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Geomorphic – Biotic Interactions on Beach Foreshores In Estuaries

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ABSTRACT

This review of research on estuarine beaches in the USAexamines the linkages between geomorphology and biota and impacts of shore protection strategies. The effects of timing and frequency of storms, wave processes, and tidal range on morphologic response, sediment activation, infiltration and exfiltration of water through the foreshore, and litter distribution on the surface are evaluated along with the impacts of human adjustments, including bulkhead construction and beach nourishment. The effects of these factors on faunal activity are illustrated by evaluating the suitability of beaches as spawning areas for horseshoe crab egg production and the resulting effect on migratory shorebirds. Future research is recommended to: 1) time biological sampling to episodic storm events to evaluate impacts of habitat modification; 2) identify spatial differences in the dimensions of the low tide terrace that control the dynamics and biological functions on the foreshore above it; 3) design biological sampling plans according to geomorphic process regimes rather than static morphologic features on the beach; 4) standardize sampling locations to facilitate comparison among different sites; 5) conduct simultaneous studies of sediment activation by waves and by fauna; 6) determine the role of litter on faunal community structure and function; 7) conduct detailed physical and biological studies at bulkheads to determine the significance of position on the intertidal profile; and 8) determine the significance of nourishing a beach with fill material significantly different from native materials.

ADDITIONALINDEXWORDS: *beach nourishment, bulkheads, horseshoe crabs, geomorphology, Delaware Bay, Puget Sound, shore protection*

INTRODUCTION

Beaches in estuaries have value as habitat (BOTTON and LOVELAND, 1989; THOM *et al*., 1994; BURGER, *et al*, 1997; SPALDING and JACKSON, 2001) but have not been a high priority area of concern, even in units of the U.S. National Estuarine Research Reserve system (CALIFORNIA DEPARTMENT OF PARKS AND RECREATION, 1996). Greater attention is placed on bay bottoms and marshes than the beaches that often separate these two environments (NORDSTROM, 1992). Literature on linkages between beach morphodynamics and ecological systems have focused on exposed ocean beach and nearshore systems (MCLACHLAN, 1983; SHORT, 1996) but not estuarine systems. Where ecological research has been conducted on estuarine beaches, the interrelationships between species and dynamic environments are rarely specified. Authors often do not distinguish between the upper foreshore and low tide terrace, grouping all intertidal species together (RIVAS and CENDRERO, 1991). The different sub-environments of the beach are characterized by different energy levels, rates of transport and sediment characteristics, making it difficult to specify cause-effect relationships among morphodynamic and biological processes.

There is a growing interest in the status of beaches in estuaries where biota are being threatened by beach loss. For example, interest in Delaware Bay beaches focuses on horseshoe crab egg production and the nutritional dependence of migratory shorebird populations on horseshoe crab eggs as well as the value of intertidal beaches as feeding areas for the prey of commercially valuable fish (SULLIVAN, 1994; DOVE and NYMAN, 1995). Interest in Puget Sound beaches focuses on the effects of shoreline armoring on habitat value for certain species of fish (MACDONALD *et al*., 1994; THOM *et al*., 1994).

The purpose of this paper is to identify what is known about the linkages between geomorphology and biota on

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estuarine beaches and suggest areas for future inquiry, primarily using examples based on research in Delaware Bay, USA. We focus our analysis on the active foreshore above the low tide terrace (tidal flat) where wave and swash processes are the dominant agents of geomorphic change.

MORPHOLOGIC AND SEDIMENTOLOGIC CHANGES

Estuarine Foreshore Characteristics

Estuarine beaches are found fronting bluffs and marshes and on the bayside of barriers and spits (Fig. 1). They are characterized by a steep foreshore, with little microtopographic variation, and a broad flat low tide terrace (NORDSTROM, 1992). Foreshore sediments reflect both provenance and wave energy level. The greatest variation in grain-size characteristics occur where erosion of coastal bluffs delivers sediment of many sizes (Fig. 1A). Very-fine sand and fine-grained silts and clays are winnowed from the beach; coarser sands and gravels (pebbles, cobbles and boulders) are incorporated into the beach matrix. Only sand and the finer sizes of the gravel will be part of the mobile layer of sediments on the foreshore. Large cobbles and boulders form an immobile layer under the sand that accumulates on the upper beach or are stranded on the lower foreshore and low tide terrace as the shoreline migrates landward. The more stable substrate provides habitat for species not found in the sandy upper foreshore (THOM *et al*., 1994). Bluff materials under the beach that are below the depth of sediment reworking will form a wave cut terrace and retain characteristics similar to bluff materials.

Sediments that make up estuarine barriers (Fig. 1B) may be delivered from updrift or eroded from landward portions of the transgressing barrier and are usually composed of sand and pebbles. Barriers transgress marshes through a process of overwash and dune building analogous to barrier island migration but at a smaller scale. These beaches may have outcrops of marsh peat on the bayward side that are more resistant to wave erosion and less permeable beach sands above them, enhancing seaward flow from the beach water table.

Interpretation of biological value of estuarine beaches requires knowledge of the timing, rate, and scale of foreshore adjustment to wave energy, related to episodic storms (PHILLIPS, 1999), sediment activation and mixing (JACKSON and NORDSTROM, 1993; SHERMAN, *et al*., 1994), and infiltration and exfiltration of water through the foreshore (JACKSON *et al*., 1999). The vulnerability of estuarine beaches to episodic storms varies over short distances due to shoreline configuration (PHILLIPS, 1986), alongshore pattern of sediment composition (ROSEN, 1980), variations in nearshore topography and tidal range (ROSEN, 1977), and distance from the mouth of the estuary (JACKSON, 1995). Erosion and accretion is related to the

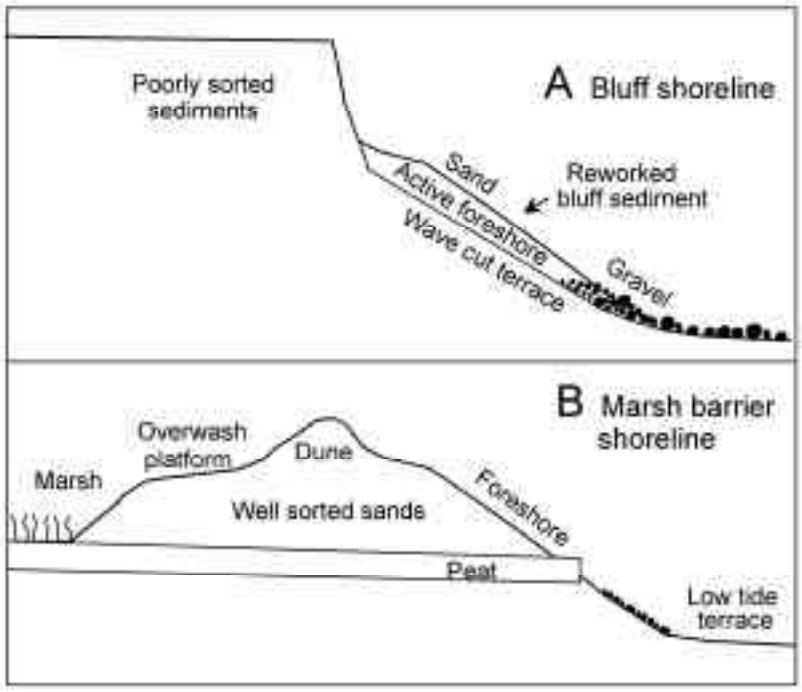


Figure 1. Common types of estuarine shores. The high relief (bluff) shoreline (A) is found in glaciated estuaries. The low relief (barrier) shoreline (B) is found fronting marshes in drowned-river valley estuaries.

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magnitude of wave energy, but event timing and sequence also influence the degree of morphologic change (PHILLIPS, 1999). BOTTON *et al.* (1992) observed that trilobite larvae of horseshoe crabs can overwinter on Delaware Bay beaches, emphasizing the biological importance of beach processes throughout the year, but April to September are the most important months for beach utilization by biota for reproduction, foraging or growth. Analysis of daily 3-hr averaged wind speeds for a four year period (1997-1999) from Delaware Bay (NOAA, 1997, 1998, 1999, 2000) reveals the likelihood for storm waves to be generated within the basin on the west and east facing beaches. The average number of days when wind speeds greater than 8.0 m s^{-1} occur decreases from March (11.25) to April (8.0) and May (6.25). In May, there were 3 events lasting 1 day each in 2000 and 5 events lasting 2 to 4 days in 1997. Late May is when migratory shorebirds stop over in Delaware Bay, where horseshoe crab eggs compose an overwhelming fraction of the shorebird diet (TSIPOURA and BURGER, 1999). Wind-generated waves may suppress horseshoe crab spawning because of increased risk of stranding-induced mortality (BOTTON and LOVELAND, 1989; SMITH *et al*., 2002) but certain low-energy beaches seem to be resistant to wave reworking during moderate onshore winds, perhaps due to wave attenuating properties of a high or wide low tide terrace. The refuge provided by these beaches might be critical to shorebird reproduction during years when wind-generated waves suppress horseshoe crab spawning on more energetic foreshores prior to or during shorebird stopover.

Foreshore Adjustment

Beach profile response may differ on sandy beaches due to differences in the dominance of longshore or cross-shore sediment transport (NORDSTROM and JACKSON, 1992). Erosion of the upper foreshore with deposition on the lower foreshore (Fig. 2, Type A) occurs where shoreline orientation is near perpendicular to the dominant high velocity winds or where sediment supply from updrift is adequate. Net change can result in removal of up to 0.84 m 3 m-1 of sediment and up to 0.26 m of vertical net change (JACKSON, 1999). The second response (Fig. 2, Type B) results in foreshore retreat with less conspicuous change in slope and occurs where shoreline orientation is at an angle to the dominant high-velocity winds or where little sediment enters from updrift sources.

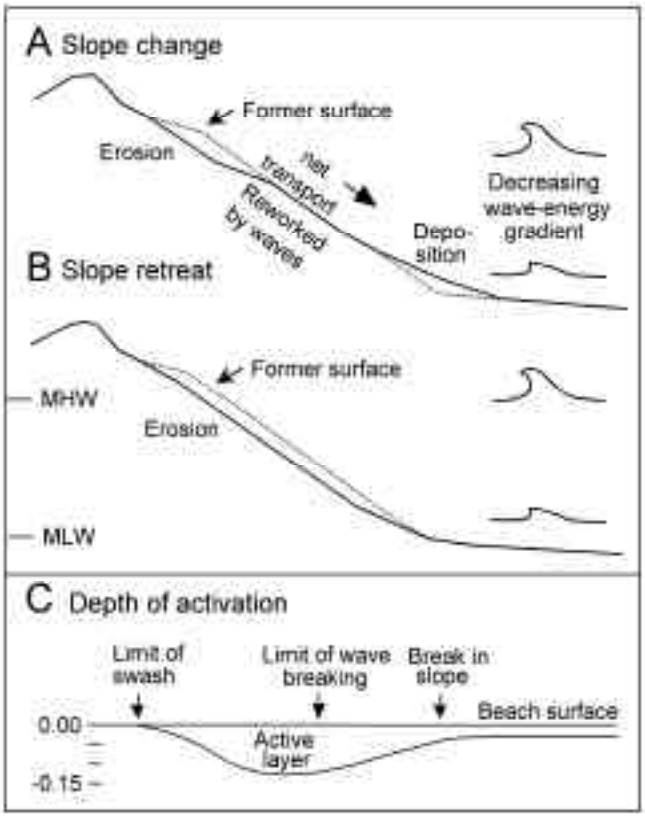


Figure 2. Morphologic change on the foreshore of a sandy beach (Aand B) in response to erosion from high energy waves (NORDSTROM and JACKSON, 1992) and depth of sediment activation on the profile of a beach having undergone adjustment to a previous storm (C) associated with wave heights of 0.50 m and periods of 4.6 s (JACKSON and NORDSTROM, 1993).

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Offshore transport of sediment from the foreshore is limited due to the cross-shore wave energy gradient that is controlled by both the elevation of the low tide terrace and the tidal range. At low tide, spilling waves break across the gently-sloping low tide terrace, dissipating their energy and limiting the distance sediment removed from the upper foreshore is transported. Waves break on the upper foreshore at higher water levels, primarily as plunging waves, concentrating their energy on the upper beach. Variations in elevation of the low tide terrace reduce or enhance the likelihood of erosion and habitat modification on the upper foreshore. Studies suggest a relationship between terrace elevation and horseshoe crab spawning on the foreshore, with little spawning activity on sandy beaches that had a low tide terrace at low elevation (BOTTON *et al*., 1988) and greatest spawning activity on steep, narrow beaches fronted by a prominent low tide terrace (SMITH *et al*; in review). A linkage between population fitness and wave energy is the hypothesized mechanism for selection of low-energy beaches. Increased wave energy might cause an increase in mortality induced by swash stranding among adults and a decrease in fecundity due to erosion of eggs. Thus, horseshoe crabs that can identify low-energy beaches, perhaps by physical cues at the bayward edge of the low tide terrace, would be favored. The role of the low tide terrace in the suitability of beaches as spawning areas has not been examined in sufficient detail to determine whether it acts as a direct control on horseshoe crab mobility and migration to the foreshore or as an indirect control in dissipating wave energy.

Interactions between beach characteristics and biological distributions need to be considered when designing biological surveys. The cross-shore distribution of egg-laying activity is a function of tidal amplitude. Crabs spawn in a narrow band on the upper foreshore where tidal range is 1.0 m but spawn in a broad band centered on mid-foreshore in tidal ranges of 2 to 3 m (SHUSTER, 1982). SHUSTER and BOTTON (1985) report no egg clutches in the lower foreshore and a maximum number of clutches on the upper foreshore 1.0 m bayward of the upper swash limit in Delaware Bay, where tidal range is about 2 m. Width of the cross-shore distribution of horseshoe crab eggs seems to vary inversely to foreshore slope because the elevation of high water on successive high tides (where egg laying occurs) falls across a wider swath of the foreshore on low sloped beaches (SMITH *et al*., in review). Consequently the area where horseshoe crab eggs are sampled must be proportional to foreshore width rather than set at a constant dimension for all beaches.

Sediment Activation and Mixing

Depth of sediment activation across a steep sandy foreshore reveals a uni-modal distribution (JACKSON and NORDSTROM, 1993; SHERMAN *et al*., 1994) with the greatest activation depths just landward of wave breaking at high water (Fig. 2C). Sediment activation is important to understand the role of waves in disturbing interstitial horseshoe crab eggs and meiofauna. Horseshoe crabs deposit their eggs 10 – 15 cm below the sediment surface and out of reach of shorebirds (BOTTON *et al*., 1994; LOVELAND *et al*., 1996). Exhumation and release of eggs to shorebirds can occur by burrowing of spawning females (MYERS, 1986; LOVELAND *et al*., 1996; BERKSON and SHUSTER, 1999) or waves, but the quantitative contribution of the two mechanisms is unknown. Eggs buried at depth will not be exhumed by most non-storm waves unless burrowing of spawning females displaces the eggs upward in the sediment column (PENN and BROCKMAN, 1994). Under low wave heights and in the absence of bioturbation, depth of activation will be < 0.03 m and exhumation of eggs by waves will be confined to the top few centimeters. A high energy event (breaking wave heights of 40 cm) can result in activation depths of 0.08 m (JACKSON, 1999) and combined with erosion of sediment from the upper foreshore releases a greater number of eggs.

Meiofauna spend their life cycle within the sedimentary environment (LEE *et al*., 2001) and their resilience to changes in sediment erosion and deposition is important. The abundance of meiofauna in the beach matrix is a function of wave, sediment, and tide interactions as well as chemical and physical characteristics of the water (i.e. temperature and salinity) (GIERE, 1993). Sediment disturbance will affect infaunal communities if the depth of activation is greater than the depth to which organisms reside or if the activation occurs faster than organisms can move to refuge (KRAEUTER and FEGLEY, 1994). The highest densities of meiofauna are within 0.02 m of the sand surface (HIGGINS and THEIL, 1988). Wave disturbance of the upper layers of the sediment matrix can result in migration of individuals to greater depths. SPALDING and JACKSON (2001) found lower densities in the top 0.03 m of the sediment compared to lower 0.07 m. The lower densities were attributed to activation depths of 0.04 m and subsequent migration of the meiofauna.

Surface Characteristics

Beach litter may be present on predominantly sandy beaches and is usually most conspicuous after low-energy waves rework a beach. Cross-shore differences in concentrations of litter occur in response to changes in the wave energy gradient that is a function of water level (Fig. 3). Plant litter from benthic algae, sea grasses and salt marsh vegetation is suspended in the active breakers and swash on

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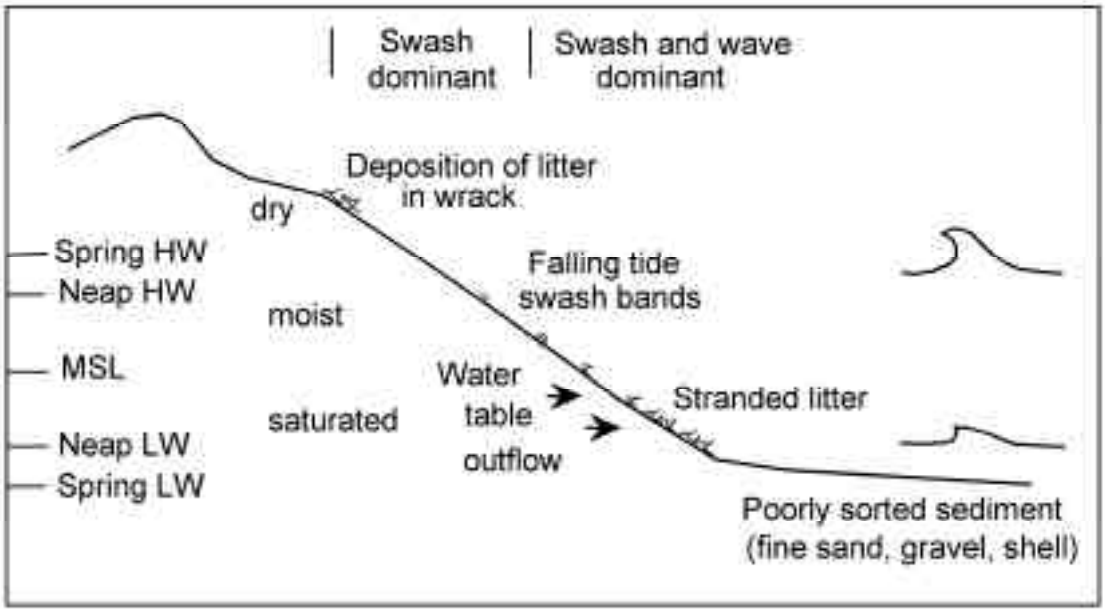


Figure 3. Variation in tidal elevation; swash and wave action; sediment moisture; and, gravel and litter accumulation across the foreshore of a sandy estuarine beach.

the higher portion of the beach and remains in suspension until deposited at the upper limit of wave uprush. The largest concentration of litter accumulates at the upper limit of swash during the long still-stand in water level at high water, forming the wrack line. Smaller bands of litter accumulate at the upper limits of individual swash uprushes during the falling tide. The reduction in turbulence associated with low wave and swash energies at low stages of the tide allows more litter to fall out of suspension and accumulate at low elevations.

Plant litter can be so abundant in some estuaries, and wave energies so low, that it completely covers the sandy beach. Although plant litter is an important source of organic material for intertidal communities, abundant plant litter can decrease habitat value. For example, extensive mats of litter that accumulate on the foreshore of Delaware Bay beaches interfere with horseshoe crab burrowing and can trap spawning crabs leading to increased incidence of stranding-induced mortality.

The wrack creates an energetic link between marine and terrestrial systems (PENNINGS *et al.*, 2000). It is inhabited by numerous amphipods and insects (JOSSELYN and MATHIESON, 1980) and is a popular foraging area for upland species. At high stages of the tide, birds follow the line of detritus left by each wave (BOTTON, 1982), although peak foraging activity appears to be at low tide (US ARMY CORPS OF ENGINEERS, SEATTLE, 1989; NORDSTROM, 1992; BURGER *et al.*, 1997). Litter lower on the beach traps horseshoe crab eggs, making them available for feeding birds. Decomposition of beach litter may allow also for slow release of particulate and dissolved organic material that can leach into the water column for use by bacteria and phytoplankton (NORDSTROM, 1992). In spring and early summer, stranded horseshoe crabs represent a large fraction of the wrack and a major input to the intertidal food web on Delaware Bay beaches (BOTTON and LOVELAND, 1989).

Infiltration and Exfiltration of Water through the Foreshore

Movement of water through the beach matrix with the rise and the fall of the tide affects use of the foreshore and viability of species by influencing erosion and deposition and flushing of oxygen and organic material (MCLACHLAN and TURNER, 1994). There is a growing literature on the mechanics of the beach water table (NEILSEN, 1990; TURNER, 1993; BAIRD *et al.*, 1998). SHUSTER (1982) suggests that crab egg viability depends on temperature, moisture and oxygen gradients across the foreshore. Moisture content on sandy estuarine beaches increases with distance offshore and densities of meiofauna decrease (SPALDING and JACKSON, 2001). PENN and BROCKMAN (1994) found that horseshoe crab egg development was lower on the lower foreshore where moisture and lower interstitial oxygen reduced development and on the upper foreshore where low moisture caused eggs to desiccate.

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Horseshoe crabs seem to spawn in reduced numbers on beaches where the depth of sediment is limited by underlying peat formations (Fig. 1B), and the eggs are buried closer to the sand surface. BOTTON *et al*. (1988) measured redox potential in a sand beach and a similar beach overlying a peat deposit. The sand beach without the peat had oxidized sediments to a depth of 0.29 m across the foreshore, and horseshoe crab eggs were found across an 8.0 m width on the upper foreshore and at depths > 0.10 m. On the beach underlain by peat, oxidized sediments were found at depths ranging from 0.10 to 0.20 m but confined to the upper foreshore. Horseshoe crab eggs were found across a 4.0 m band and at depths < 0.10 m where they can readily be reworked by moderate wave energy conditions.

Infiltration and exfiltration of water is important for survival of species living in the beach matrix. The movement of the water table over the tidal cycle is influenced by physical parameters (beach geometry, sediment size, sorting and porosity), tidal elevation, and wave setup and runup. Sediment size, sorting and shape influence porosity and permeability and have been related to species density and diversity (WEISER, 1959; JANSSON, 1967; HOCKIN, 1982; MCLACHLAN and TURNER, 1994). Medium to coarse sands are the dominant fraction on many sandy estuarine barriers, and they are well sorted in the mid to upper foreshore. Natural estuarine beaches will be well drained down to the elevation of the wave cut platform or peat formation (Fig. 1). BOTTON *et al*. (1988) speculate that the beach water table may offer a potential explanation for why reduced spawning activity is observed on sandy foreshores containing peat formations. The water passing over the peat layer is depleted of oxygen and enriched with hydrogen sulfide before discharge to the bay on the falling tide. Horseshoe crabs may be capable of detecting the hydrogen sulfide and avoid these areas during spawning.

There is a time lag in water table response to tidal fluctuations associated with the hydraulic conductivity of the beach sediments (NIELSEN, 1990). JACKSON *et al*. (1999) found that the tidal elevation fall was twice as fast as the fall in the elevation of the beach water table. Water table outflow plays a role in the distribution of biological detritus after the swash zone has migrated seaward. Shorebirds prefer to feed in wet sand and mud (CLARK and GELVIN-INNVAER, 1995) and often forage on the lower foreshore near the water table outcrop at lower stages of the tide.

EFFECTS OF SHORE PROTECTION METHODS

Human actions impact estuarine shores in myriad ways. This review examines only shore protection measures that threaten recreational resources and productive habitat. Bulkheads and beach nourishment are examined in detail because these methods now are the leading options in estuaries.

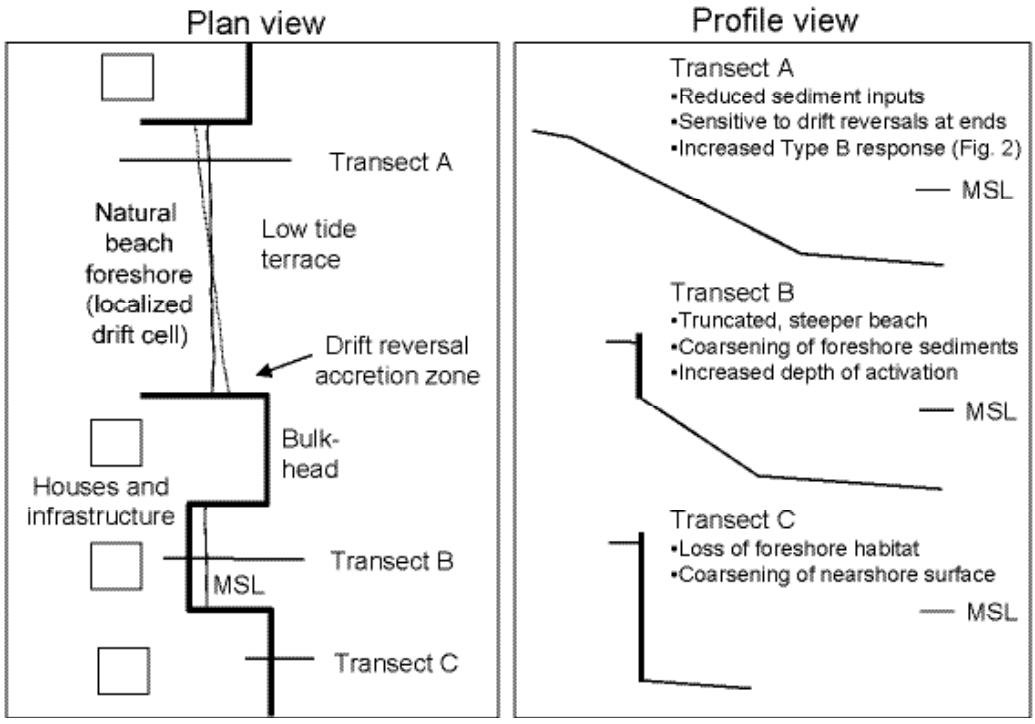


Figure 4. Effect of bulkheads on an estuarine shore.

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Bulkheads

Bulkheads are vertical structures designed to hold land in place while protecting against erosion from low-energy waves and swash. They are the most common erosion control measure in estuaries, and their lengths are increasing through time (CANNING and SHIPMAN, 1993; DOUGLASS and PICKEL 1999). Construction of bulkheads on private properties is often incremental, and structures built at a later time are often farther landward than structures built earlier. Bulkheads located farther bayward can act as barriers to longshore transport of sediment (SHIPMAN and CANNING, 1993). Shorelines protected by bulkheads often have a complex configuration with beaches of different widths isolated from each other by artificial headlands formed by short lengths of protective walls (Fig. 4). The closed drift segments help maintain sediment in these beach enclaves but the structures restrict longshore transport of sediments and biota. Local reversals of longshore transport within the confined beaches can increase foreshore mobility near the ends of the segments (Fig. 4, Transect A), contributing to cycles of beach change (Type B response, Fig. 2). Progressive loss of sediment bayward of a bulkhead will cause the structure to intersect the beach at a lower elevation on the profile through time. The interaction of waves with the structure results in an increase in wave reflection and turbulence, nearshore current velocities, and sediment activation and transport at the base of the structure (KRAUS, 1988; KRAUS and MCDOUGAL, 1996; MILES *et al*., 1997). Changes in infiltration and exfiltration of water through the beach due to the presence of the structure below the sand surface can result in changes in moisture content of sediments (PLANT and GRIGGS, 1992). These conditions can lead to coarsening of beach foreshore sediments, increased scour and steepening of the foreshore slope, reducing the suitability of these areas as habitat (THOM *et al*., 1994). The sequence of changes seaward of a bulkhead progresses from truncation of the upper foreshore (Transect B, Fig. 4) to elimination of the foreshore (Transect C, Fig. 4) (THOM *et al.* 1994). A significant conclusion of many studies of impacts of shore armoring is that the level of physical impacts increases significantly as armoring is placed successively seaward of high water (MACDONALD *et al*., 1994).

There are few process-based studies of bulkheads, and many inferences are based on structures in freshwater and marsh environments or conceptual arguments. Data are often qualitative or anecdotal (STARKES, 2001), and it is not possible to quantitatively predict the effects of shoreline armoring on the ecology of beaches and the biological resources they support (THOM *et al*., 1994). THOM *et al*., (1994) recommend systematic studies of existing sites; experimental studies to evaluate new or unique technologies; and development of models to assess cumulative impacts.

Elimination of horseshoe crab spawning areas by bulkheads low on the intertidal profile has been noted (BOTTON *et al.*, 1988; DOVE and NYMAN, 1995), but the effect of bulkheads higher on the profile has not been examined. Little is known about the effect of bulkheads on meiofauna. General zonation models link cross-shore meiofaunal density to oxygen and moisture content of the beach, but these models are sensitive to local conditions (FIELD and GRIFFITHS, 1990; MCLACHLAN and TURNER, 1994). SPALDING and JACKSON (2001) found significant differences in meiofaunal density at a site fronting a bulkhead compared to an unaltered site. Increased energy at the base of the bulkhead resulted in the transport of meiofauna with eroded sediments. THOM *et al*. (1994) suggests that habitat function fronting bulkheads may change and new species will dominate as sediment composition changes to coarser sizes.

Beach nourishment

Nourishment operations in estuaries have been designed to increase dimensions of existing beaches for extra protection; create or increase wildlife habitat; provide cosmetic surfaces for recreation platforms; or restore recreational beaches and revive the vitality of resorts (NORDSTROM 1992). Past nourishment operations had greatest value in urban areas where beaches are needed for both recreation and protection (NORDSTROM, 1992), but there is increasing interest in creating beaches as wildlife habitat where armoring has eliminated the upper beach (STARKES, 2001) or where hard clay substratum or marsh peat have been uncovered by erosion. Beaches have also become opportunistic disposal sites for sediments made available in dredging projects.

Studies from ocean shorelines indicate that there can be minimal biological effects of beach nourishment where projects are properly designed (NELSON 1993). Nourishment is normally considered environmentally-compatible, but it can result in differences in beach slope and sediment characteristics from pre-nourishment conditions and cause loss of bay-bottom habitat as the backbeach and foreshore are extended seaward. Short-term losses can occur due to turbidity and burial of organisms on the pre-nourished beach. Juvenile horseshoe crabs inhabit the low tide terrace (RUDLOE, 1981), and burial by sediments eroding from a nourished foreshore have not been studied. Our concern in this paper is change in the conditions of the active foreshore, where the most critical factor affecting beach change and habitat value in the long term is the grain size characteristics of the fill.

Conspicuous differences in the form and mobility of estuarine beaches can occur with subtle differences in grain

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size characteristics. Finer grain size of fill sediment can lead to flattening of foreshore slope, burial of surface gravel, increase in aeolian transport landward of the beach, and increase in mobility of the profile, (with more frequent episodes of burial of the inner low tide terrace in the erosional phase of storm cycles). A wider, flatter beach with well sorted sand and lack of surface gravel is more attractive for recreation, but these changes have unknown biological impacts.

Finer-grained sediments (silts, clays) in beach fill are often considered a problem because of increased turbidity during placement, but these sediments also will affect biota and the structure of habitats after they settle and are incorporated into the beach matrix. A significant proportion of fine-grained materials will create different moisture-retention characteristics and, if they settle as layers, may create substrate more resistant to waves and burrowing by organisms. The hydraulic conductivity in the beach may decrease, causing lower rates of water table discharge. Resistant layers may cause ponding of surface water on the backshore (WRIGHT and BUTLER 1984), and the increased surface runoff may create gullies in the beach (NORDSTROM 1992).

Fine-grained sediments in the active wave and swash zones are reworked from the fill deposits and removed, and sediments in the active layer may become similar to native beach materials. However, the depth of reworking by estuarine waves is limited, resulting in a wave-cut terrace in fill deposits that may be closer to the surface than the depth reached by burrowing organisms. Data form Delaware Bay, presented earlier, indicate that the depth that horseshoe crabs deposit their eggs would be greater than the active layer on an eroding nourished beach.

Gravel is used as fill where natural beaches are coarse-grained (SHIPMAN, 2001), and it can be used to enhance longevity of fill where grain sizes are coarser than the equilibrium size for the wave climate (JOHNSON and BAUER, 1987). Coarser grain sizes may increase the cost effectiveness of fill operations designed for shore protection, but size, shape and sorting characteristics of gravel affect mobility, and there is a difference in kinds of habitat and value of habitat associated with the different types of gravel used in nourishment operations (WILLIAMS and THOM, 2001). The most productive and diverse portions of the beaches in Puget Sound appear to be in mixed sand, gravel, mussel bed and boulder substrate rather than sand (ARMSTRONG *et al*., 1976), but the optimum condition would be difficult to achieve in most nourishment operations. Sand is readily transported and reworked and is likely to be favored for recreational use, particularly where it is well sorted, but may be undesirable where biota are adapted to a less mobile surface. Whether placed on a gravel or sand beach, use of fill material (including opportunistic sources from navigational dredging) that differs from native material must be carefully evaluated for impacts to biota.

FUTURE ASSESSMENT

This review of research on estuarine foreshores points to the need for collaborative efforts by biologists and gemorphologists to: determine the effect of episodic events; identify broad scale spatial controls on modification and use of the foreshore; identify the effect of wave and swash processes on biological density and diversity; differentiate between wave-induced and biota-induced changes to beach sediments; determine effects of shore protection measures on biological processes; and evaluate effects of changes in sediment characteristics of the beach due to nourishment operations. Suggestions for ways of integrating research include the following:

1. tie biological sampling programs to periods of morphological change caused by episodic events as well as periods of stability, so sampling is timed relative to habitat modification as well as habitat use;

2. determine how the low tide terrace acts as a direct control on migration of fauna to the foreshore and as an indirect control in dissipating wave energy and influencing morphologic change;

3. measure biological variables relative to specific geomorphic process regimes and sediment characteristics rather than arbitrary distances from beach features such as the break in slope or mean high water line;

4. non-dimensionalize cross-shore location by the width of the active profile to allow for better comparison of results from sites where foreshore dimensions differ;

5. conduct simultaneous studies of depth of sediment activation by waves and by organisms;

6. determine the role of litter on faunal community structure and functioning and how the role of litter is affected by protection structures;

7. sample physical and biological processes and characteristics at bulkheads to determine the significance of location of the structure on the intertidal profile;

8. determine the dimensions, sediment characteristics and hydrodynamic properties of the wave-reworked portion of beachfills and the impact on biota in comparison to the inactive layer below it; and,

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9. evaluate the impact of nourishing a beach with material that has significantly different grain size characteristics from native materials.

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