over the tidal cycle. In contrast, 0.45 kg of sediment tracer (blue tracer) was entrained from the upper foreshore tracer plot by swash flows, but only 6 grams of this material was trapped in the uprush and backwash over the tidal cycle.

A cumulative percent distribution was plotted in order to compare quantities of sediment tracer trapped from the mid and upper foreshore over the rising, high and falling stages of the tide (Figure 4.13 A and B). Greater quantities of sediment tracer were trapped from the mid-foreshore tracer plot in the backwash relative to the uprush during the rising tide (07:40 to 09:15) (Figure 4.13 B). The bed was observed to undergo erosion during this time period as was evident in the greater quantities of total load trapped in the backwash relative to the uprush (Figure 4.15 C). Quantities of sediment tracer trapped in the uprush and backwash were similar during the high (09:20 to 10:20) and falling tide (10:25 to 12:15) (Figure 4.13B).

The first traces of sediment tracer from the upper foreshore tracer plot (blue tracer) were trapped at 08:20 (Figure 4.13A). The quantities of sediment tracer from the upper foreshore trapped in the uprush during the rising tide (07:40 to 09:15) were greater than those trapped in the backwash. Tracer quantities trapped from the upper foreshore tracer plot in the uprush and backwash were comparable during high tide (09:20 to 10:20), but quantities trapped in the backwash exceeded those trapped in the uprush during falling tide (10:25 to 12:15). Data revealed that quantities of sediment tracer trapped from the upper foreshore in the uprush during the rising, high and falling stages of the tide comprised 71%, 24% and 6% respectively. In contrast, sediment tracer trapped from the upper foreshore in the backwash during the rising, high and falling stages of the tide comprised 52%, 28% and 20%, respectively (Figure 4.13A). Explanations for differences in quantities of sediment tracer exhumed from the mid and upper foreshore tracer plots are described in the following section.

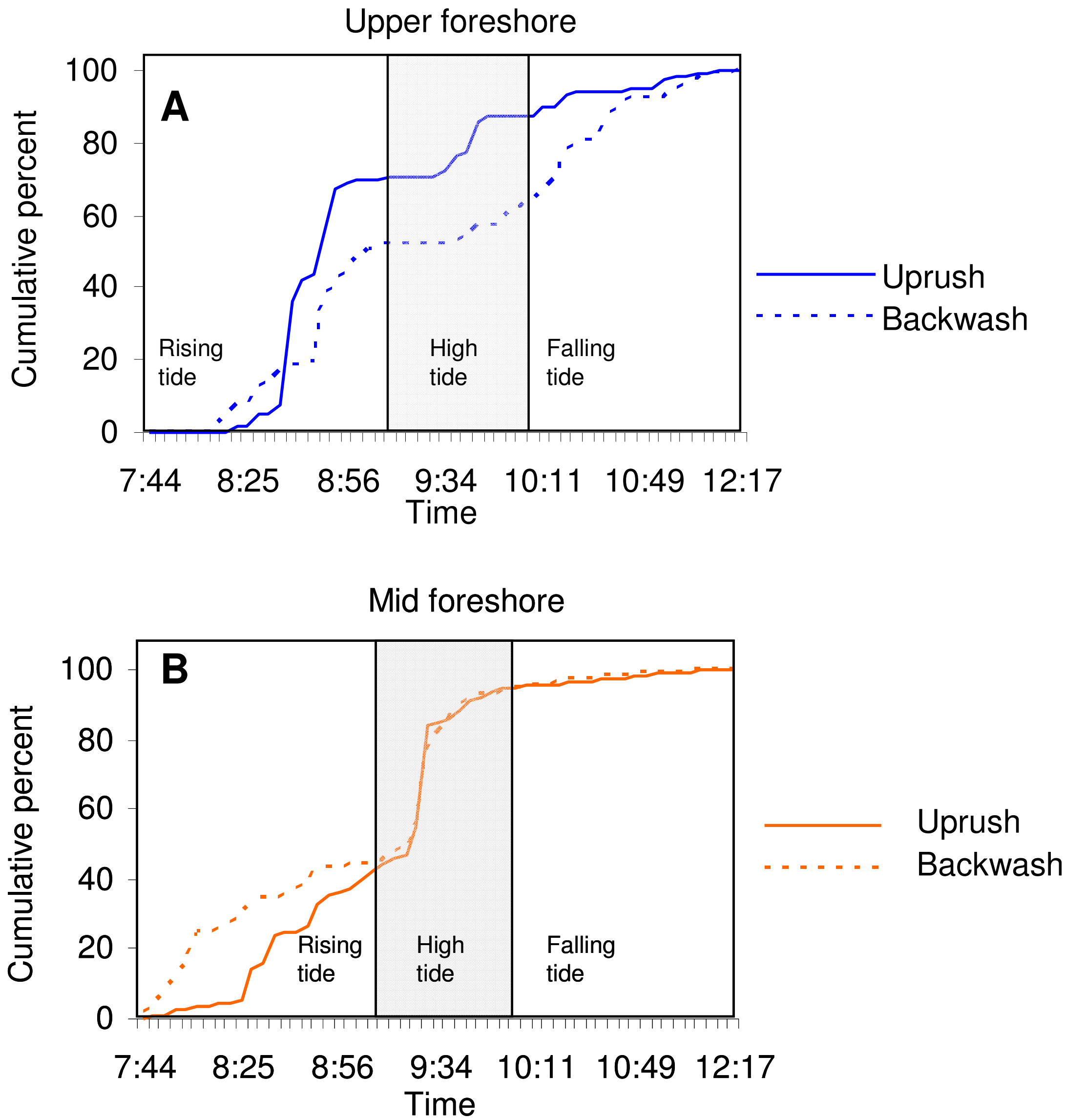


Figure 4.13 Cumulative percent distributions of sediment tracer trapped over the tidal cycle from the upper foreshore tracer plot (A) and mid-foreshore tracer plot on October 12, 2007 (B).

Swash Characteristics Influencing Transport of Horseshoe Crab Egg and Sediment Tracer over the Tidal Cycle

Data reveal that time averaged quantities of sediment tracer trapped from the mid-foreshore tracer plot (orange tracer) during the rising tide between 07:40 and 08:20 were significantly greater in the backwash compared to the uprush (Wilcoxon signed rank test, $z = 3$, $p = 0.024$, $N = 9$). Net transport of sediment tracer was directed onshore between 08:25 and 09:15, with significantly greater quantities of tracer trapped in the uprush compared to the backwash (Wilcoxon signed rank test, $z = 65$, $p = 0.005$, $N = 11$). Waves broke 2 m bayward of the mid-foreshore tracer plot during the rising tide, and quantities of sediment tracer trapped were those entrained by swash processes alone (Figure 4.14). However, it is important to note that sediment tracer from the mid-foreshore (orange tracer) and upper foreshore tracer plot (blue tracer) observed in traps between the time periods 07:40 to 09:15 was material that was entrained by swash events of relatively large widths and transported to the location of the foreshore where trapping occurred (2 m bayward of the mid-foreshore tracer plot). Measured total load trapped on the mid-foreshore in the uprush ranged from 1.5 to 118.7 kg m^{-1} and in the backwash ranged from 0.9 to 49.8 kg m^{-1} during the rising tide (Figure 4.15C). Total load trapped in the uprush was significantly greater than in the backwash, implying that net total load transport was in the onshore direction (Wilcoxon signed rank test, $p = 0.000$, $N = 20$).

It is not possible to correlate time averaged swash characteristics with quantities of sediment tracer in transport during the rising tide because trapping occurred bayward of the plots and quantities trapped were not those entrained and transport instantaneously during trapping. Conditions in the swash that led to entrainment of tracer are as follows.

Swash widths were low between 07:40 and 08:20 when waves broke on the foreshore 17 m from the dune crest, and the upper swash limit was at the location of the mid-foreshore tracer plot (Figure 4.14). Cross-shore velocities and longshore velocities between 07:40 and 08:20 in the upper swash were low relative to other stages of the tide, and mean swash depths ranged from 0.05 to 0.07 m. The shear stresses required to mobilize sand and the smallest granules present on the surface of the bed was 1.29 N m^{-2} (Figure 4.16). Bed shear stresses calculated from mean cross-shore flow velocities between 07:40 and 08:20 were therefore observed to be insufficient to mobilize sediment tracer from the mid-foreshore tracer plot.

Cross-shore flows revealed an increase in mean velocities in an offshore direction, which could explain the increased exhumation and transport of sediment tracer from the mid-foreshore in backwash flows between 07:40 and 08:20 (Figure 4.16). Durations of backwash flows were greater than those in the uprush. As swash widths increased, the lower swash zone moved to the location of the mid-foreshore tracer plot, and greater quantities of sediment tracer were entrained from the mid-and upper tracer plot between 08:25 and 09:15. Shear stresses at the bed in the lower swash zone were also greater between 08:25 and 09:15 compared to those generated at the bed between 07:40 and 08:20 in the upper swash zone, which played an important role in the entrainment of greater quantities of sediment tracer from the mid-foreshore tracer plot (Figure 4.16). Instruments were not located in the upper swash between 08:25 and 09:15 close to the upper foreshore tracer plot, thus bed shear stresses could not be estimated at that location.

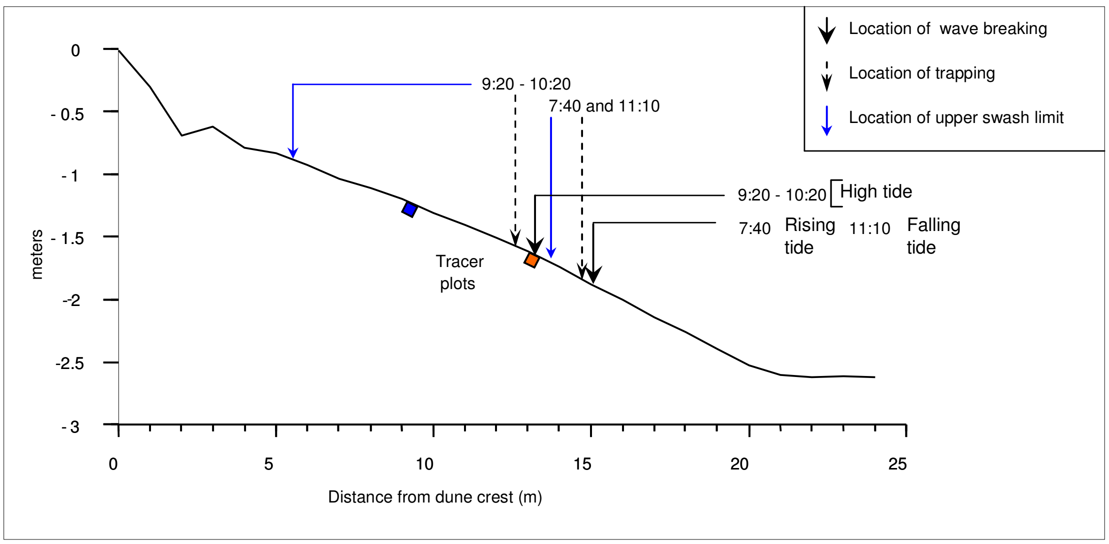


Figure 4.14 Location of trapping relative to wave breaking and the upper limit of swash over the tidal cycle during the rising tide on October 12, 2007.

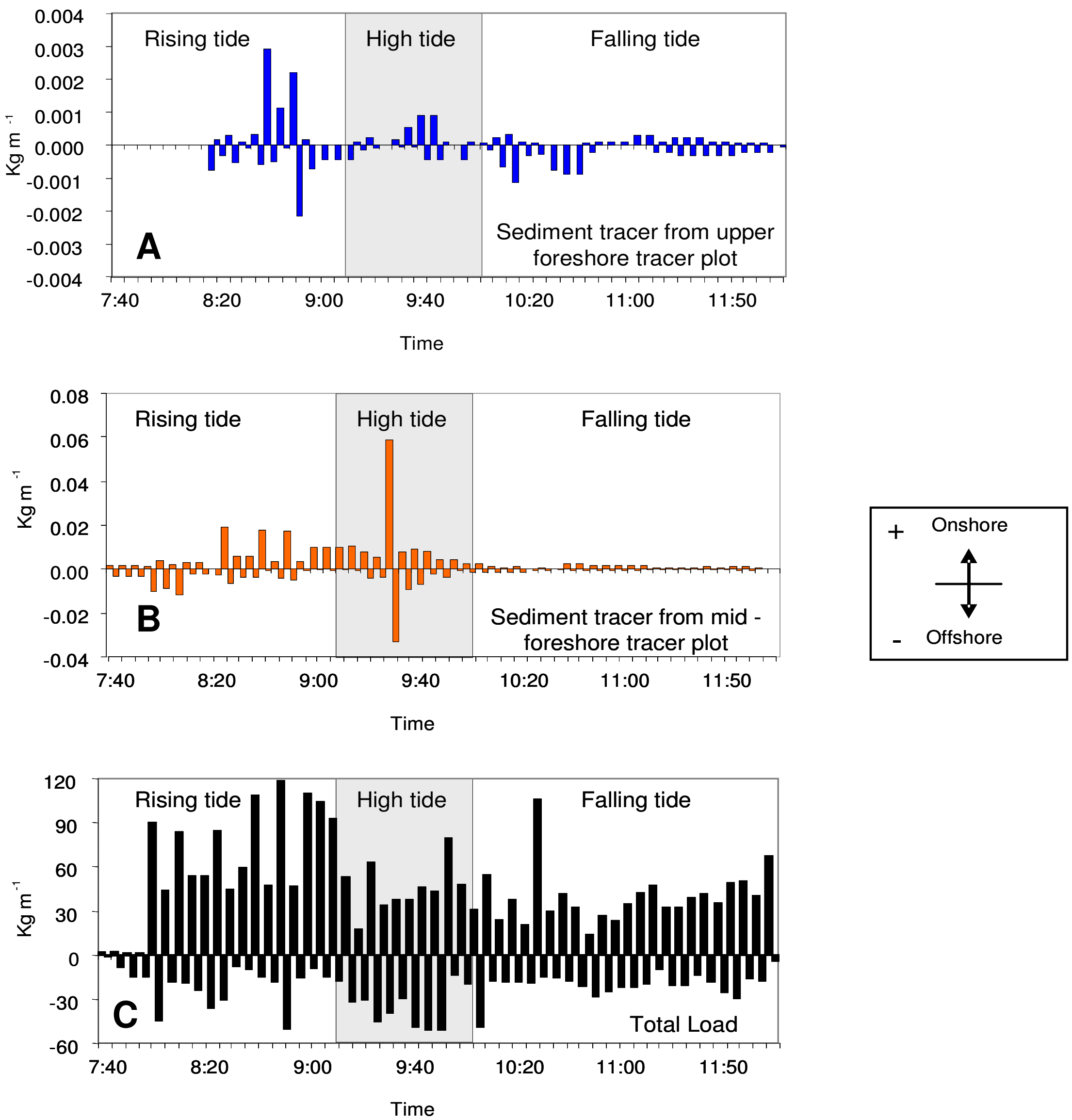


Figure 4.15 Quantities of sediment tracer trapped from the mid-foreshore tracer plot (A), upper foreshore tracer plot (B), and total load (C) trapped in the uprush and backwash over the tidal cycle on October 12, 2007.

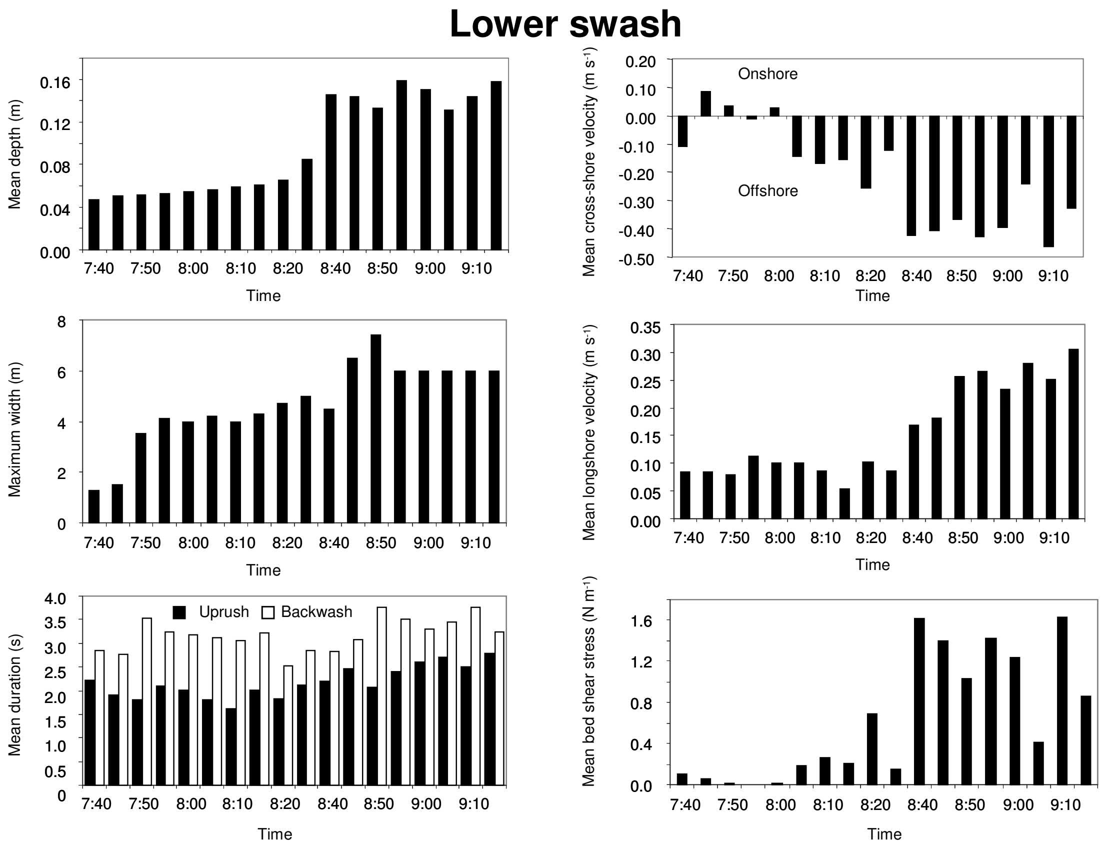


Figure 4.16 Characteristics in the lower swash during the rising tide on October 12, 2007.

Waves broke at the location of the mid-foreshore tracer plot between 09:20 and 10:20, and trapping occurred just landward of the plot location (Figure 4.14). Greater quantities of sediment tracer (orange tracer) were trapped from this location compared to quantities trapped during the rising tide by swash processes alone (Figure 4.15B). A Wilcoxon signed rank test revealed significantly greater quantities of sediment tracer transported from the mid-foreshore tracer plot in the uprush compared to the backwash during high water ($p = 0.023$, $N=11$). Sediment tracer from the upper foreshore (blue tracer) observed in traps during high water was material that had been exhumed and remobilized during prior swash events (Figure 4.15A). Quantities of sediment tracer from the upper foreshore trapped during high water were much lower than those trapped during the rising tide. Quantities of total load trapped in the uprush and backwash ranged from 17.8 to 79.3 and 13.3 to 50.8 kg m^{-1} respectively (Figure 4.15C), but a statistically significant difference between quantities of total load transported during high water in the uprush and backwash was not observed.

Swash depths in the lower swash zone landward of wave breaking at the location of the mid-foreshore tracer plot ranged from 0.15 m to 0.18 m during high water, whereas those in the upper swash zone close to the upper foreshore plot range between 0.07 to 0.08 m (Figure 4.17). Durations of backwash flows were also greater than those in the uprush. The location of the upper limit of swash was 5 m landward of the dune crest, putting the upper foreshore tracer plot in the mid-swash region during high water (Figure 4.13).

Negative values of mean cross-shore flows represent flows that were being directed offshore. Positive values of mean longshore flows suggest that flows were moving in a northward direction (Figure 4.17). Data reveal that bed shear stresses in the lower swash zone calculated from mean cross-shore flows during high water were much higher than those generated at the bed in the mid-swash region in the vicinity of the upper foreshore tracer plot (Figure 4.17). While shear stresses in the lower swash zone were capable of entraining sand and granule size sediment from the mid-foreshore tracer plot, those generated in the mid-swash did not have the potential to entrain sediment from the upper part of the beach. This could explain the greater quantities of sediment tracer trapped from the mid-foreshore (orange tracer) and lower quantities of tracer trapped from the upper foreshore tracer plot (blue tracer) during high water. Mean longshore current velocities were observed to be greater in the mid-swash compared to those observed in the lower swash, suggesting that sediment at the location of the upper foreshore tracer plot was more likely to move in an alongshore direction (Figure 4.17).

A multiple regression analysis was conducted using quantities of sediment tracer trapped on the mid-foreshore as a dependant variable and flow characteristics (breaking wave height, mean cross-shore flow velocity, mean longshore flow velocity, mean duration, mean depth) measured on the mid-foreshore as independent variables to produce a model that would best describe tracer transport from that location. Breaking wave heights at the mid-foreshore between 09:20 and 10:20 did not vary much (1.09-1.11 m) while trapping occurred, therefore it alone could not explain tracer exhumation and transport. However, adding swash characteristics to the multiple regression model revealed that mean cross-shore flow velocities ($p = 0.035$, $r^2 = 0.74$) and mean longshore flow velocities ($p = 0.008$ $r^2 = 0.74$) in the lower swash zone played an important role in tracer exhumation and transport from the mid-foreshore tracer plot during high water.

Quantities of sediment tracer trapped in the backwash did not vary significantly over high water (Figure 4.15B), and wave and swash characteristics were not able to explain exhumation and transport in offshore moving flows.

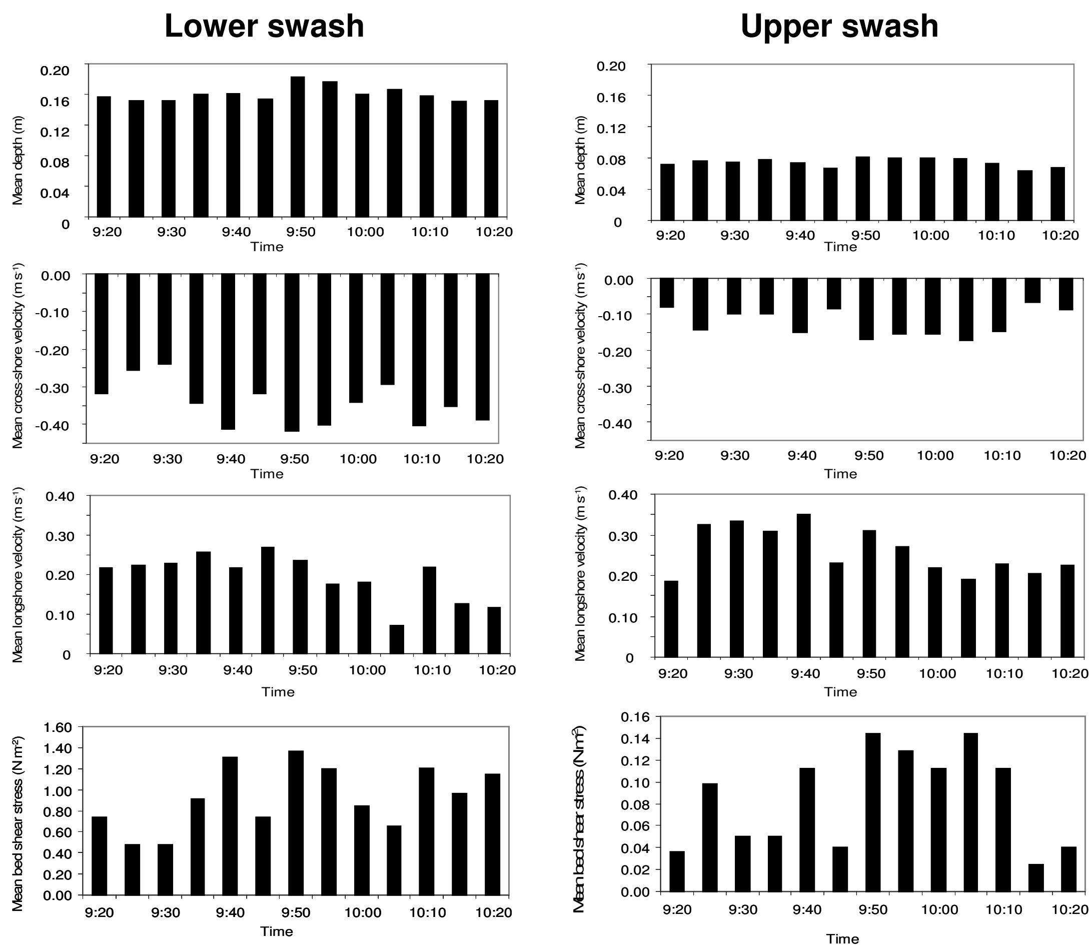


Figure 4.17 Characteristics in the lower and upper swash during high water on October 12, 2007 based on five minute averages.

During the falling tide, the zone of wave breaking lies at the location of the mid-foreshore tracer plot between 10:25 and 11:00, and moves 2 m bayward between 11:10 and 12:10 (Figure 4.14). Quantities of sediment tracer trapped from the mid and upper foreshore tracer plots were the lowest compared to quantities trapped over the rising and high tide. A Wilcoxon signed rank test revealed significantly greater quantities of sediment tracer trapped from the mid-foreshore tracer plot in the uprush compared to the backwash during the falling tide ($p = 0.011$, $N = 17$). Total load immersed weights transported in the uprush and backwash ranged from 13.6 to 105.4 and 3.4 to 29.4 kg m^{-1} respectively (Figure 4.15C), and net direction of total load transport was onshore. Similar to the rising and high tide, quantities of sediment tracer trapped from the upper foreshore tracer plot (blue tracer) during the falling tide represented material that was either being entrained by relatively wide swash widths from the upper foreshore tracer plot, or from locations across the foreshore where this material had been reworked into foreshore sediment by swash events over the tidal cycle (Figure 4.15A).

Mean cross-shore flow velocities decreased in the lower swash at the location of the mid-foreshore tracer plot as mean water depths decreased, but the northward directed longshore velocities did not vary over the falling tide (Figure 4.18). Mean longshore flow velocities were lowest during the falling tide compared to other stages of the tide at the location of the mid-foreshore tracer plot. Data reveal that shear stresses between 10:25 and 11:00 in the lower swash were capable of entraining sediment tracer from the mid-foreshore tracer plot, but tracer quantities trapped were significantly low compared to quantities trapped from the same location during rising tide.

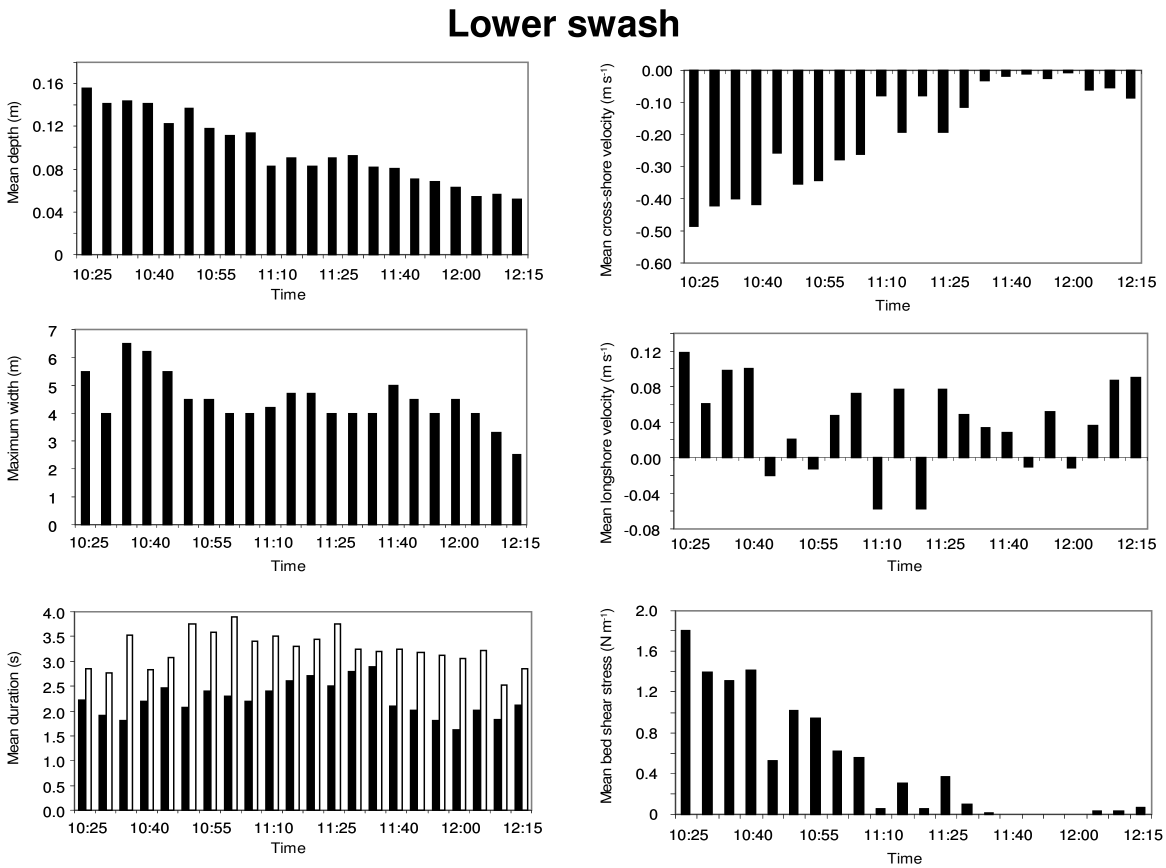
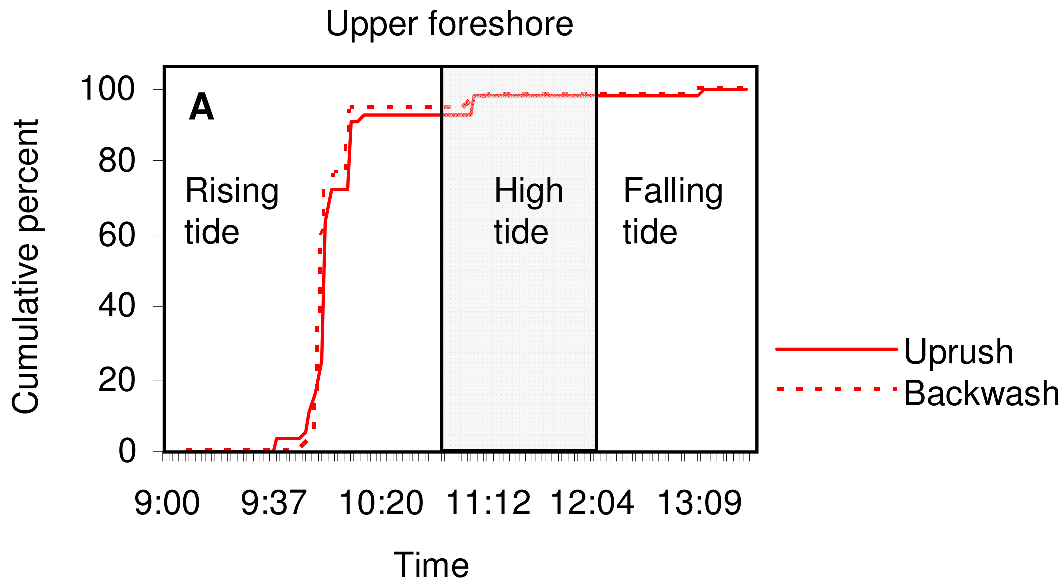


Figure 4.18 Characteristics in the lower swash during the falling tide on October 12, 2007 based on five minute averages.

4.4.2 Spatial and Temporal Trends in Quantities of Eggs, Sediment Tracer and Total Load Trapped on October 14, 2007

Depth of activation measurements made after trapping at low tide reveal that approximately 62% of egg and sediment tracer injected into the mid-foreshore was activated by waves and swash processes whereas 16% of tracer from the upper foreshore was entrained by swash processes only (Figure 4.6). Recoveries of egg and sediment tracer injected into the mid and upper foreshores were higher than those recovered on October 12, 2007. A total of 1147 eggs (1.15% of total quantities of eggs exhumed from the mid-foreshore) of the estimated 224000 eggs that were exhumed from the mid-foreshore plot were trapped in the uprush and backwash over the tidal cycle. In contrast, only 109 eggs (0.11% of total quantities of eggs entrained from the upper foreshore plot) of the estimated 100000 eggs entrained from the upper foreshore were trapped in the uprush and backwash over the tidal cycle. Cumulative percent distributions revealed that significantly greater quantities of egg tracer were trapped during the rising tide from the mid and upper foreshore tracer plots (Figures 4.19 A and B).

Greater quantities of sediment tracer were trapped relative to the egg tracer from the mid and upper foreshore tracer plots. 148 grams (3% of total sediment tracer exhumed from the mid-foreshore) of the exhumed sediment tracer was trapped in the uprush and backwash from the mid-foreshore tracer plot. Only 13 grams (0.58% of total sediment tracer entrained from the upper foreshore plot) of the 2.25 kg of sediment tracer entrained from the upper foreshore tracer plot by locally generated shear stresses was trapped in the uprush and backwash over the tidal cycle. Cumulative percent distributions reveal greatest sediment tracer quantities trapped from the mid and upper foreshore tracer plots during the rising tide with predominant onshore transport (Figures 4.20 A and B). Quantities of sediment tracer trapped decreased during high tide in the uprush and backwash. An increase in tracer transport was observed during the falling tide with greater quantities being trapped in the backwash compared to the uprush from both plots (Figures 4.20 A and B). Egg and sediment tracer recoveries from the upper foreshore tracer plot were lower compared to those from the mid-foreshore plot because sediment at that location were activated to lower depths due to swash processes alone whereas those at the mid-foreshore tracer plot were activated by both wave and swash processes. Data suggest that egg tracer was dispersed rapidly from the swash zone whereas sediment tracer remained to be transported by wave and swash processes over the tidal cycle.



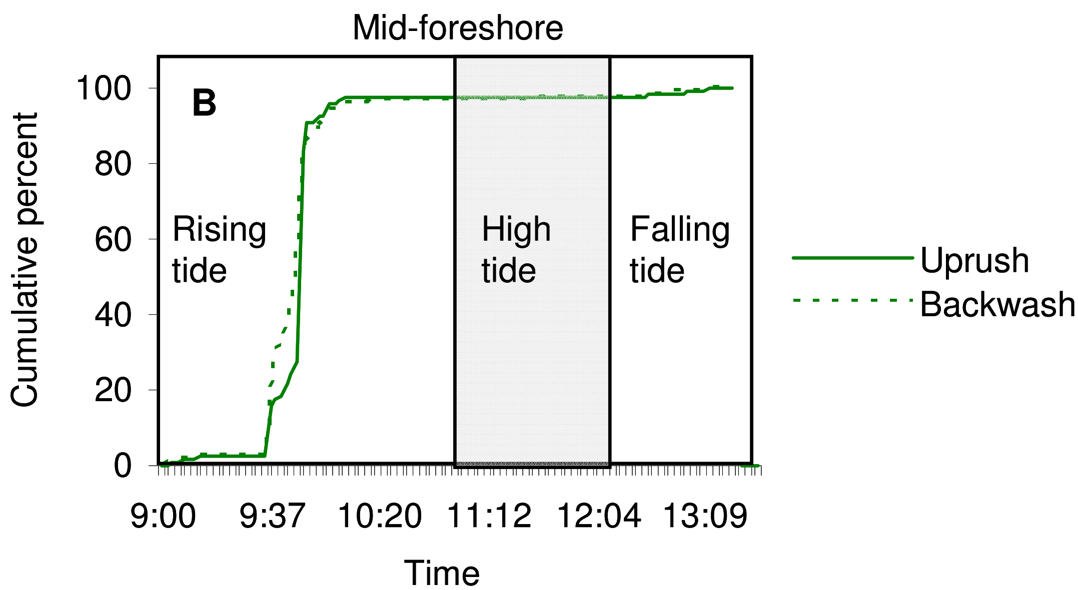
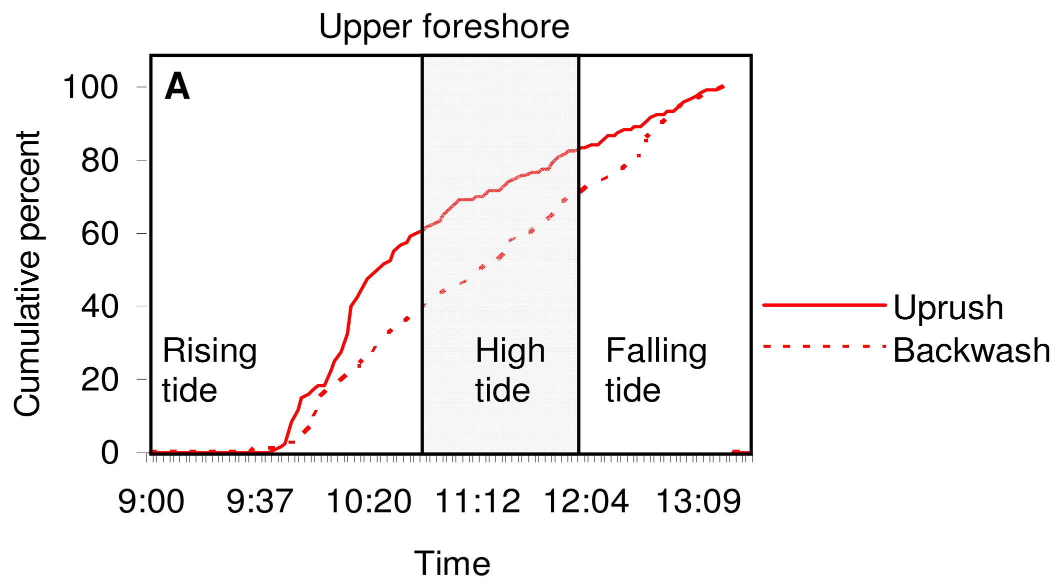


Figure 4.19 Cumulative percent distributions of egg tracer trapped from the upper foreshore tracer plot (A) and mid-foreshore tracer plot (B) over the tidal cycle.



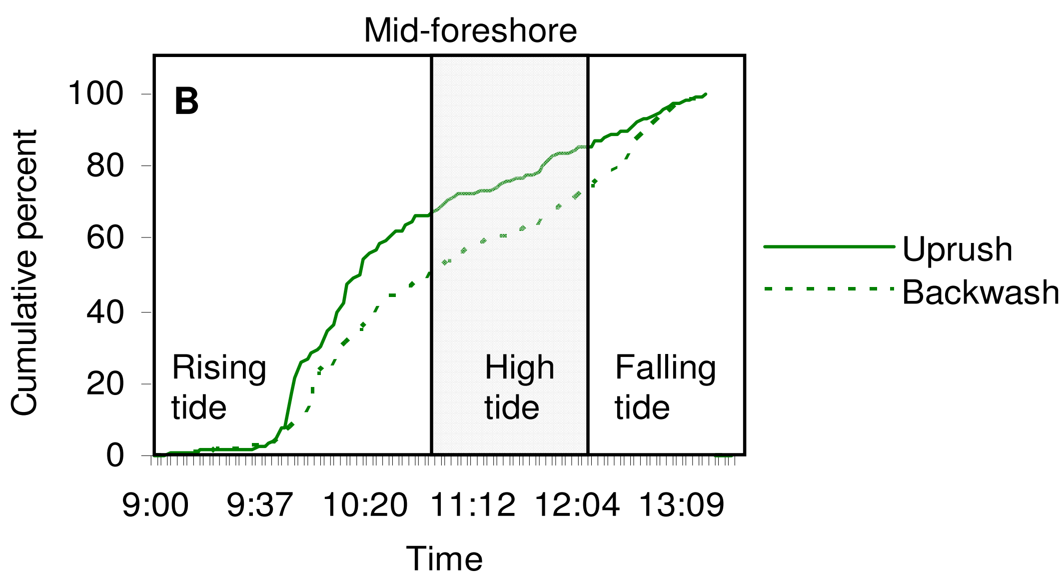


Figure 4.20 Cumulative percent distributions of sediment tracer trapped from the upper foreshore tracer plot (A) and mid-foreshore tracer plot (B) over the tidal cycle.

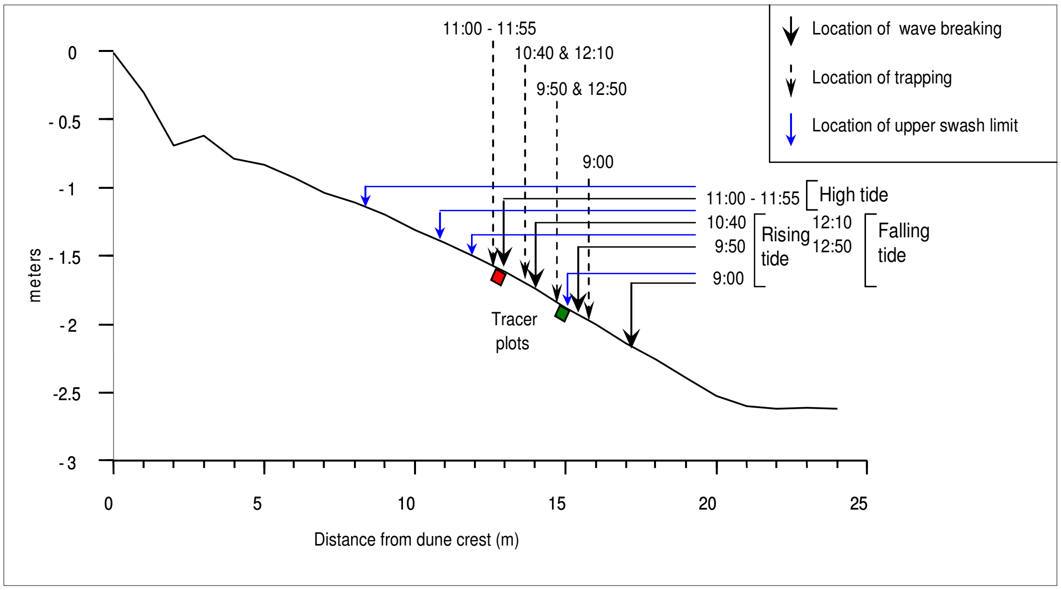


Figure 4.21 Location of trapping relative to wave breaking and the upper limit of swash over the tidal cycle on October 14, 2007.

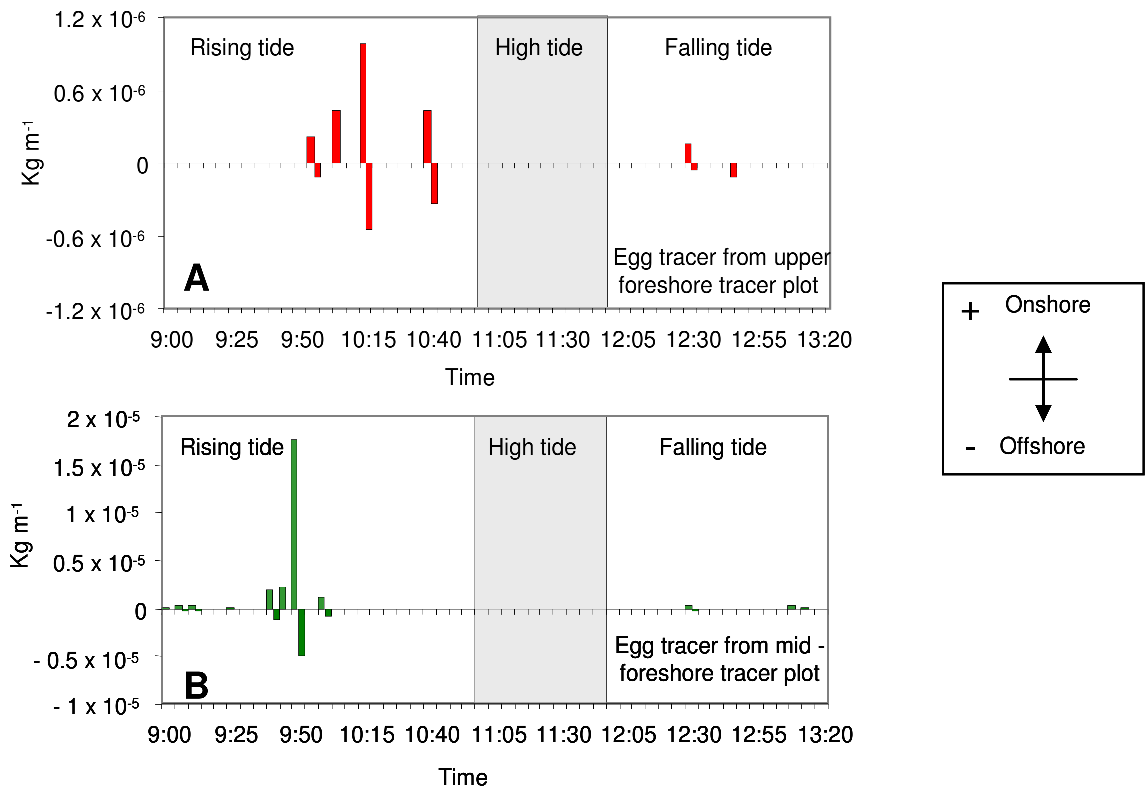


Figure 4.22 Quantities of egg tracer from the upper foreshore tracer plot (A) and mid-foreshore tracer plot (B) trapped in the uprush and backwash over the tidal cycle on October 14, 2007.

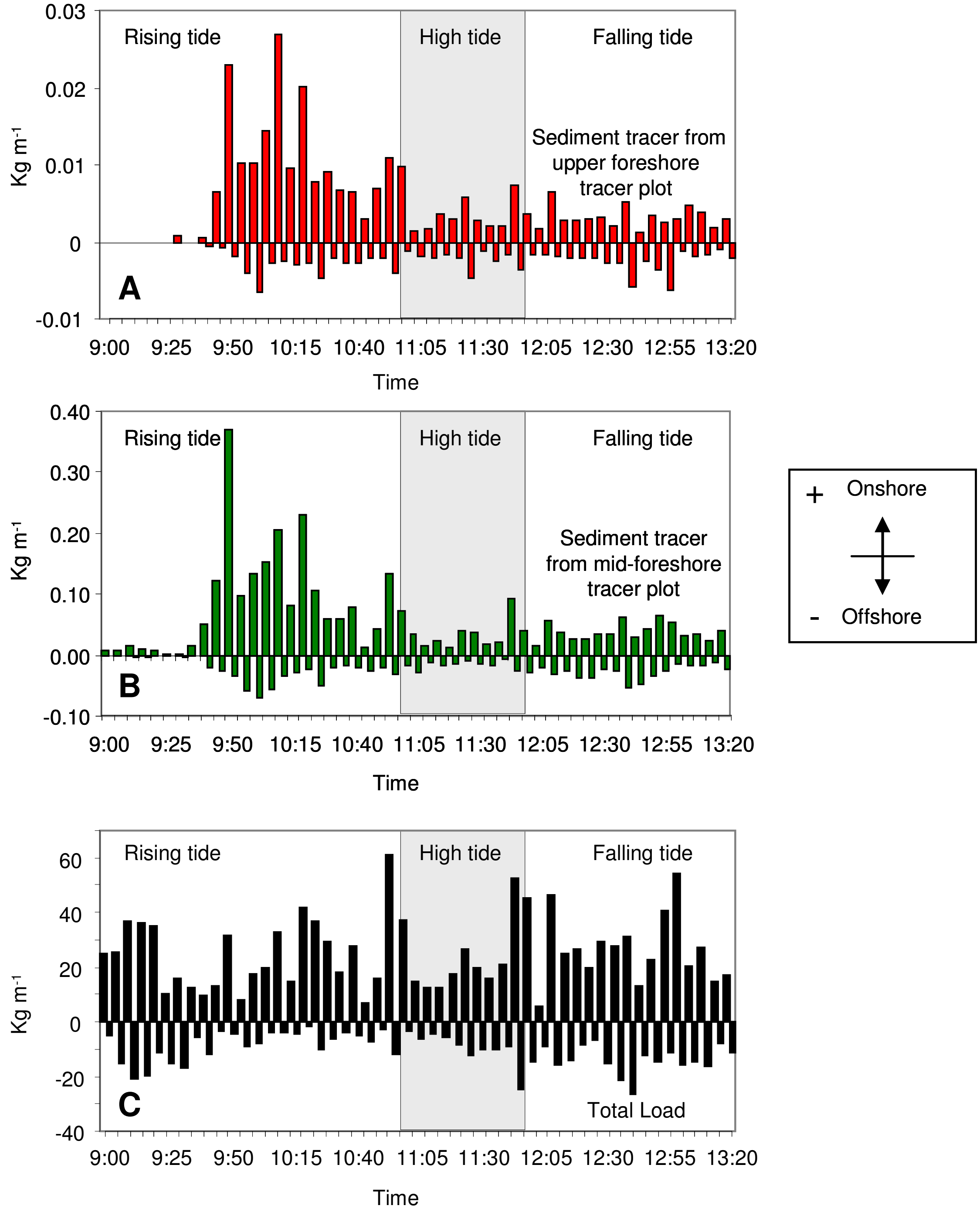


Figure 4.23 Quantities of sediment tracer trapped from the upper foreshore tracer plot (A), mid-foreshore tracer plots (B), and total load (C) trapped in the uprush and backwash over the tidal cycle on October 14, 2007.

<u>Swash Characteristics Influencing Horseshoe Crab Egg and Sediment Tracer Transport Over the Tidal Cycle on October 14, 2007</u>

Exhumation and transport of tracer (green eggs and sediment) from the mid-foreshore tracer plot was initiated at 09:00 during the rising tide when sediment at that location was activated by the first few swash events (Figures 4.21 A and B). Shear stresses at the bed at the beginning of trapping (09:00 to 09:15) could not be calculated because the instruments located 15 m from the dune crest at that time were not recording measurements in sufficient depths of water (< 0.03 m). Quantities of egg and sediment tracer trapped between 09:00 and 09:15 on the mid-foreshore represent the lowest quantities of material trapped over the tidal cycle (Figures 4.22 and 4.23).

Data reveal an increase in the quantities of tracer (green eggs and sediment) trapped at the mid-foreshore between 09:20 and 10:15 when waves broke just bayward of the mid-foreshore tracer plot (Figures 4.22 and 4.23). Significantly greater quantities of sediment tracer were trapped in the uprush compared to the backwash between 09:20 and 10:15 (Wilcoxon signed rank test, $z = 65$, $p = 0.005$, $N = 11$). Significantly greater quantities of egg tracer were also trapped in the uprush compared to the backwash from the mid-foreshore (Wilcoxon signed rank test, $z = 19.5$, $p = 0.075$, $N = 6$). The net immersed weight sediment transport was in the onshore direction, with uprush immersed weights ranging between 8.1 to 35.2 kg m^{-1} and backwash immersed weights ranging from 3.2 to 16.6 kg m^{-1}.

Entrainment and transport of egg and sediment tracer from the upper foreshore (red tracer) occurred by swash flows at 09:25 (Figures 4.22 and 4.23). Trapping took place on the mid-foreshore approximately 15 m from the dune crest between 09:20 and 10:15 (Figure 4.21), and red tracer from the upper foreshore tracer plot observed in traps between this time period represented material that has been entrained by swash events of relatively long widths and transported to the mid-foreshore. A Wilcoxon signed rank test revealed transport of significantly greater quantities of sediment tracer trapped from the upper foreshore in the uprush compared to the backwash between 09:20 and 10:15 ($z = 36$, $p = 0.014$, $N = 8$), but the quantities of eggs in transport were similar.

Swash flow characteristics measured in the lower swash zone at the location of the mid-foreshore tracer plot during trapping between 09:20 and 10:15 are reported in Figure 4.24. The dotted lines represent events when swash characteristics between the uprush and backwash represent a 1:1 relationship. Bed shear stresses required to mobilize sand and the smallest granules were 0.88 N m^{-2} and 1.60 N m^{-2} in the uprush and backwash respectively. Shear stresses were observed to be significantly greater in the backwash than those in the uprush (Wilcoxon signed rank test, $z = 0$, $p = 0.003$, $N = 12$). Mean uprush depths were greater than those in the backwash, but a statistically significant difference was not observed. Maximum velocities over 5 min intervals ranged from 0.81 to 2.46 ms^{-1} in the uprush and 0.91 to 1.89 ms^{-1} in the backwash. Durations in the backwash were observed to be significantly greater than those in the uprush (Wilcoxon signed rank test, $z = 0$, $p = 0.003$, $N = 12$). Cross-shore velocity skewness (-0.93 to -1.46) values calculated from mean flows were negative values, suggesting that mean flows between 09:20 and 10:15 were skewed offshore.

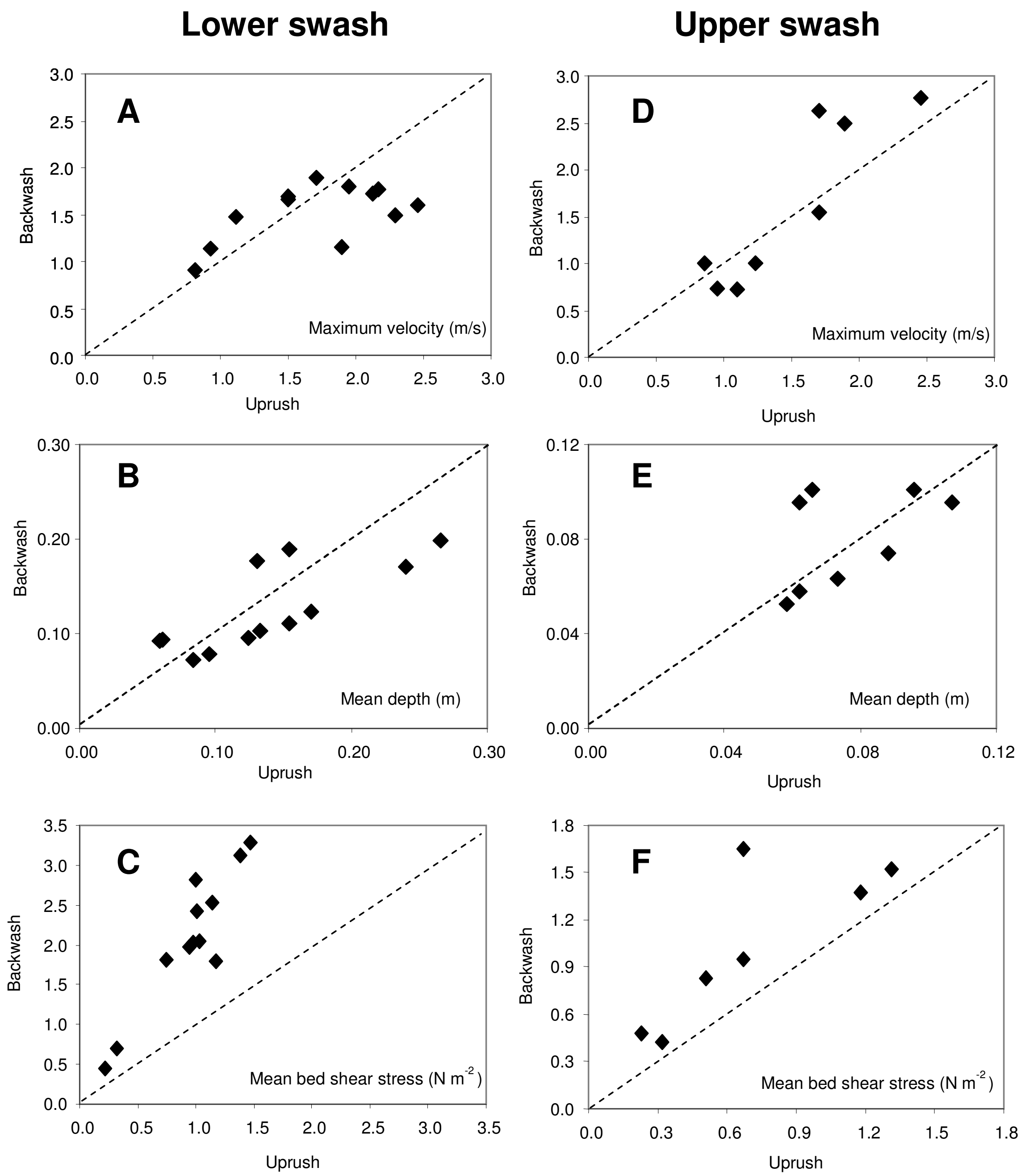


Figure 4.24 Characteristics in the lower swash (A to C) and upper swash (D to F) between 09:20 and 10:15 on October 14, 2007 based on five minute averages.

Flow characteristics in the upper swash zone at the location of the upper foreshore tracer plot between 09:20 and 10:15 cannot be directly correlated with quantities of egg and sediment tracer (red tracer) trapped at the mid-foreshore, but need to be identified in order to understand conditions that were responsible for entrainment of red tracer from that location. Mean bed shear stresses were observed to be significantly greater in the backwash than those in the uprush (Wilcoxon signed rank test, $z = 0$, $p = 0.014$, $N = 8$), however shear stresses in both onshore and offshore flows in the upper swash did not have the potential to entrain sand and granules present at that location (Figure 4.24 F). Mean uprush and backwash depths were similar. Maximum velocities were also similar in the uprush and backwash in the upper swash zone. Negative skewness (-0.62 to -0.91) values reveal that mean flows were also skewed offshore in the upper swash zone.

The measured bed shear stresses in the lower swash zone were greater than those in the upper swash between 09:20 and 10:15 (Figures. 4.24 C and F) which could explain why more tracer was trapped from the mid-foreshore plot than the upper foreshore tracer plot (Figure 4.23 A and B). A multiple regression analysis was conducted using quantities of egg and sediment tracer trapped on the mid-foreshore as dependant variables and breaking wave height, mean shear stress, maximum velocity, mean duration, mean depth measured on the mid-foreshore as independent variables. Data analysis revealed that breaking wave heights ($p = 0.016$, $r^2 = 0.92$) were most responsible for exhuming increasing quantities of sediment tracer from the mid-foreshore tracer plot between 09:20 and 10:15 and transporting them onshore. Depths ($p = 0.008$, $r^2 = 0.83$) and maximum velocities ($p = 0.012$, $r^2 = 0.83$) of backwash flows were strong predictors of sediment transport in the backwash. This implies that greater quantities of sediment tracer are entrained and transported offshore as backwash depths increase, and an increase in peak flow velocities in the backwash will increase the likelihood of sediment tracer moving offshore. Quantities of egg tracer trapped on the mid-foreshore were low (Figure 4.22B), and data were not sufficient to produce a statistically significant relationship between quantities of egg tracer exhumed and swash processes. However, peaks in quantities of egg tracer trapped coincide with those of the sediment tracer, suggesting that waves were the primary mechanism responsible for exhuming egg tracer from the mid-foreshore and transporting them onshore (Figures 4.22 and 4.23).

The zone of wave breaking moved closer to the upper foreshore tracer plot between 10:20 and 11:00, positioning the lower swash zone just bayward of the plot location (Figure 4.21). A comparison revealed greater bed shear stresses between 10:20 and 11:00 in the lower swash zone relative to those generated in the upper swash between 09:20 and 10:15. An increase in the entrainment and transport of sediment tracer from the upper foreshore (red tracer) maybe attributed to the increase in the shear stresses generated by swash flows. A single peak in egg entrainment and transport is observed between this time period. Waves broke just landward of the upper foreshore tracer plot between 11:00 and 11:55 during the high water still stand (Figure 4.21). No egg tracer was trapped between this time period even though waves broke closest to the upper foreshore tracer plot relative to other time periods over the tidal cycle (Figure 4.22). Quantities of sediment tracer trapped in the uprush and backwash also did not vary with changes in flow characteristics in the uprush and backwash. The early part of the falling tide (10:20 to 12:40) when waves broke approximately 14 m landward of the dune crest and the upper swash was at the location of the upper foreshore tracer plot was also not associated with an increase in quantities of tracer trapped from the upper foreshore tracer plot (Figure 4.23 A). Data reveal that the quantities of sediment tracer in transport between 10:20 and 12:40 were controlled primarily by the quantities of total load in transport. A least squares analysis revealed that the correlation between quantities of total load transported in the uprush of instantaneous swash events and the mean ($p = 0$, $r^2 = 0.66$) and maximum uprush velocities ($p = 0$, $r^2 = 0.68$) was significantly strong. An increase in the velocity of uprush events meant that greater quantities of sand, granules and sediment tracer were entrained and transported onshore.

Mean bed shear stresses were significantly greater in the backwash than those in the uprush between 1020 and 1250 (Wilcoxon signed rank test, $z = 4$, $p = 0$, $N = 29$). Shear stresses in the uprush and backwash were capable of entraining sand and granules from the upper foreshore tracer plot (Figure 4.25 C). Mean uprush depths were significantly greater than those in the backwash (Wilcoxon signed rank test, $z = 420$, $p = 0$, $N = 29$). Maximum velocities over 5 min intervals ranged from 1.67-2.84 ms^{-1} in the uprush and 1.48-2.76 ms^{-1} in the backwash. Mean durations in the backwash were observed to be significantly greater than those in the uprush (Wilcoxon signed rank test, $z = 0.000$, $p = 0.000$, $N = 29$). Cross-shore flows were skewed offshore between 10:20 and 12:50 with skewness values ranging between -1.09 to -1.61.

Sediment tracer from the mid-foreshore tracer plot (green tracer) observed in traps between 10:20 and 12:50 when trapping occurred on the upper foreshore was material that had been exhumed during the rising tide (between 09:00 and 10:15), and transported to the upper foreshore by swash flows (Figure 4.23A). The quantities of this material observed in traps thus cannot be related to time averaged swash characteristics observed between 10:20 and 12:50. A possible explanation for the lack of increased exhumation and transport of tracer from the upper foreshore tracer plot (red tracer) after the rising tide could be that the plot became buried in the large quantities of total load that are transported over individual swash events (Figure 4.23 C). The few peaks in egg transport observed between 1020 and 1250 suggest that eggs were more likely to move onshore. However, because quantities entrained and trapped between this time period were so low, statistical tests could not be performed to link variation in quantities to swash processes.

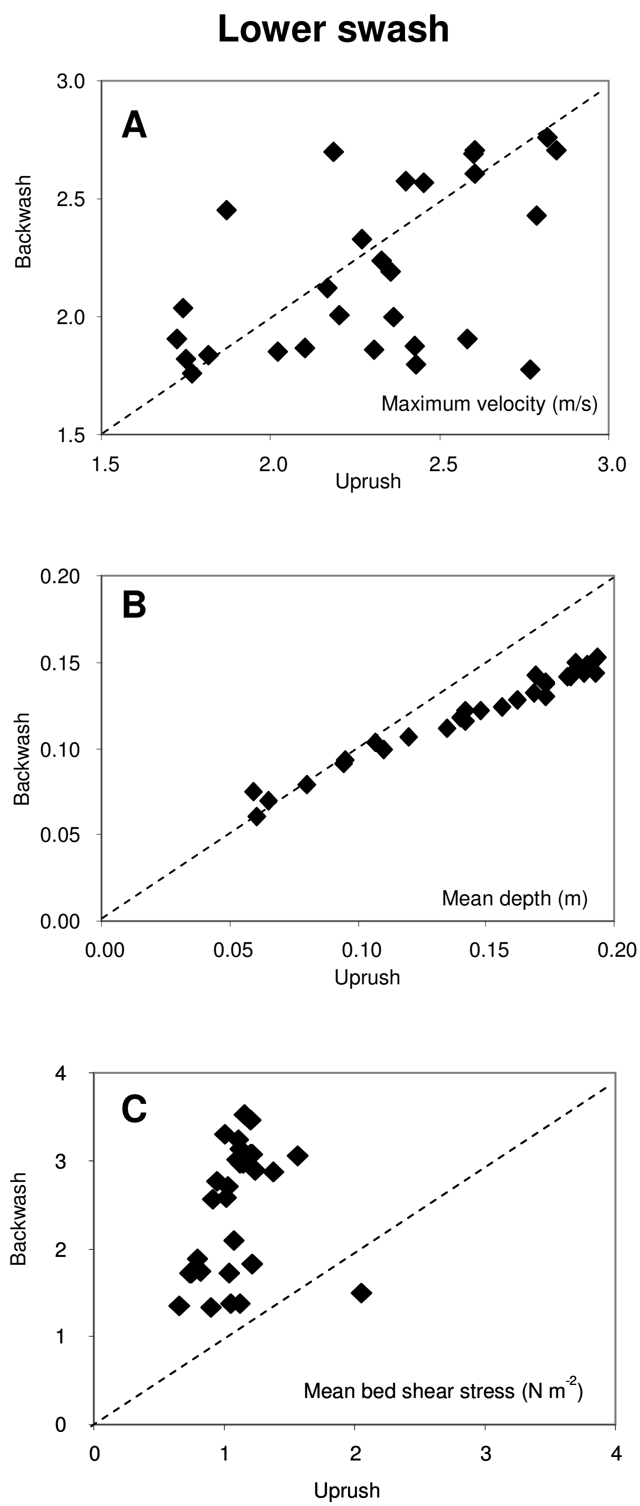


Figure 4.25 Characteristics in the lower swash (A to C) between 1020 and 1250 on October 14 based on five minute averages.

Waves broke just landward of the mid-foreshore tracer plot during the latter stages of the falling tide (12:55 and 13:20) when the last samples were trapped in the uprush and backwash (Figure 4.21). Quantities of sediment tracer trapped from the mid-foreshore were lower compared to those trapped during the rising tide when waves broke at the same location and breaking wave heights were comparable (Figure 4.23B). Data reveal that significantly greater quantities of sediment tracer were exhumed and transported from the mid-foreshore tracer plot in the uprush compared to the backwash by wave breaking and swash flows during the falling tide between 12:30 and 13:20 (Wilcoxon signed rank test, z = 21, p = 0.036, N = 6). A few peaks in the quantities of eggs in transport were observed in uprush flows, but these quantities were significantly lower than those trapped during the rising tide (Figure 4.22 B). Sediment tracer trapped from the upper foreshore between 12:30 and 13:20 represented material that was exhumed and transported to the mid-foreshore by swash events of relatively large width during the rising and high tide. No eggs were trapped from the upper foreshore between 12:30 and 13:20. Greater quantities of total load were trapped in the uprush relative to the backwash. Uprush immersed weights ranged between 14.7 to 54.0 kg m^{-1} and backwash immersed weights ranged between 7.9 to 16.3 kg m^{-1}. (Figure 4.23 C). Cross-shore flows were skewed offshore during the falling tide between 10:20 and 12:50 with skewness values ranging between -0.51 to -1.88.

Mean bed shear stresses were observed to be greater in the backwash than those in the uprush between 12:30 and 13:20, but a statistically significant difference was not

observed. Mean uprush depths were significantly greater than those in the backwash (Wilcoxon signed rank test, z = 6, p =0.036, N= 6). Maximum velocities over ranged from 1.21 to 1.39 ms^{-1} in the uprush and 0.89 to 1.38 ms^{-1} in the backwash. Mean durations in the backwash were observed to be significantly greater than those in the uprush (Wilcoxon signed rank test, $z = 6$, $p = 0.036$, $N = 6$). Data reveal that the measured bed shear stresses in the lower swash just landward of wave breaking were capable of entraining sediment tracer from the mid-foreshore tracer plot during falling tide (Figure 4.26). Water depths in the upper swash at the location of the upper foreshore tracer plot were low between 12:30 and 13:20 and instruments were not able to record continuous measurements. Therefore, shear stresses generated at the bed within swash flows on the upper foreshore could not be estimated and compared with those in the lower swash. Quantities of sediment tracer transported in the uprush and backwash were low compared to quantities transported during rising tide (Figure 4.23 A and B), and statistical analysis reveal that wave and swash characteristics did not appear to control the variation in quantities trapped during the falling tide.

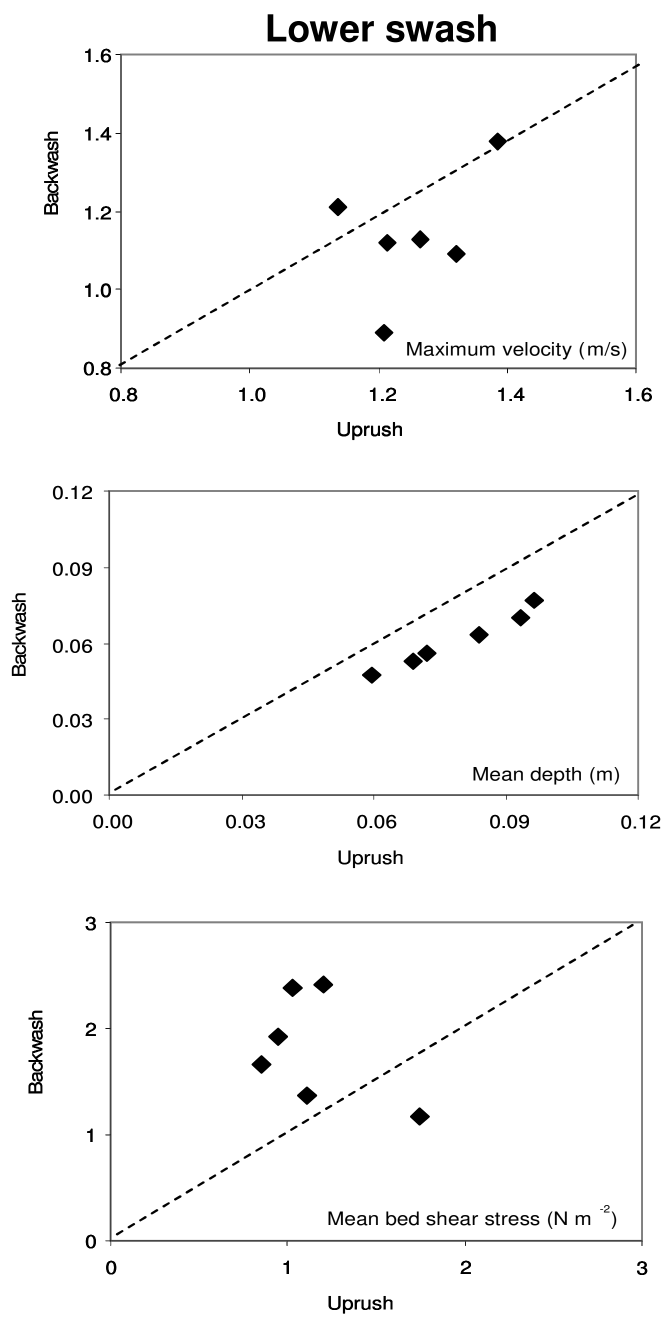


Figure 4.26 Characteristics in the lower swash between 12:55 and 13:20 on October 14, 2007 based on five minute averages.

CHAPTER 5

DISCUSSION

5.1 Overview

This study has been a response to a lack of detailed knowledge on processes in the swash that are responsible for horseshoe crab egg and sediment exhumation and transport on sandy estuarine beaches. Swash parameters (mean and maximum velocity, shear stresses, duration and depth) in the uprush and backwash, as well as the lower and upper swash were significantly different but these results alone were not able to explain entrainment and transport of horseshoe crab eggs and movement of gravel in or over the sand over the tidal cycle. Results suggest that since flows were skewed offshore, dominant transport of eggs and sediment should occur in the backwash whereas data suggest that the inverse is true. Turbulence generated from the collapse of plunging waves on the steep foreshore was the primary mechanism responsible for entrainment of gravel and eggs buried at depth in the mid-foreshore. Results suggest that region of the foreshore that is likely to see greatest concentrations of spawning crabs and deposition of egg clusters also has the highest potential to lose eggs by both wave activation and bioturbation. Eggs deposited on the upper foreshore will remain buried unless storm waves or bioturbation can cause exhumation.

5.2. Characteristics of Sediment in Transport in the Swash Zone

Sandy estuarine beaches with a gravel component (Figure 2.3), such as the one examined here, exhibit a pattern of surface sediment characterized by an accumulation of gravel at the upper swash uprush limit at high water, a sandy surface that extends to about mid-foreshore, and an accumulation of gravel at the lower foreshore (Nordstrom and Jackson, 1993). Data suggest that this pattern is, in part, influenced by the changes in availability of gravel sized material over the tidal cycle.

Differences in Percent Gravel during Rise versus Fall

Tidal rise and fall play an important role in sediment transport on the foreshore because tides affect the distribution of wave energy over the profile and the duration any given region on the foreshore will be reworked by breaking waves and swash (Duncan, 1964). The significant differences in the percent gravel trapped on the rise versus fall of the tide are a function of transport conditions in the breakers and swash that preferentially transport the gravel fraction. The percent gravel trapped in the swash (especially in the uprush) during the rising tide (Table 4.1) is closer to the 7.5% gravel in the bed prior to trapping. This gravel is mined and incorporated into the step.

The increase in the quantity of gravel in the swash uprush approaching the time of high water when the step is located on the upper foreshore (Table 4.1, Figures 4.12 and 4.12) suggests that gravel that accumulates in the step during tidal rise is the primary source of gravel to the swash zone there. Turbulence associated with plunging waves repeatedly lifts and drops pebbles within a step and some of the coarser material makes its way into the uprush (Strahler, 1966). The energy under the incident peak during the early rising tide on an estuarine beach is low (Nordstrom, 1992) and the step is not as well developed as at high tide. Thus the importance of the step as a source of gravel to the swash is less after bore collapse when water levels are low. As the tide rises, offshore water depths and wave energies increase and an increasing proportion of gravel to sand is transported in the swash**.** The high tide still-stand is characterized by stationarity of the swash zone and progressive removal of gravel from the mobile layer, limiting the likelihood of granules and pebbles moving in the uprush resulting in a greater proportion of sand in transport (Figure 5.1B). The bed becomes primarily sand, with the coarsest particles stranded at the upper limit of swash at high tide as observed previously by Nordstrom and Jackson (1993). Through time, fewer pebbles are recaptured by subsequent swashes and moved offshore in the backwash.

The increase in percent gravel trapped in the uprush and backwash during the early falling tide (Figure 5.1C) can be attributed to the large volume of gravel that accumulated in the step over time and a rate of step migration down the beach slope that is slower than the rate of migration of the breakers. This process places the step within the lower swash zone, leading to the mobilization of coarser sediment sizes. As the tide falls, gravel will be carried down the beach in the backwash. Gravel particles once set into motion by turbulence or shear stresses under breaking waves are likely to move down slope on steep beaches (Osborne et al. 2006).

The well rounded pebble fraction is readily transported down the beach in the backwash during the falling tide. This hydrodynamic shape sorting of pebbles is in agreement with field observations of Orford (1975) and Ciavola and Castiglione (2009) who observed the accumulation of discoid particles on the upper part of the beach and movement of the more rounded and pivotable particles downslope. The largest grains may also be transported farther down slope in the backwash due to their greater momentum.

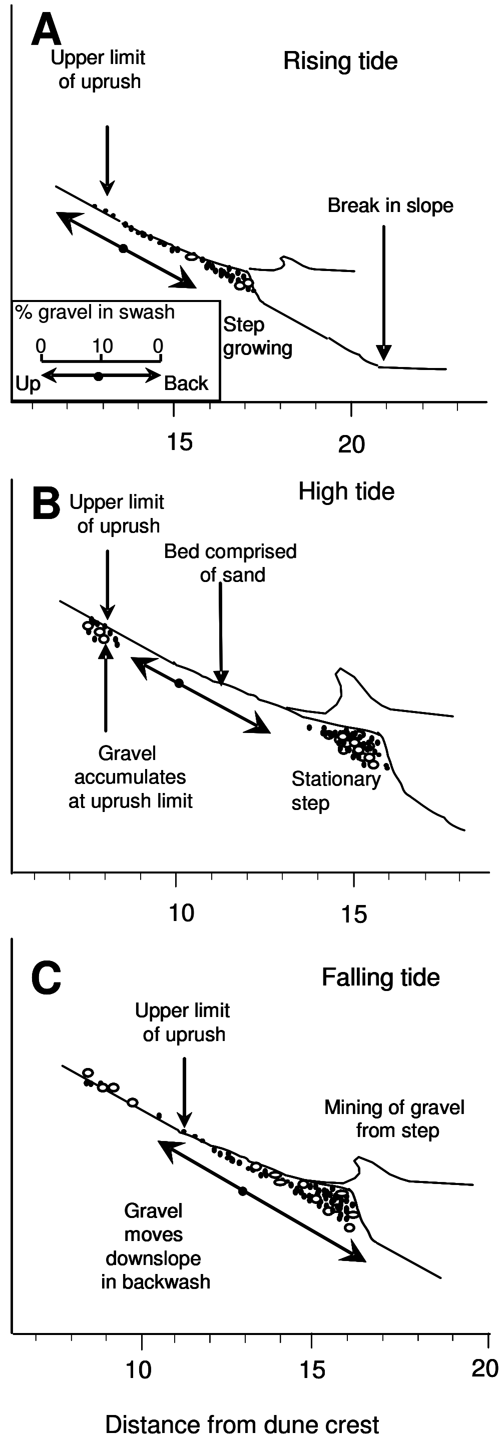


Figure 5.1 Conceptual model of changes in the percentage of gravel distribution in the swash zone of a steep estuarine foreshore. Source: Saini et al., 2011 (Article in press).

The differences in percent gravel trapped over time do not appear to be due to variations in location of trap placement within the swash zone. When the step lies close to the location of trapping, sediment entrained by bore collapse will be advected into the uprush (Austin and Buscombe, 2008), and coarser sediment is likely to be in suspension close to the breakers. If the step lies farther away from the location of trapping, the potential for capture of gravel diminishes because coarser particles settle to the bed before they can be trapped. The position of the step relative to the location of trapping was between 2.0 and 2.8 m, and this variation would not account for the differences observed.

Explanations for Preferential Movement of Gravel

Sediment transported in the swash can be inherited from bore collapse (Petti and Longo, 2001; Austin and Masselink, 2006) or result from bed shear stress that entrains sediment within the swash zone (Wilcock, 1996, Barnes et al., 2009). Gravel can be transported when critical shear thresholds in the swash zone are not exceeded if overpassing (Nordstrom and Jackson 1993), changes in bed roughness due to prior swash events (Austin and Buscombe, 2008) or inheritance from wave breaking (Jackson et al., 2004) occur. Overpassing occurs because gravel particles have low pivoting angles; project into swash flows, and therefore have a greater probability of entrainment and movement over the sand fraction (Everts, 1973; Komar and Li, 1988). A single swash event may cause instantaneous textural changes on a bed comprising of a range of sediment sizes by altering the sediment transport thresholds for transport during a subsequent swash event. An increase in the bed roughness during a swash event may increase bed shear stresses and turbulence, leading to greater sediment transport; cause larger particles to be preferentially transported due to protrusion into the flow or may cause reduced mobility due to the larger entrainment thresholds of the bigger grains. Due to these reasons, a velocity event of similar magnitude during the next swash event may result in a completely different rate of bed motion (Austin and Buscombe, 2008). Gravel observed in traps during events when flows are incompetent to mobilize coarser material can also enter the swash zone as a result of turbulence associated with bore collapse seaward of the base of the true swash zone and/or the interaction between an uprush and the previous backwash (Jackson et al. 2004).

The contribution of gravel to the swash zone from wave breaking on the step (bore collapse) is a possible explanation for the changes documented in the size distributions that occur on the rising tide just prior to high water. The time period from 10:17 to 10:46 reveals an increase in percent gravel (Table 4.1) but on three of the four swash events sampled then the bed shear stress in the uprush did not exceed the threshold to move pebbles in transport (Table 4.2). Those pebbles are likely the result of wave breaking on the step. Plunging waves on estuarine beaches are converted directly to swash (Nordstrom, 1992), providing a mechanism for mining gravel directly from the step and transporting it up the foreshore. It is likely that the interaction of successive swash events enhances sediment suspension in the swash, contributing to gravel movement.

Capture of previously deposited gravel particles at the swash limit may account for the increase in pebbles trapped in the backwash at 10:17 while the tide was still rising. The width of the uprush at 10:17 was 4.5 m (relative to the previous uprush width of 3.3

m) revealing greater potential to capture gravel deposited on the bed by previous swash events above the sampling point.

During falling tide, the differences in the uprush and backwash distributions are not due to flow incompetency in the swash zone. The calculations of shear stress assume that the bed is comprised of one grain size but on the study beach gravel is moved in or over sand. Overpassing may play an important role in transporting pebbles since the shallow backwash depths provide a low angle of attack, making it easier for coarser particles with high pivoting angles to protrude above the sand into the flow and move downslope (Nordstrom and Jackson, 1993). The high degree of roundness coupled with the low sphericity of the pebble clasts on the beach increase their probability of entrainment and movement over the sand particles.

Velocity events of similar magnitude may result in different rates of bed motion depending on bed roughness (Austin and Buscombe, 2008), and an increase in the bed roughness due to prior swash events could increase bed shear stresses and turbulence, leading to greater sediment transport. However, this process is unlikely because the study beach is predominantly sand with a small gravel fraction, and isolated pebble clasts on the sand bed should not account for the changes in gravel in the traps.

5.3 Egg and Sediment Tracer Transport on October 12 and October 14, 2007.

Results of the tracer experiments reveal sediment and egg transport is controlled predominantly by wave breaking and advection of sediment into the uprush and accounts for the greater quantities of sediment and eggs trapped in the uprush relative to the backwash despite offshore directed flows in the swash zone (Jackson et al., 2004; Masselink and Puleo, 2006). Temporal trend of eggs trapped over the tidal cycle reveal a pronounced peak in number of eggs in the swash during the rise with a pronounced decrease in number of eggs transported as water levels fell during the falling tide. Nordstrom et al. (2006) found a similar increase in the number of eggs trapped in the uprush during rising tide but found no relationship between wave heights and quantity of eggs in the swash. Results from October 14 revealed an increase in wave energy with tidal rise but quantities of eggs in transport did not increase beyond the early stages of the rising tide. Swash widths in the upper swash zone during rising tide were wide enough to entrain a small proportion of eggs from the upper foreshore but local shear stresses in the swash at high tide were not capable of entraining or transporting sediment despite higher wave heights.

Bioturbation, Wave Activation and Foreshore Response

Bioturbation and wave activation are necessary to exhume horseshoe crab eggs at depths initially laid during spawning. In the absence of spawning or when spawning densities are low, wave activation is the principal process for exhuming eggs from the beach matrix (Jackson et al., 2005). Previous studies identify the importance of high wave heights and swash events with large widths associated with spring tides as being the most important mechanisms in exhuming buried eggs from the lower and upper foreshore (Yamahira, 1996; Martin and Swiderski, 2001). Smith et al. (2002) report that higher wave heights would increase depths of activation, but horseshoe crab spawning would be suppressed if wave heights exceeded 0.30 m. Wave heights on October 14 exceeded this value and resulted in activation depths less than the depth that horseshoe crabs lay their eggs. The implication is that under wave heights monitored in this study, the likelihood for spawning would be low and thus egg availability would be limited to the activation depth.

An increase in spawning density will cause successive sets of burrowing crabs to disturb eggs that are buried to depths that cannot be activated by waves and these eggs will be mobilized to the surface (Smith, 2007). Only two locations on the foreshore were monitored during the tracer deployments but the area of the beach where exhumation potential was greatest, based on the activation depth and egg tracer recovery, coincides with the location on the foreshore where cumulative cross-shore egg distribution is highest (Weber and Carter, 2009). While a considerable portion of these eggs can be exhumed due to the position of wave breaking on the foreshore, eggs buried landward of wave breaking will be unavailable without sufficient spawning densities. The results of this study confirm the joint and sequential roles of bioturbation and wave activation to increasing egg availability to shorebirds.

Morphologic adjustment of the foreshore on estuarine beaches also can change the vertical position of horseshoe crab eggs in the beach matrix (Jackson et al., 2008) in response to erosion or accretion of the profile (Nordstrom and Jackson, 1992). Moffat and Thomson (1978) reported that exhumation of grunion eggs from the sand matrix was dependant on erosion by waves associated with a tidal range higher than when eggs were initially buried. Breaking wave heights averaging 1.1 m during high water on October 12 exhumed no eggs due to accretion on the foreshore. If no subsequent storms disturb the foreshore sediment, eggs will remain buried, undergo development into larvae if conditions are optimal (Weber and Carter, 2009) and remain unavailable to shorebirds for foraging. Results of this study suggest that eggs buried in the upper foreshore have the greatest likelihood for remaining in the beach matrix but conditions in this region of the foreshore reduces their chances for development (Penn and Brockmann, 1994; Jackson et al., 2008). Similar observations were reported by Yamahira (1997) and Martin and Swiderski (2001) who reported that eggs of species that spawned in the upper intertidal zone will remain buried and develop if oxygen and moisture levels are optimal for development, but are at risk of desiccation if swash flows do not reach the location where eggs are buried.

Movement of Sediment and Eggs

Movement of sediment and eggs is predominantly onshore despite offshore directed flows in the swash and this confirms findings of previous studies on swash sediment transport on exposed ocean beaches (Masselink and Russell, 2006). Onshore sediment transport is attributed to factors such as enhanced bed shear stresses in the uprush (due to flow acceleration, bore turbulence or infiltration effects) and advection of bore-entrained sediment into the swash zone. Sediment transport in the swash zone of steep beaches is a function of wave breaking and advection into the swash (Hughes et al., 1997; Jackson et al., 2004). Turbulence generated from bore collapse is able to extend its influence into the shallow waters of the uprush and consequently on the bed effectively suspending and transporting sediment in an onshore direction (Puleo et al., 2000; Butt et al., 2004). Jackson et al. (2004) reported that sediment entrained during bore collapse just seaward of the lower swash zone was advected into the uprush and transported up the beach along with sediment that was locally entrained by shear stresses at the bed. Plunging breakers at the field site allows increased energy dissipation and associated turbulence even though swash asymmetries are directed offshore, therefore enhancing uprush sediment transport. Local shear stresses in the swash did not exceed the threshold for entrainment of sediment and thus exhumation of eggs and sediment was limited during the higher stages of the tide despite higher wave heights. The low quantities of eggs and sediment entrained from the upper foreshore are a function of the decreasing depths and flow velocities approaching the uprush limit.

5.4 Concluding Statement

This dissertation extends the results of previous investigations of gravel transport on estuarine beaches by identifying process conditions that influence sediment transport in the uprush and backwash and account for the significant increase in percent gravel during fall versus rise of the tide. The results highlight the importance of the exhumation of gravel from the beach matrix by wave breaking and transport in the swash during rising tide and the rate of breaker migration relative to step migration during the falling tide. High wave energies reported during high water result in gravel escaping from the step and being transported in the swash uprush with subsequent deposition as a gravel band on the upper foreshore. Overpassing and greater momentum of the larger particles and the stranding of the step in the lower swash were factors that led to an increase in the quantity of gravel trapped in the backwash during falling tide.

Energetic bore collapse on the mid-foreshore region of the steep estuarine foreshore played a significant role in generating onshore transport of sediment and eggs even though mean swash flows were directed offshore. Rates of egg and sediment transport were greater on October 14, 2007 even though mean wave heights were lower than those observed on October 12, 2007. On October 14, quantities of eggs exhumed and transported from the mid-foreshore by wave and swash processes during the rising tide were greater than quantities entrained from the upper foreshore by swash flows alone. Quantities of total load in transport on both days were high and significant accretion was observed across the upper foreshore on October 12, 2007. Results imply that wave and swash processes on steep, estuarine beaches can cause significant morphological changes across the foreshore which has critical implications for egg availability to shorebirds.

REFERENCES

Austin, M.J. and Masselink, G. (2006) Observations of morphological change and sediment transport on a steep gravel beach. *Mar. Geol.*, **229**, 59-77.

Austin, M.J. and **Buscombe, D.** (2008) Morphological change and sediment dynamics of the beach step on a macrotidal gravel beach. *Mar. Geol.,* **249**, 167-183.

Atlantic States Marine Fisheries Commission (1999). Stock Assessment Report No. 98-01 (Supplement) **47**, Washington, DC.

Atlantic States Marine Fisheries Commission (2005) Terms of Reference Report for the Stock Assessment of Atlantic Coast Horseshoe Crabs: A Proposed Framework. Washington. **85**.

Bagnold, R.A. (1963). Mechanics of marine sedimentation. In: *Hill, M.N. (Ed.), The Sea. Wiley-Interscience New York* . 507-528.

Baker, A.J., González P.M., Piersma, T., Niles, L.J., de Lima Serrano do Nascimento, I., Atkinson, P.W., Clark, N.A., Minton, C.D.T., Peck, M.K., and **Aarts, G.** (2004) Rapid population decline in red knots: fitness consequences of decreased refuelling rates and late arrival in Delaware Bay. *Proc. Roy. Soc. London (B)*, **271**, 875-882**.**

Bargmann, G. (1998) Forage fish management plan. Washington Department of Fish and Wildlife Report.

Barnes M.P., O'Donoghue, T., Alsina J.M. and **Baldock**, **T.E.** (2009) Direct bed shear stress measurements in bore-driven swash. *Coast. Eng*., **56**, 853-867.

Bascom, W. M. (1959) Beach processes and coastal hydrodynamics, In: Part three: The relationship between sand size and beach face slope. Dowden, Hutchinson and Ross Inc. Stroudsburg, Pennsylvania.

Beach R.A., and **Sternberg, R.W**. (1992) Suspended sediment transport in the surf zone: Response to incident wave and longshore current interaction. **108**. 275-294.

Blenkinsopp, C.E., Turner, I.L., Masselink, G. and **Russell, P.E**. (2010) Validation of volume continuity method for estimation of cross-shore swash flow velocity. *Coast. Eng*. **57**, 953-958.

Bodge, K. R., and **Dean, R. G.** (1987). Short-term impoundment of longshore transport. In: *Proc. Coast. Sed. '87, ASCE*, pp. 468-483. New York.

Botton, M.L., Loveland, R.E., and **Jacobsen T.R.** (1988) Beach erosion and geochemical factors: influence on spawning success of horseshoe crabs (Limulus polyphemus) in Delaware Bay. *Mar. Biol.,* **99**, 325-332.

Botton, M.L., Loveland, R.E., and **Jacobson, T.R**. (1994) Site selection by migratory shorebirds in Delaware Bay, and its relationship to beach characteristics and abundance of horseshoe crab (Limulus polyphemus) eggs. *Auk* 111, 605-616.

Botton, M.L., and **Loveland, R.E.** (2003) Abundance and dispersal potential of horseshoe crab (Limulus polyphemus) larvae in the Delaware Estuary. *Estuaries,* **26**, 1472-1479.

Brady J.T. and **Schrading, E.,** (1983) Habitat sustainability index models: horseshoe crab (spawning) Delaware Bay, New Jersey and Delaware (developed for the U.S. Army Corps of Engineers, Philadelphia District, Pennsylvania - Cape May Villas and Reeds Beach Habitat Evaluation Procedures).

Brockmann, H.J. (1990) Mating behavior of horseshoe crab, Limulus polyphemus. *Anim Behav*, **114**, 206-220.

Brown, G.G., and **Clapper D.L**. (1981) Procedures for maintaining adults collecting gametes, and culturing embryos and juveniles of the horseshoe crab, Limulus Polyphemus In: *Hinegardner RT, Atz JW, Fay RC, Fingerman M, Josephson RK, Meinkoth NA, Miller JW, Rice ME, Muckenhirn NA, Pye VI, editors. Laboratory animal management: Marine invertebrates. Washington, DC: National Academy Press*. 268-290.

Burger, J and **Montevecchi, W.A**. (1975) Nest Site Selection in the terrapin *Malaclemys terrapin*. *Copeia*,**1**, 113-119.

Burger, J., Niles, L. and **Clark, K.E**. (1997) Importance of beach, mudflat and marsh habitats to migrant shorebirds on Delaware Bay. *Biol. Conserv.*, **79**, 283-292.

Butt, T., Russell, P. and **Turner, I.L**. (2001) The influence of swash infiltration-exfiltration on beach sediment transport: onshore or offshore. *Coast. Eng.*, **42**, 35-52.

Butt, T., Russell, P.E., Puleo, J., Miles, J. and **Masselink, G.** (2004) The influence of bore turbulence in the swash and inner surf zones. *Cont. Shelf. Res.*, **24**, 757-771.

Butt, T. and **Russell, P.E**., (2005) Observations of hydraulic jumps in high energy swash. *J. Coastal. Res.*, **21**, 1219-1227.

Castro, G., and **Myers J.P**. (1993) Shorebird predation on eggs of horseshoe crabs during spring stopover on Delaware Bay. *Auk* ,**110**, 927-930.

Ciavola, P. and **Castiglione, E**. (2009) Sediment dynamics of mixed sand and gravel beaches at short time-scales. *J. Coastal. Res*., **56**, 1751-1755.

Clark, F. N. (1925) The life history of *Leuresthes tenuis*, an atherine fish with controlled spawning habits. California Division of Fish Game Fish. Bulletin 10, 51.

Conley, D.C., and **Griffin, J.G**. (2004) Direct measurements of bed stress under swash in the field. *J. Geophys.l Res.,***109,** C03050.

Conley, D.C., and **Inman, D.L.** (1994) Ventilated oscillatory boundary- layers. *J. Fluid. Mech.* **273**, 261-284.

Conover, D.O., and **Kynard, B.E**. (1984) Field and laboratory observations of spawning periodicity and behavior of a northern population of the Atlantic silverside, *Menidia menidia* (Pisces: Atherinidae). *Env. Biol. Fish,***11**, 161-171

Cox, D.T., Hobensack, W., and **Sukumaran, A.** (1998) Bottom stress in the inner surf and swash zone. Proc. 27th Int. Conf. Coast. Eng. ASCE, 108-119.

Cox, D.T., and **Hobensack, W.A.,** (2001). Temporal and spatial bottom stress variations in the swash zone. *J.Geophy. Res.*. In Review.

Curtiss, G.M., Osborne, P.D. and **Horner-Devine, A.R**. (2009) Seasonal patterns of coarse sediment transport on a mixed sand and gravel beach due to vessel wakes, wind waves, and tidal currents. *Mar. Geol.*, **259**, 73-85.

Duncan, J.R. (1964) The effects of water table and tide cycle on swash - backwash sediment distribution and beach profile development. *Mar. Geol*., **2**, 186-197.

Durant, J.M., Hjermann, D.O., Anker-Nilssen, T., Beaugrand, G., Mysterud, A., Pettrolelli, N. and **Stenseth, N.** (2005) Timing and abundance as key mechanisms affecting trophic interactions in variable environments. *Ecol. Lett.,* **8**, 952-958.

Dethier, M.N., Ruesink, J., Berry, H., Sprenger, A.G. and **Reeves, B.** (2010) Restricted ranges in physical factors may constitute subtle stressors for estuarine biota. *Mar. Env. Res.*, **69**, 240 - 247.

Edwards, T. (1997) Sediment transport in the swash zone of a sandy beach. Unpublished Honours thesis. Department of Environmental Engineering. University of Australia. Nedlands.

Ehlinger, G.S. and **R.A. Tankersley**, (2003). Larval hatching in the horseshoe crab, *Limulus* polyphemus: Facilitation by environmental cues. *J. Exp. Mar. Biol. Ecol.* ,**292**, 199-212.

Elfrink, B. and **Baldock, T**. (2002) Hydrodynamics and sediment transport in the swash zone: a review and perspectives. *Coast. Eng*., **45**, 149-167.

Everts, C.H. (1973) Particle overpassing on flat granular boundaries. *J. Waterw. Port Coast. Ocean Eng.,***99,** 425-428.

Fenster, M.S., Knisley, C.B. and **Reed, C.T.** (2006) Habitat Preference and the Effects of Beach Nourishment on the Federally Threatened Northeastern Beach Tiger Beetle, Cicindela dorsalis dorsalis: Western Shore, Chesapeake Bay, Virginia*. J. Coast. Res*., **22**, 1133-1144.

Freire. P., Taborda, R. and **Silva, A.M**. (2007) Sedimentary characterization of Tagus estuarine beaches (Portugal). *J. Soils and Sediments.,* **7**, 296-302.

Freire, P., Ferreira, O., Taborda, R., Oliveira, F.S.B.F., Carrasco, A.R., Silva A., Vargas, C., Capitao, R., Fortes, C.J., Coli, A.B. and **Santos, J.A.**, (2009). Morphodynamics of fetch-limited beaches in contrasting environments*. J. Coast. Res.,* **SI56**, 183-187.

Galbraith, H., Jones, R., Park, R., Clough, J., Herrod-Julius S., Harrington, B., and **Page, G.** (2002) Global climate change and sea level rise: potential losses of intertidal habitat for shorebirds. *Waterbirds*, **25**, pp.173-183.

Goda. Y. (1970) A Synthesis of Breaker Indices. Transactions of the Japanese Society of Civil Engineers, **2** , 227-230.

Grant, U.S. (1948). Influence of water the table on beach aggradation and degradation. *J. Mar. Res.,* **7**, 655-660.

Griem, J. N. & Martin, K. L. M., (2000). Wave action: The environmental trigger for hatching in the California grunion, *Leuresthes tenuis* (Teleostei: Atherinopsidae). *Mar. Biol.* **137**, 177-181.

Greenwood, B. and **Hale, P.B**. (1980) Depth of activity, sediment flux, and morphological change in a barred nearshore environment. In: *The Coastline of Canada* (Ed. S.B. McCann), *Geol. Surv. Canada Paper 80-10*, Ottawa. 89-109.

Hallermeier, R. J. (1981) A profile zonation for seasonal sand beaches from wave climate., *Coast. Eng*. **4**, 253-277.

Hardisty, J., (1986). A morphodynamic model for beach gradients. *Earth Surf. Proc. Land.*, **11**, 327-333.

Hata, D. (2008) Report of the 2007 Horseshoe crab spawning activity in Delaware Bay: 1999-2007. Report to the ASMFC Horseshoe Crab Technical Committee.

Holland, K.T. and **Puleo, J.A**. (2001) Variable swash motions associated with foreshore profile change. *J.Geophys. Res.,* **106**, 4613-4623.

Hughes, M.G., Masselink, G. and **Brander, R.W**. (1997) Flow velocity and sediment transport in the swash zone on a steep beach. *Mar. Geol.*, **138**, 91-103.

Hughes, M.G. & Baldock, T.E., (2004) Eulerian flow velocities in the swash zone: field data and model predictions. *J.Geophys. Res.,***109**, C08009.

Isla, F.I. and **Bujalesky, G.G**. (2004) Morphodynamics of a gravel-dominated macrotidal estuary: Rio Grande, Tierra del Fuego. *Asociación Geológica Argentina.*, **59**, 220-228.

Ivamy, M.C. and **Kench, P.S**. (2006) Hydrodynamics and morphological adjustment of a mixed sand and gravel beach,. Torere, Bay of Plenty, New Zealand. *Mar. Geol.*, **228**, 137-152.

Jackson, N.L., (1995) Wind and Waves: Influence of Local and Non-Local Waves on a Meso-scale Beach Behavior in Estuarine Environments. *Ann. Am. Assoc. Geogr.* ,**85**, 21-37.

Jackson, N.L., (1999) Evaluation of criteria for predicting erosion and accretion on an estuarine sand beach. Delaware Bay, New Jersey, *Estuaries*, **99**, 215-223.

Jackson , N. L., Nordstrom K.F., and **Smith, D.R**. (2002). Geomorphic - biotic interactions on beach foreshores in estuaries. *J. Coast. Res.,* **36**, 414-424.

Jackson, N.L., Masselink, G. and **Nordstrom, K.F.** (2004) The role of bore collapse and local shear stresses on the spatial distribution of sediment load in the uprush of an intermediate-state beach. *Mar. Geol.*, **203**, 109-118.

Jackson, N.L., Smith, D.R. and **Nordstrom, K.F.** (2005) Comparison of sediment characteristics on nourished and un-nourished estuarine beaches in Delaware Bay, New Jersey. *Zeit. Geomorph.*, **141**, 31-45.

Jackson, N.L., Smith, D.R., and **Nordstrom, K.F.** (2008) Physical and chemical changes in the foreshore of an estuarine beach: implications for viability and development of horseshoe crab Limulus polyphemus eggs, *Mar. Ecol. Prog. Ser.,* **355**, 209-218.

Jensen, S.G., Aagaard, T., and **Baldock, T.E.** (2010) Swash zone bed level changes and sediment entrainment at the surf swash boundary, *Proc. Int. Conf. Coast. Eng*. 32.

Karpanty, S.M., J. Cohen, J.D. Fraser and **J. Berkson. 2011.**Sufficiency of Horseshoe Crab Eggs for Red Knots During Spring Migration Stopover in Delaware Bay USA. *J. Wildlife Manage*., **75**, 984-994

Kirk, R.M. (1970) Swash zone processes: An examination of water motion and the relations between water motion and foreshore response on some mixed sand-shingle beaches, Kaikoura, New Zealand. *Unpublished Ph.D. Thesis Geography Department University of Canterbury.*

Kobayashi, N. (1999). Wave Runup and Overtopping on Beaches and Coastal Structures. Page 95- 154 in *P. L-F. Liu (ed), Advances in Coastal and Ocean Engineering* -Vol. 5. *World Scientific.*

Komar, P.D. and **Li, Z.** (1986) Pivoting analyses of the selective entrainment of sediments by shape and size with application to gravel threshold. *Sedimentology,* **33**, 425-436.

Komar, P.D. (1991). Littoral sediment transport. In: *Herbich, J.B. (Editor.), Handbook of Coastal and Ocean Engineering,* Volume II. *Gulf, Houston*, 681-714.

Kraeuter, N.J., & Fegley, S.R. (1994) Vertical disturbance of sediments by horseshoe crabs (Limulus polyphemus) during their spawning season. *Estuaries Coast.,* **17**, 288-294.

Kraus, N.C. and **Dean, J.L.** (1987) Longshore sediment transport rate distributions measured by trap. Coastal Sediments. *Am. Soc. Civ. Eng*., 881- 896.

Krumbein W.C. and **Pettijohn F.J**. (1938) Manual of Sedimentary Petrography. Appleton- Century-Crofts: New York.

Kreamer, G. and **Michels, S**. (2009) History of Horseshoe Crab Harvest on Delaware Bay. In: *Biology and conservation of horseshoe crabs* (Eds. J.T. Tanacredi, M.L. Botton, and D.R. Smith)., Springer, New York. 299-313.

Larson, M., Kubota, **S.** and **Erikson, L**. (2004) Swash-zone sediment transport and foreshore evolution: field experiments and mathematical modelling. *Mar. Geol.,* **212**, 61-79.

Lastra, M., Dugan, J.E., & Hubbard, D.M. (2002). Burrowing and swash behavior of the Pacific mole crab Hippa pacifica (Anomura, Hippidae) in tropical sandy beaches. *J. Crust. Biol.,* **22**, 53-58.

Martin, K.L.M. and **Swiderski, D.L**. (2001). Beach Spawning in Fishes: Phylogenetic Tests of Hypotheses. *Am. Zool,.* **41**, 526-537.

Martin, K. L. M., R. C. Van Winkle, J. E. Drais, and H. Lakisic. 2004. Beach spawning fishes, terrestrial eggs, and air breathing. *Physiol. Biochem. Zool.*, **77**, 750-759.

Masselink, G. and **Hughes, M.G**. (1998) Field investigation of sediment transport in the swash zone. *Cont. Shelf. Res*., **18**, 1179-1199.

Masselink, G. and **Puleo, J.A**. (2006) Swash-zone morphodynamics. *Cont. Shelf. Res*., **26**, 661-680.

Masselink, G., and **Russell, P.** (2005) Field measurements of flow velocities on a dissipative and reflective beach- implications for swash sediment transport. In: *Proc. Coast. Dynam.*, *In American Society of Civil Engineers*.

Masselink, G., and **Russell, P**. (2006) Flow velocities, sediment transport and morphological change in the swash zone of two contrasting beaches. *Mar. Geol*., 227, 227-240.

McIntyre, A.D., Munro, A. L.S., and **Steele, J.H**. (1970) Energy flow in a sand ecosystem. In:*Marine food chains, J.H. Steele (ed.), Oliver and Boyd, Edinburgh* 19-31.

Michels, S., Smith, D., and **Bennett, S.** (2008) Horseshoe crab spawning activity in Delaware Bay. 1999-2007. *Report to the ASMFC Horseshoe Crab Technical Committee..*

Miles, J., Butt, T., and **Russell, P**. (2006) Swash zone sediment dynamics: A comparison of a dissipative and an intermediate beach. *Mar. Geol.* 231,181-200.

Moffatt, N. M. and **Thomson, D. A.** (1978) Tidal influence on the evolution of egg size in the grunions (*Leuresthes*, Atherinidae). *Env. Biol. Fishes.,***3,** 267-273.

Morrison, R.I.G., Ross, R.K., and Niles, L.J. (2004) Declines in wintering populations of Red Knots in southern South America, *Condor,*106 pp. 60-70.

Nielsen, P. (1992) Coastal Bottom Boundary Layers and Sediment Transport. *Advanced Series on Ocean Engineering,* Vol. 4. *World Scientific Publishing, Singapore.*

Nielsen, P. (2002) Shear stress and sediment transport calculations for swash zone modelling. *Coast. Eng.,* **45***,* 53-60.

Niles, L.J., Sitters, H.P., Dey, A.D., Atkinson, P.W., Baker, A.J., Bennett, K.A., Carmona, R., Clark, K.E., Clark, N.A., Espoz, C., González, P.M., Harrington, B.A., Hernández, D.E., Kalasz, K.S., Lathrop, R.G., Matus, R.N., Minton, C.D.T., Morrison, R.I.G., Peck, M.K., Pitts, W., Robinson R.A., and **Serrano, I.L.** (2008) Status of the Red Knot, Calidris canutus rufa, in the Western Hemisphere. *Stud. Avian Biol.* **36**, 1-185.

National Oceanic and Atmospheric Administration (NOAA) (2007a) *Tide Tables (2007) East Coast of North and South America*. U.S. Department of Commerce, Washington, D.C.

National Oceanic and Atmospheric Administration (NOAA) (2007b) *Center for Operational Oceanographic Products and Services, Tides and Currents. Brandywine Shoal Light*, Delaware: Meteorological Observations.

Nordstrom, K.F. (1980). Cyclic and seasonal beach response: a comparison of oceanside and bayside beaches. *Phys. Geog.,***1**, 177-196.

Nordstrom, K.F. (1992) *Estuarine Beaches*. Elsevier Science Publishers, London.

Nordstrom, K.F. and **Jackson, N.L.** (1993) Distribution of surface pebbles with changes in wave energy on a sandy estuarine beach. *J. Sed. Res*., **63**, 1152-1159.

Nordstrom, K.F., Jackson, N. L., Smith, D.R. and **Weber, R**. (2006) Transport of horseshoe crab eggs by waves and swash on an estuarine beach: Implications for foraging shorebirds. *Estuar. Coast. Shelf. Sci.,***70**, 438-448.

Orford, J..D. (1975) Discrminiation of particle zonation on a pebble beach. *Sedimentology*., **22**, 441- 463.

Osborne, P.D., MacDonald, N.J. and **Reynolds, W.J.** (2006) Response of mixed sediment beaches to wake wash from passenger only fast ferries: Rich Passage, Washington., *Proc. Coast. Eng.,* **3**, 3105-3116.

Penn, D and **Brockmann, H.J.** (1994) Nest-site selection in the horseshoe crab, *Limulus polyphemus. Biol. Bull*., **187**, 373-384.

Petti, M. and **Longo, S**. (2001) Turbulence experiments in the swash zone. *Coast. Eng*., **43**, 1-24.

Pierce, J. C., Tan, G., and **Gaffney, P. M.** (2000) Delaware Bay and Chesapeake Bay populations of the horseshoe crab *Limulus polyphemus* are genetically distinct., *Estuaries,* 23:690-698.

Pooler P.S., Smith D.R., Loveland R.E., Botton M.L., and **Michels S.F**. (2003) Assessment of sampling methods to estimate horseshoe crab (*Limulus polyphemus*) egg density in Delaware Bay. *Fish. Bull.,* **101**, 698-703

Powers, M.C. (1953) A new roundness scale for sedimentary particles. *J. Sed. Petrol*. **23**, 117-119.

Puleo, J.A., Beach, R.A., Holman, R.A., and **Allen, J.S.** (2000) Swash zone sediment suspension and transport and the importance of bore generated turbulence. *J. Geophys. Res.,* **105**, 17021-17044.

Puleo, J.A., Holland, K.T., Plant, N., Slinn, D.N., and **Hanes, D.M.,** (2003) Fluid acceleration effects on suspended sediment transport in the swash zone. *J. Geophys. Res.,*108, pp. 3350.

Quick, M.C.(1991) Onshore-offshore sediment transport on beaches. *Coast. Eng.* 15, 313-332.

Raudkivi, A. J. (1998) Loose Boundary Hydraulics. *Taylor & Francis* 1998.

Rice, C.A. (2006) Effects of shoreline modification on a northern Puget Sound beach - microclimate and embryo mortality in surf smelt (*Hypomesus pretiosus). Estuar. Coast.,***29***,*63-71.

Rudloe, A. (1979) Locomotor and light responses of larval horseshoe crabs, Limulus polyphemus (L.). *Biol. Bull.,* **157**, 494-505.

Saini, S., Jackson, N.L. and **Nordstrom, K.F.** (2011) Characteristics of sediment in transport in the swash zone of a steep estuarine foreshore., *Sedimentology*, (accepted).

Sherman D.J., Nordstrom K.F., Jackson N.L. and **Allen J.R.** (1994) Sediment mixing depths on a low-energy reflective beach. *J. Coast. Res*., **10**, 297-305.

Short, A.D. (1999) Beachface and shoreface morphodynamics. *Chichester: John Wiley & Sons.*

Shuster, C.N., and **Botton, M.L.** (1985) A contribution to the population biology of horseshoe crabs, Limulus polyphemus (L.) Delaware Bay. *Estuar. Coasts*.,**8**, 363-372.

Shuster, Jr CN and **Sekiguchi K** (2003) Growing up takes about ten years and eighteen stages. In: Shuster CN, Barlow RB, Brockman HJ (eds) The American Horseshoe Crab. Harvard University Press, Cambridge, pp 103-132.

Smith, D.R., Pooler, P.S., Loveland, R.E., Botton, M.L., Michels, S.F., Weber, R.G., and **Carter, D.B.** (2002) Horseshoe crab (Limulus polyphemus) reproductive activity on Delaware Bay beaches: Interactions with beach characteristics. *J. Coastal. Res.,* **18**:730-740.

Smith, D.R., and **Michels, S.F**. (2006). Seeing the elephant: importance of spatial and temporal coverage in a large-scale volunteer-based program to monitor horseshoe crabs. *Fisheries* 31:485-491.

Smith, D. R. (2007) Effect of horseshoe crab spawning density on nest disturbance and exhumation of eggs: a simulation study. *Estuar. Coast.,* **30**, 287-295.

Smith, D., Botton, M.L., Tanacredi, J.T., Rudkin, D.M., and **Young**, **G.A.** (2009) Horseshoe Crabs: An Ancient Ancestry Revealed. In: Biology and Conservation of Horseshoe Crabs, (Eds. Tanacredi, J.T., M.L. Botton and D. Smith). Springer US, New York, 25-44.

Smith, D., M.L. Botton, J.T. Tanacredi, K. Sekiguchi, and **C.N. Shuster**, (2009). Limits on the Global Distribution of Horseshoe Crabs (Limulacea): Lessons Learned from Two Lifetimes of Observations: Asia and America. In: Biology and Conservation of Horseshoe Crabs, (Eds. Tanacredi, J.T., M.L. Botton and D. Smith) . Springer US, New York, 5-24.

Smith, D., Jackson, N.L., Nordstrom, K.F., and **Weber, R.W**. (2011) Beach characteristics mitigate effects of onshore wind on horseshoe crab spawning: implications for matching with shorebird migration in Delaware Bay. *Anim. Conserv.* 1-10.

Soulsby, R.L. (1997) Dynamics of Marine Sands: *A Manual for Practical Applications, Thomas Telford, London.*

Soulsby, R.L. and **Whitehouse, R.J.S.W.** (1997). Threshold of sediment motion in coastal environments. *Proc. Pacific Coasts and Ports '97 Conf.*, Christchurch, **1**, 149-154. University of Canterbury, New Zealand.

Spalding, V. and **Jackson, N.L.**, (2001) Effect of bulkheads on meiofaunal abundance in the foreshore of an estuarine sand beach. *J. Coast. Res.* **17**, 363-370.

Strahler, A.N. (1966) Tidal cycle of changes in an equilibrium beach, Sandy Hook, New Jersey. *J. Geol.*, **74**, 247-268.

Swan, B. L., Hall, W. R., Jr., and **Shuster, C. N., Jr.** (1996) Annual survey of horseshoe crab spawning activity along the shores of Delaware Bay: 1990-1995 *summary,35-39.* In: *J. Farrell and C. Martin (eds.), Proceeding of the Horseshoe Crab Forum: Status of the Resource. University of Delaware Sea Grant College Program, Lewes, Delaware.*

Swart, D.H. (1974) A schematization of onshore-offshore transport. *Proc. Am. Soc. Civ. Eng.* 884-900.

Taylor. M. H., DiMichele, L., and **Leach**., **G. J.,** (1977). Egg stranding in the life cycle of the mummichog, *Funduluis heteroclirus*. *Copeia*, 397-399.

Thornton, L., and **Jackson, N.L.,** (1998) Spatial and temporal variation in debris accumulation and composition on an Estuarine Shoreline, Cliffwood Beach, New Jersey, USA. *Mar. Poll. Bull.,* **36,** 705-711.

Turner, I.L. and **Masselink, G**. (1998) Swash infiltration - exfiltration and sediment transport. *J. Geophys. Res.,* **103**, 30813-30824.

Walker, B. (1952). A guide to the grunion, Cal Fish and Game 38:409-420.

Walls, E. A., J. Berkson, and **S. A. Smith**. (2002). The horseshoe crab, *Limulus polyphemus*: 200 million years of existence, 100 years of study. *Rev. Fish. Sci*., 10, 39-73.

Wang, P., Kraus, N. C. and **Davis, R. A**., **Jr**. (1998) Total rate of longshore sediment transport in the surf zone: Field measurements and empirical predictions. *J. Coast. Res.,* **14**, 269-283.

Weber, R.G. and **Carter, D.B.** (2009) Distribution and development of Limulus egg clusters on intertidal beaches in Delaware Bay. In: *Biology and conservation of horseshoe crabs* (Eds. J.T. Tanacredi, M.L. Botton, and D.R. Smith), Springer, New York, 249-266.

Wieser, W. (1959) The effect of grain size on the distribution of small invertebrates inhabiting the beaches of Puget Sound, *Limnol. Oceanogr.***4**, 181-194.

Wilcock, P.R. (1996) Estimating local bed shear stress from velocity observations. *Water. Resour. Res*., **32**, 3361-3366.

Wu, S.Y., Najjar, R., and **Siewert, J.** (2009) Potential impacts of sea-level rise on the Midand Upper-Atlantic Region of the United States. *Climatic Change,* **95**,121-138.

Yamahira, K. (1996) The role of intertidal egg deposition on survival of the puffer, *Takifugu niphobles* (Jordan et Snyder), embryos. *J. Exp. Mar. Biol. Ecol.,* **198**, 291-306.

Yamahira, K. (1997) Proximate factors influencing spawning site specificity of the puffer fish *Takifugu niphobles. Mar. Ecol. Prog. Series.*, **147**,11-19.