Armoring of Estuarine Shorelines and Implications for Horseshoe Crabs on Developed Shorelines in Delaware Bay

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Introduction

Alteration of estuarine shores to increase their economic value is a long practiced tradition in the United States. On unconsolidated shorelines, these modifications can alter the physical form and response of beach as well as the ecosystem functions these environments provide. Recent attention in Delaware Bay has focused on natural and human-induced changes occurring to sandy landward-migrating barriers that front marsh systems. These changes are important for the American horseshoe crab (*Limulus polyphemus*) that annually spawn in the foreshores of these barriers.

Female horseshoe crabs dig nests in the swash zone at high water during spring tides (fig. 1) and deposit their eggs approximately 15–20 cm below the sand surface (Smith and others, 2002; Weber and Carter, 2009). The foreshore sediment matrix acts as an incubator for the eggs and tides and waves deliver oxygen and moisture. Eggs that remain in the sediment develop at a temperature-dependent rate (Weber and Carter, 2009). Eggs that are exhumed before developing become available to a variety of consumers, including migratory shorebirds (Castro and Myers, 1993; Botton and others, 1994). Spawning and subsequent egg development success is important to population viability for species under stress because of commercial demand. Horseshoe crab population growth rate is most sensitive to early life stage parameters including egg viability and development (Grady and Valiela, 2006; Sweka and others, 2007). Declines in the American horseshoe crab population in Delaware Bay from past harvest and foreshore modification for shore protection have raised concerns for the species and dependent species that consume excess crab eggs (Atlantic States Marine Fisheries Commission, 1998; Niles and others, 2009; Smith and others, 2009).

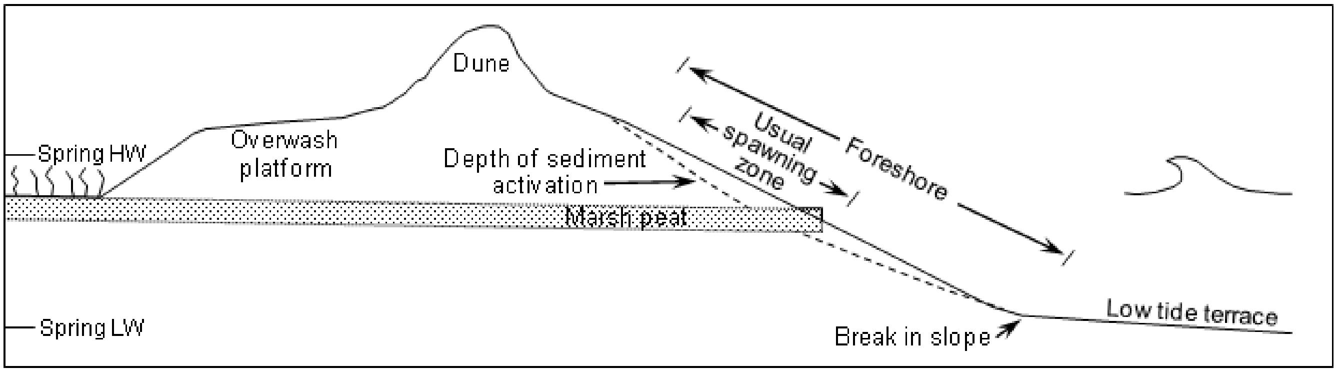

Figure 1. Schematic of an estuarine barrier transgressing over a marsh and exposing peat on the foreshore.

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The horseshoe crab is not the only species that lives in the aquatic environment but spawns on the intertidal foreshore. Several species of fish have evolved upper intertidal spawning behavior in ocean and estuarine environments (Martin and Swiderski, 2001, Martin and others, 2004). In Puget Sound, surf smelt (*Hypomesus pretiosus*) (Rice, 2006) spawn in the intertidal foreshore of beaches, and the abiotic stresses associated with shoreline modification may be similar to the stresses on the horseshoe crab in Delaware Bay.

This short review highlights some of the important links between foreshore dynamics and habitat suitability on developed shoreline reaches modified by shore protection projects in Delaware Bay with particular attention to the American horseshoe crab. For the horseshoe crab, the most important foreshore processes are related to episodic storms that affect cycles of erosion and accretion, swash and wave processes that affect sediment mixing and activation, and tides that affect infiltration and exfiltration of water through the sediment. Erosion of the foreshore during storms can result in either the removal of sediment from the upper foreshore and deposition on the lower foreshore or the horizontal landward displacement of the foreshore. The type of foreshore response to storms is a function of the orientation of the shoreline to the dominant waves. Erosion during storms can reach the depths of horseshoe crab nests and result in removal of the eggs from the foreshore. The higher the waves, the greater the depth of reworking of the foreshore sediments, which can lead to the exhumation of eggs to shallower depths in the foreshore where they may be more vulnerable to desiccation. Shore protection projects that employ bulkheads or beach nourishment can alter these processes and the suitability of the foreshore for spawning and subsequent egg development.

Horseshoe Crab Habitat on the Delaware Bay Shoreline

Delaware Bay is a drowned river valley estuary located on the mid-Atlantic coast of the United States (fig. 2*A*). Tides are semidiurnal, with a mean range of 1.6 m and a spring range of 1.9 m (National Oceanic and Atmospheric Administration, 2006). The shoreline where most horseshoe crab spawning occurs comprises unconsolidated sandy barriers fronting large marsh systems with sediment supplied by eroding low Holocene highlands (Kraft and others, 1979). The barriers initially formed where there was sufficient sediment supply and wave energy capable of reworking the sedimentary deposits (Knebel and others, 1988). The foreshores of these barriers are relatively steep (approximately 6°), consist of medium to coarse sands, and are approximately 8–12 m wide between the upper limit of swash at spring tides and the break in slope that demarcates the intersection with the offshore bay bottom or low tide terrace (fig. 1). The dominant energy reworking the shoreline is from waves generated within the bay although ocean swell is important in the lower reaches near the mouth of the estuary. Locally generated waves that break on the foreshore generally do not exceed 0.50 m in height and are of short period (< 4 s). The processes of most importance to spawning horseshoe crabs are the heights of the breaking waves, which determine the depth of sediment activation associated with wave breaking and the velocities of the uprush and backwash of the swash where horseshoe crabs spawn (fig. 1). Spawning horseshoe crabs favor conditions of low wave heights and swash velocities that increase spawning success and the likelihood of their eggs remaining in the beach matrix to develop.

The shoreline segments used most heavily by spawning horseshoe crabs are within the mid-region of the bay (Smith and others, 2002) and many are backed by human settlements that have altered the foreshores fronting them. Optimal spawning habitat is generally considered to be sandy foreshores without peat outcrops or hard protection structures (bulkheads) in the intertidal zone (Botton and others, 1988). The most recent baywide assessment estimated 24 percent of the shoreline was optimal for horseshoe crab spawning (Lathrop and Allen, 2005). Bulkheads were the most common form of shore protection on the east and west side of Delaware Bay (fig. 2*B*) until the 1960s when the state of Delaware began nourishing eroding beaches on the west side (fig. 2*C*). The state of New Jersey continues to favor bulkhead construction for shoreline protection, but encourages the use of beach nourishment where possible (Jackson and Nordstrom, 2009).

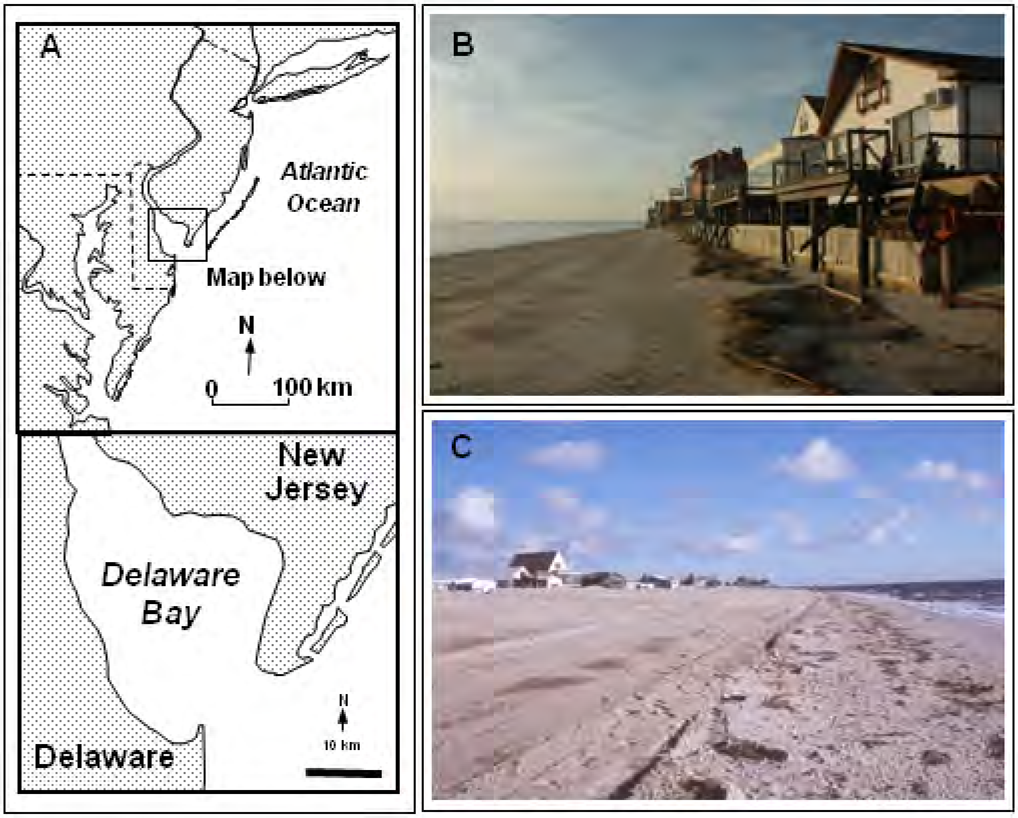

Figure 2. Locator maps (*A*), east side (*B*), and west side (*C*) of Delaware Bay.

Effects of Bulkheads on Sediment and Biota

Despite the prominence of bulkheads on estuarine shores, there have been few process-based studies of these structures. Studies of the effects of bulkheads on sediment and biota in estuaries are confined to changes in sediment characteristics, profile elevation, and species abundance fronting specific structures (Thom and others, 1994; Spalding and Jackson, 2001). Many inferences on the effects of bulkheads in estuaries are based on data for other vertical structures in ocean environments (Kraus, 1988, Kraus and McDougal, 1996; Miles and others, 1997), laboratory tests in wave tanks (Twu and Liao, 1999), purely conceptual arguments, or data that are commonly qualitative or anecdotal (Starkes, 2001). Research on the effects of shore parallel structures on open coasts has focused on the differences in waves, currents and beach change fronting structures and on adjacent beaches. The interaction of waves with the structure results in an increase in wave reflection and turbulence, nearshore current velocities, sediment activation, and longshore sediment transport at the base of the structure (Kraus, 1988; Plant and Griggs, 1992; Kraus and McDougal, 1996; Miles and others, 1997). Empirical field studies note the formation of scour pits immediately fronting shore-parallel structures after storms (Morton, 1988), causing a lowering of the profile (Birkemeier and others, 1991), narrowing of the beachface (Hall and Pilkey, 1991) and slower recovery of the profile after storms (Nakashima and Mossa, 1991). Support for these findings in estuaries remains uncertain without further assessment.

Bulkheads in Delaware Bay were built incrementally in the past, resulting in a complex planform configuration (fig. 3) with beaches of different widths isolated from each other by artificial headlands formed by short shore-perpendicular lengths of protective walls (Jackson and others, 2002). Bulkheads constructed at different elevations on the beach have potential advantages and disadvantages over both natural shorelines and long bulkheads built to a single design. On the positive side, beach enclaves remaining between bulkheads may have lower wave energies than their natural counterparts, increasing their suitability for horseshoe crab spawning. The shore-perpendicular ends of bulkheads can serve as traps for eggs transported alongshore in the swash zone.

Visual observation has documented use of areas near groins and jetties by shorebird populations for foraging in Delaware Bay (Botton and others, 1994). The

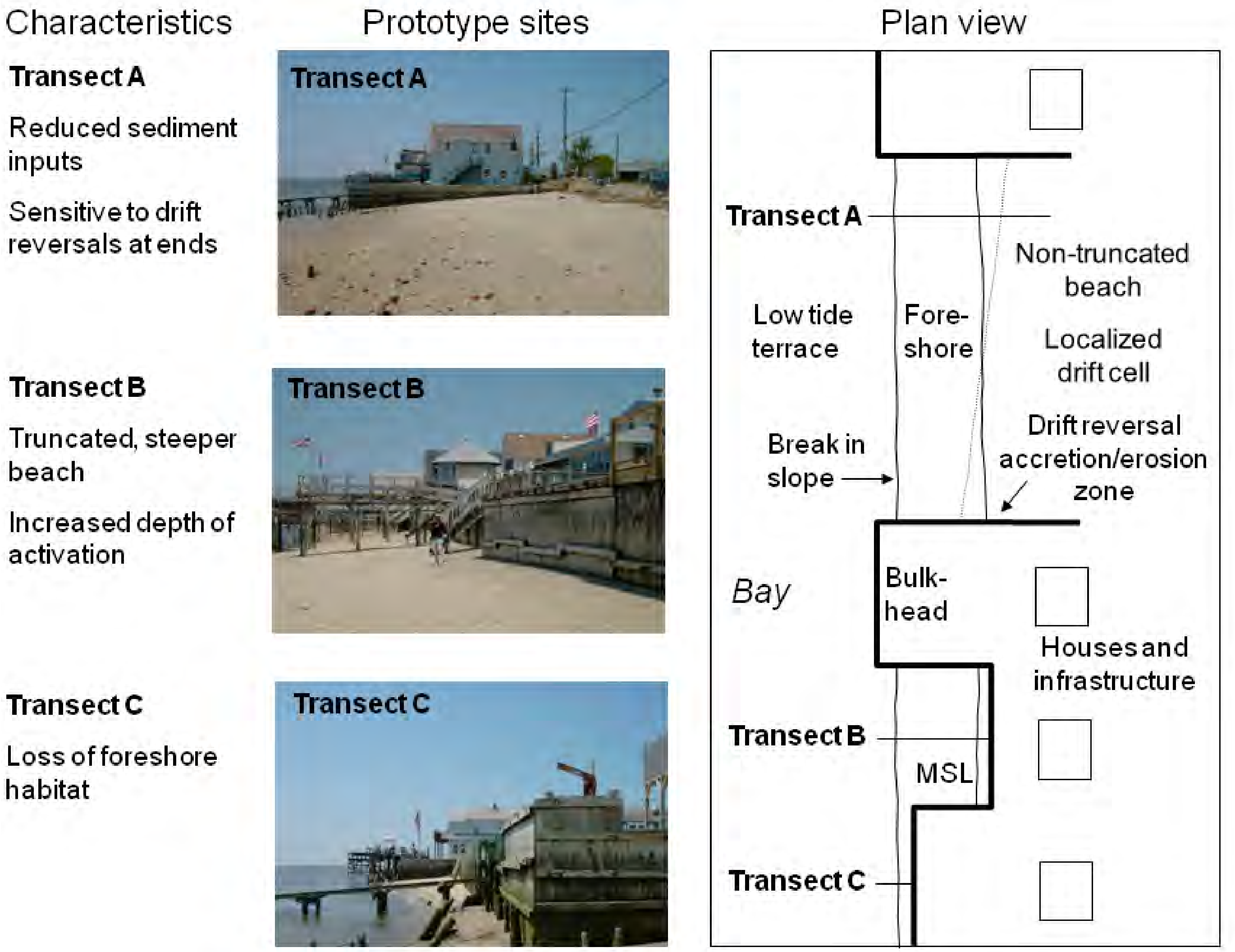

Figure 3. Complex platform configuration and differences in beach width resulting from incremental bulkhead construction.

shore-perpendicular ends of bulkheads help maintain sediment in the beach enclaves between them. Bulkheads built farther landward than adjacent bulkheads (setback bulkheads) allow for longer cross-shore gradients, and the structures are exposed to lower wave energies and can be built at smaller size and for less money (Zelo and Shipman, 2000). On the negative side, the shore-perpendicular ends of structures may restrict longshore transport of sediments and biota that would lead to exchanges between adjacent natural areas and bulkheads and between enclaves within bulkheaded segments. Local reversals of longshore transport within the confined beaches because of shifts in wind direction and wave approach can increase foreshore mobility near the ends of the compartments (fig. 3, Transect A), increasing the effect of local storm-related cycles of erosion and accretion (Nordstrom and Jackson, 1992). The resulting increase in sediment activation and transport near the ends of these enclaves could increase rates of egg exhumation beyond background levels. The sequence of changes seaward of a bulkhead progresses from truncation of the upper foreshore (fig. 3, Transect B) to eventual elimination of the foreshore (fig. 3, Transect C) over time. The elimination of the active foreshore leads to elimination of horseshoe crab habitat (Botton and others, 1988), but it is less clear what effect a bulkhead above mean water level has on horseshoe crab spawning or subsequent egg development (fig. 3, Transect B).

Bulkheads have the ability to alter wave-sediment interaction immediately bayward of them. For horseshoe crabs these changes can increase energy near the structure and may make it difficult for females to burrow into the foreshore or reduce the likelihood for their eggs to remain in the beach and develop. Bulkheads higher on the beach may affect only swash uprush/backwash processes at high water levels and affect horseshoe crab spawning during spring tides. At elevations that come under the effect of wave processes, sediment activation fronting a bulkhead may exceed activation depths relative to a beach not backed by a bulkhead. Preliminary unpublished results from a field investigation in Delaware Bay, in which differences in net bed elevation and sediment activation at bulkheaded and adjacent un-bulkheaded foreshores were compared, suggest that during periods of low wave energies ($H_s < 0.20$ m) the magnitude of sediment activation fronting bulkheads is not as great as the magnitude of activation due to bioturbation, suggesting that egg exhumation by processes immediately fronting bulkheads are not a threat to egg development. During periods of high wave energies ($H_s > 0.25$ m) ,the magnitude of sediment activation fronting a bulkhead is greater than at similar elevations on adjacent un-bulkheaded beach enclaves and depths reached by spawning horseshoe crabs. This effect is localized (within 3.0 m horizontal distance from the structure) but may include a high percentage of the spawning zone where the bulkhead truncates the upper foreshore and nests are concentrated near the structure.

Beach Nourishment as an Alternative Shoreline Protection Method and Effects on Horseshoe Crab Habitat

Beach nourishment can be used to protect human infrastructure and restore habitat (Nordstrom, 2005). Nourishment can be preferable to bulkhead construction for addressing erosion problems in estuaries because it restores the sediment budget on an eroding shoreline, but it can lead to changes in sedimentary characteristics and geometry of the beach profile, which in turn can affect both spawning and egg development. Nourishment used solely for shore protection creates a cross shore profile that is much wider and often higher than pre-nourishment conditions (Jackson and others, 2002). From an ecological perspective, the differences in geometry of the cross-shore profile may lead to changes in location of spawning activity, particularly when a scarp forms on the intertidal profile as a result of creation of an overly high backshore. Low wave energy conditions suppress reworking of fill sediments by in situ wave activation or erosion/accretion cycles. Sediment entrained by the combined effects of waves and bioturbation, and subsequently transported by currents, can lower the elevation of the foreshore profile, removing the previous wave-reworked veneer and increasing the likelihood that eggs will be laid in unreworked fill.

Matching sediment characteristics (size, sorting) of the fill with native sediment is important to ensure that sediment will remain on the active profile. Fill comprising sediment that is coarser than the native sediment can increase longevity of nourishment projects, but finer sediment may be more beneficial to development of horseshoe crab eggs. Egg development to embryo stage is affected most by temperature, and development to larval stage is affected by oxygen of the interstitial beach (Jackson and others, 2008). Desiccation can be a leading threat where moisture content of sediments is low (Penn and Brockman, 1994). Sediment size and sorting affects infiltration and exfiltration of water through the beach, which in turn, control temperature, moisture and oxygen conditions, and egg viability and development (Shuster, 1982). Sediment for nourishment operations in Delaware Bay have come from sources upland, offshore, or within the numerous creeks that dissect the shoreline. Comparison of textural properties of foreshore sediment on the eastern and western sides of Delaware Bay reveal that unnourished beaches have coarser grain sizes with a larger percent gravel fraction than nourished beaches (Jackson and others, 2005). Comparison of horseshoe crab egg viability and development on a coarser grained unnourished beach with a finer grained nourished beach reveal that viability is threatened in the upper foreshore of the unnourished beach where moisture retention is low (Jackson and others, 2007). These findings suggest that current nourishment practices in Delaware Bay, and use of sediment that is finer than native sediment, may favor horseshoe crab egg viability and subsequent development.

Conclusions

The challenge of providing habitat value for beaches is critically linked to the problem of finding suitable means of protecting human infrastructure from beach erosion and flooding as elucidated in the example of the horseshoe crab. There is great interest from federal, state, and private agencies in using shore protection projects to enhance habitat while still allowing and protecting human development, but knowledge of the interaction between beach and biological processes in estuaries is still rudimentary. Beach nourishment is likely to preserve habitat value better than bulkheading, but nourishment can decrease habitat value as well as enhance it, depending on morphology and sediment characteristics of the pre-nourished beach. The possibility of decreasing habitat value is of particular concern because the application of nourishment may be more widespread in the future.

Bulkheads can allow fronting beaches to function like adjacent beaches provided the structure intersects the intertidal foreshore above spring tide elevation. Over the long-term, the structure may have direct effects (foreshore elimination) or indirect effects (altering wave-sediment interaction) as erosion progresses and the structure intersects at progressively lower elevations on the profile. The shoreline will require future nourishment (and renourishment) to re-establish the intertidal habitat. Alternatives to constructing bulkheads such as using woody debris alone or in combination with beach sediment nourishment on eroding shorelines in Puget Sound seem promising for optimizing shore protection and habitat value. Precautionary measures, such as land acquisition by nongovernmental organizations and government agencies, may be effective in protecting biologically important areas in estuaries, but nourishment seems to offer the best way to restore beach habitat in the developed areas of Delaware Bay.

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