Appendix C. Review of Shoreline Armoring Literature

Jill M. Coyle[1] and Megan N. Dethier[2]

Introduction

This document reviews existing literature that assesses the role of shoreline armoring in impacting nearshore processes. It began as a synthesis of background material for the Shoreline Armoring Working Group (SAW), an outgrowth of the Puget Sound Nearshore Ecosystem Restoration Project (PSNERP). PSNERP is a large-scale, ecosystem based restoration project focused on protecting and restoring the natural processes and functions of the Puget Sound basin. The literature review covers both peer reviewed and technical documentation on themes related to shoreline armoring and coastal stability, including ecology, geomorphology, and ocean engineering. Although numerous technical and scientific papers have been written on the issues of nearshore processes, armoring, coastal management, and Puget Sound beaches, few consider these issues together. The literature we assessed present varying degrees of relevance to the topic of shoreline armoring in the Puget Sound, but all are included in the bibliography.

Background Physical Setting and Geomorphology of Puget Sound

The Puget Sound is an active geological region, bordered by the Cascade Mountains to the east and the Olympics to the west. Tectonic activity is driven by the subduction of the Juan de Fuca plate under the North American plate. Puget Sound beaches are formed on wave-cut platforms set into the steep walls of marine basins, carved by the last glacial retreat approximately 16,000 years ago (Finlayson, 2006). The repeated advances and retreats of the Puget Lobe of the Cordilleran ice sheet left behind large mixed deposits of clays, silts, gravels, and boulders.

Steep cliffs border approximately 80 percent of the Earth's ocean coasts, occurring at all latitudes (Emery and Kuhn, 1982). Most Puget Sound estuarine beaches are backed by these landforms, creating coastal bluffs fronted by narrow mixed sand and gravel beaches (Shipman, 2004; Johannessen and MacLennan, 2007). These beaches generally are composed of a thin veneer of sediment overlying a flat eroded platform (Shipman, 1995). The main processes providing sediment to the shores of the Puget Sound are erosion and reworking of the sea cliffs. Sediment delivery from the bluff to the beach varies seasonally, annually, and with long-term changes in climate and water level (Meadows and others, 2005). It also varies with the rate of local shoreline recession or accretion (Finlayson, 2006). Bluff erosion is affected by weather, waves, steepness, bluff stratigraphy, abundance and type of vegetation present (Finlayson, 2006); erosion rates can vary from a fraction of an inch to over 2 ft/yr (Shipman, 2004). Small-scale bluff retreat associated with crumbling and sloughing is a relatively continuous process, while larger landslides are more episodic (Gerstel and others, 1997), adding large pulses of sediment to the system.

Waves in the Puget Sound are generated by local winds blowing over the glacially-formed fjords and are not influenced by Pacific Ocean swell conditions. Puget Sound waves, therefore, have limited fetch and low energy, and are linked strongly with local wind patterns. Wind direction is predominantly from the south or southwest in the winter and from the west or northwest in the summer, although local topography often controls wind direction. Winter winds are stronger, generated by more frequent, vigorous storms moving inland from the Pacific Ocean (Finlayson, 2006). Very little quantitative wave data are available for Puget Sound, but most sites are characterized by short period waves of low height. At one sampled site, the median significant wave height during a fall-spring period was 0.24 m, with a period of 2 seconds (Finlayson, 2006). Even storm waves are relatively small (<1 m), with short periods (<4 sec). Boat wakes provide an additional energy source to many beaches, especially in the calm summer months and in passages that are otherwise low-energy (Osborne, 2010).

In Puget Sound, tides are the second most important forcing mechanism shaping beaches after waves (Finlayson, 2006). Tides are mixed semidiurnal, with ranges varying from mesotidal (1.9 m) in the northern areas to macrotidal (4.4 m) in the south. High tides are nearly equal in range while low tides experience more variance. The twice-daily highs and lows move the swash zone across the beach profile, governing the amount of time each part of the beach is exposed to air and wind or wave processes, which in turn affects sediment erosion and transport. The greater the exposure to larger waves, the greater the sediment transport potential (Finlayson, 2006).

[1] University of Washington, Seattle, Washington.

[2] University of Washington, Biology Dept. and Friday Harbor Laboratories, Friday Harbor, Washington. 98250, mdethier@u.washington.edu.

A key process to understanding the effects of armoring on Puget Sound beaches is the local importance of net short-drift, or littoral cells. A littoral cell is a compartmentalized coastal sector that consists (ideally) of a sediment source (for example, an eroding bluff), a zone of transport where waves move sediment alongshore in a relatively predictable direction, and a terminus where sediment is deposited on the beach or carried into deeper water. Puget Sound has ~860 such cells, ranging in length from 15 m to over 30 km, with an average of about 2.5 km (Johannessen and MacLennan, 2007). There are also ca. 230 areas of no net shore-drift, for example, in enclosed embayments and on rocky shorelines. This large number of short drift cells, many of which have at least some of their sediment supply cut off by shoreline modifications (see below), creates a situation where cumulative impacts are likely substantial but difficult to document.

This physical setting of Puget Sound means that beaches are primarily of mixed sediment, as is typical of previously glaciated areas. Mixed-sediment beaches are under-represented in the scientific literature, other than for sedimentological investigations or studies of long-term geomorphological change (Mason and Coates, 2001; Buscombe and Masselink, 2006). Puget Sound's beaches differ from low-energy beaches elsewhere, most of which have smaller tidal ranges and are composed of finer-grained sediments (Hegge and others, 1996). The mixed sediment beaches of Puget Sound have high permeability, resulting in swash with an upward wash that may be faster or higher volume than the backwash, leading to an asymmetrical swash zone (Finlayson, 2006). Sediment of most sizes can be mobilized shoreward during the up-rush, where the heavier particles settle out and only finer grained sediments move seaward with the waves. This onshore migration of coarse material leads to a relatively steep beach profile. As a result of these processes, most beaches in Puget Sound are characterized by narrow, steep foreshores and low-gradient, 'low-tide' terraces. The break in slope generally correlates with a change in grain size from coarse materials higher on the beach to finer grained sands below the break (Finlayson, 2006). Therefore, Puget Sound beach profiles are steeper and have more pronounced concavity than most beaches in similar energy regimes (Finlayson, 2006).

Shoreline Development and Armoring

Rapidly increasing human populations and expanding urbanization and development are intensifying pressures on coastal systems worldwide (Clark, 1996). Sandy beaches are widely recognized as increasingly threatened by human uses of the coast (Brown and McLachlan, 2002; Schlacher and others, 2006, 2007; Defeo and others, 2009), and the same issues apply to estuarine shorelines like those in Puget Sound. Sea level rise and other predicted effects of climate change will place even more pressures on these ecosystems, exacerbating erosion, further degrading habitat, and increasing rates of shoreline retreat (Nordstrom, 2000; Slott and others, 2006). The dual pressures of increasing numbers of people living near the water and rising sea level will continue to reduce intertidal habitat (Douglass and Pickel, 1999). In the Puget Sound region, the majority of shoreline development is in the form of residential housing. In attempts to protect eroding properties, the typical reaction to coastal hazards is the construction of seawalls, bulkheads, revetments, or other hardened structures. Currently, approximately one third of the Puget Sound's shoreline is armored (Finlayson, 2006), creating a remarkable ~1,300 km of hardened shore including a nearly continuous 115 km of railway revetment (Johannessen and MacLennan, 2007). Seawalls are perceived as a secure form of coastal defense because they provide a physical and often substantial barrier between the land and the sea. The perception of increased security they elicit, however, needs to be balanced against the environmental problems that they may cause (El-Bisy, 2007). Seawall impacts may occur in front, at the ends, under, and behind the wall. All of these areas need to be considered in order to undertake a complete assessment of the tradeoffs of seawalls in coastal defense (French, 2001).

Generalizing about armoring impacts is very difficult because physical (morphological and hydrodynamic) responses depend on the setting: types of sediment, beach morphology, position in a drift cell, and local wave and current regimes. Armoring impacts may occur via combinations of at least five distinct mechanisms (detailed below and illustrated in fig. 1) that vary both in the length of time for impacts to occur post-construction, and in the degree to which the impacts have been demonstrated.

Encroachment, or 'placement loss' is the most obvious and immediate effect of shoreline modifications. With the exception of armoring built directly against the bluff, most modifications involve covering some portion of the upper beach, including the storm berm or dune, often with fill behind the structure. In Puget Sound, some armoring is built much further down on the shore, with extensive fill covering the upper and middle beach. Any encroachment leads to direct loss of habitat area for various biota (see Impacts on Nearshore Biology, below), and reduces the beach area where logs (large woody debris) and beach wrack accumulate. These losses, in turn, can prevent or slow the development of beach vegetation and dune habitats because of the reduction in organic input and stabilization of the substrate (Dugan and Hubbard, 2010), as well as the colonization of invertebrates (see below).

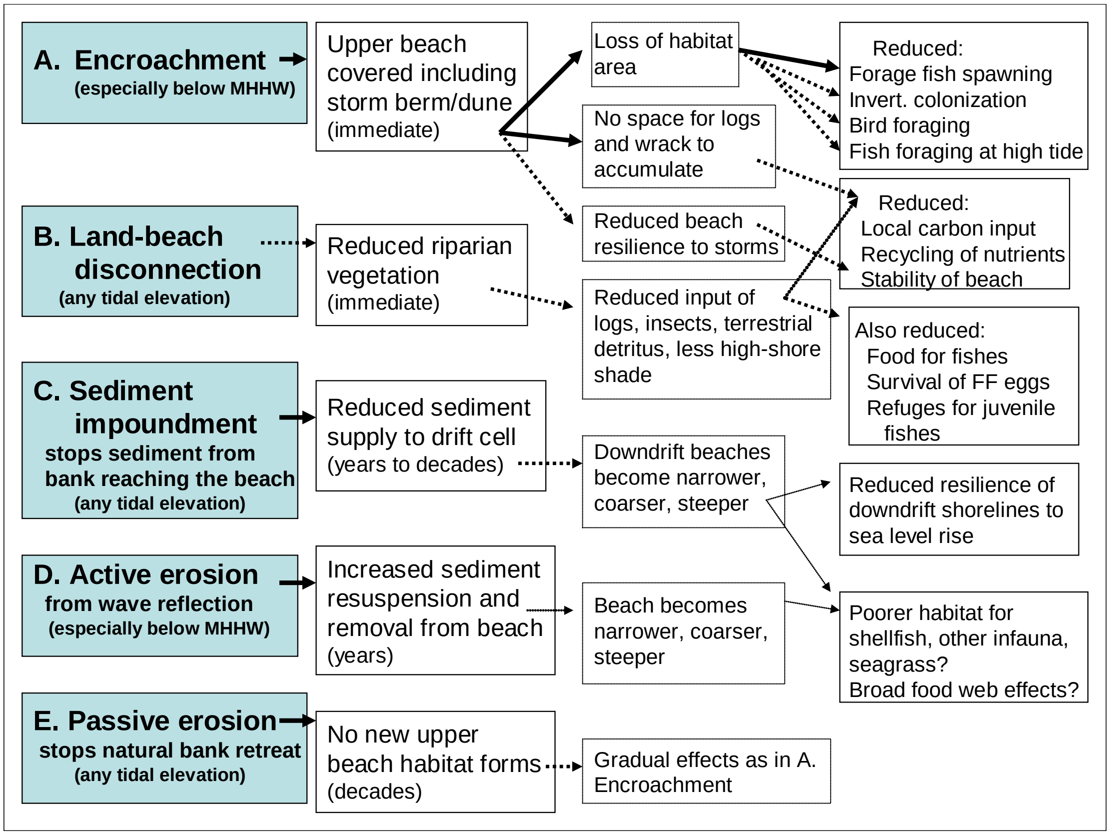

Figure 1. Five mechanisms by which armoring could alter shoreline processes and functions, and their ultimate impacts on nearshore biota. MHHW = mean higher high water. Linkages that are more certain (for Puget Sound) are shown with more solid arrows.

Land-beach disconnection can occur with armoring placed at any elevation on the shore. Most shoreline modifications are accompanied by loss of natural riparian vegetation, such as the overhanging or fallen trees that characterize unmodified shorelines in Puget Sound. These losses, and the lack of area for driftwood accumulation, reduce shade on the beach as well as the transfer of nutrients, carbon, insects, and other ecosystem elements between land and sea (see Nearshore Biology).

Sediment impoundment, where a shore-parallel structure such as a bulkhead or seawall prevents sediment eroding from the bluff onto the beach, occurs regardless of the elevation of the armoring (Pilkey and Wright, 1988). Its effects take longer to be realized than placement loss, especially if normal bluff erosion is slow or highly episodic. However, this loss of sediment supply to the local drift cell may be one of the most significant impacts to nearshore ecosystems, especially in terms of cumulative effects. In such sediment-starved areas, the system's ability to maintain down-drift beaches decreases; in some areas, beaches become thinner and narrower and bluff recession rates in adjacent unarmored areas increase (Shabica and Pranschke, 1994; Nairn and Parson, 1995; Nairn and Willis, 2002; Griggs, 2005). For example, Herrera Environmental Consultants, 2005) found that upper beach habitat area and overall beach width declined in front of armoring structures in Thurston County, Washington. Deficits in sediment supply also affect the ability of a beach to recover from erosive events, such as large storms (Morton, 1988). Structures built perpendicular to the shorelines, such as groins and jetties, impact coastal processes by obstructing sediment transport alongshore, causing sediment accumulation up-drift and erosion down-drift (Johannessen and MacLennan, 2007). These effects are initially local, but long-term permanent reductions in littoral sediment supplies may directly impact the entire downdrift shoreline reach (Meadows and others, 2005), depending on the size of the structure and the dynamics of the littoral cell.

Armoring structures, especially when placed below mean high water, may affect the shoreline by causing active erosion because of wave reflection. This possible acceleration of erosion is debated and continues to be a controversial subject (Griggs, 2005; Basco, 2006). Placement of a seawall on the beach may alter the hydrodynamic environment as the wall interacts with the waves, ultimately altering sediment transport and beach morphology. Griggs and others, 1994) collected seven years of data on open coast seawalls in Monterey Bay. Beach profiles were surveyed at armored sites, including impermeable vertical walls and more sloped, permeable revetments, and at adjacent unarmored sites. The long study period made it possible to distinguish normal seasonal variation from longer-term trends. During the seasonal transition from a summer to a winter beach, the natural berm was cut back preferentially in front of seawalls compared to at unarmored sites, and scour was observed downdrift of the structures. Reflection at the lateral ends of seawalls caused local erosion and arcuate indentations that extended from 50 to 150 m alongshore. Mechanisms causing such active erosion vary, and are undoubtedly site-dependent. One may involve elevation of groundwater level, which reduces percolation of swash and thus increases the velocity of backwash. This results in increased mobility of sediment in front of seawalls, and thus the overall lowering of the beach face (Plant and Griggs, 1990). Another mechanism involves increased sediment suspension and transport caused directly by wave reflection. Miles and others (2001) examined the effects of a seawall on hydrodynamics and sediment transport on sandy beaches in South Devon, UK. They found that under the experimental conditions, up to three times more sediment was held in suspension in front of the seawall than at an unarmored beach measured during similar wave conditions. On armored beaches, sediment concentration increased in shallower water and with increasing wave height. Wave reflection also significantly reduced onshore sediment transport by waves.

Spalding and Jackson (2001) carried out a 1-day field study at three armored sites on a sandy estuarine beach in Raritan Bay, N.J. to investigate hydrodynamics and sediment characteristics and their effects on species abundance. The sites varied in the types of bulkhead and how low each extended on the shore. Over one tidal cycle, the beach in front of the farthest seaward structure showed the greatest depth of sediment activation and net change in sand surface elevation. It also had the lowest meiofaunal density.

Several models (for example, Rakha and Kamphuis, 1997) and long-term studies (for example, Hearon and others, 1996; Basco and others, 1997), however, have not demonstrated measurable effects of armoring on active erosion or beach profiles, even over relatively long time periods. Clearly further research is needed to clarify under what conditions (type or elevation of armoring, type of sediment, sources of sediment, wave energy, etc.) and at what time scales these processes occur.

The prevention of passive erosion at modified shorelines is an effect that may take decades to become visible. Armoring, regardless of its elevation, halts the natural bank retreat that accompanies sea level rise or land subsidence. Because the bank or bluff cannot retreat, no new upper beach habitat forms. If the coastline is undergoing net long-term erosion, as is occurring rapidly on the Atlantic and Gulf coasts of the U.S., the previous landward recession of the shoreline will be converted to vertical erosion in front of a seawall; thus fixed seawalls contribute to the narrowing and eventual loss of intertidal zones in front of them (Griggs and others, 1994; Douglass and Pickel, 1999; Taylor and others, 2004). For example, aerial photographs of the shoreline of Oahu from 1928 or 1949 to 1995 show an island-wide narrowing and lowering of beaches in front of armoring structures (Fletcher and others, 1997). The lowering of beaches in front of coastal armoring structures can lead to severe unintended consequences, such as increased wave energy and attack, threatening structural stability and the eventual failure of man-made hardening structures, or the loss of recreational beach area (Lawrence and Chadwick, 2005). In Puget Sound, regardless of whether active erosion is occurring in front of the extensive armoring, as sea level rises there will be “coastal squeeze” when shoreline features are unable to move landward because of armoring, leading to gradual loss of the beach.

Extensive data show that for open-coast beaches, via a combination of these mechanisms, seawalls and revetments produce a measurable impact on the shoreline that extends for many times their length (for example, Komar, 1976; O’Brien and Johnson, 1980; Berek and Dean, 1982; Carter and others, 1986; Dean and Work, 1993; Shabica and Pranschke, 1994; Nairn and Parson, 1995; Parson and others, 1996; but see Hearon and others, 1996). This probably is true both for large and for smaller, privately maintained shore protection structures, although such physical impacts take time to manifest, making them difficult to quantify. Long-term impacts of armoring also depend on the amount of sediment that comes from bluffs versus other sources; without detailed sediment budgets, this assessment is difficult. A careful study of a seawall constructed on a sandy beach in Chile found few physical changes to the beach after 20 months (Jaramillo and others, 2002). However, studies from older armoring projects often show very clear impacts, including year-round loss of upper intertidal zones and narrowing of mid-intertidal zones of beaches in front of seawalls (for example, Dugan and Hubbard, 2006; Dugan and others, 2008). Griggs and Taitt (1988) examined four cliff-backed sites in Monterey Bay, California. The beaches were primarily wide and sandy, undergoing significant seasonal changes in width. Each beach had a protective structure installed at different locations on the beach face. Frequent surveys over the course of a year demonstrated negative impacts such as net erosion and increased scour even on beaches far from the armored sites.

The distance at which these impacts occurred was directly related to the length of the seawalls; longer walls produced more deleterious and wide-ranging alongshore effects (Griggs and Taitt, 1988; but see Basco and others, 1997; Basco, 2006, for contrasting data).

Impacts on Nearshore Biology

The Puget Sound Nearshore Ecosystem Restoration Project (PSNERP) defines the "nearshore" environment as, "the estuarine/delta, marine shoreline and areas of shallow water from the top of the coastal bank or bluffs to the water at a depth of about 10 meters relative to Mean Lower Low Water" (PSNERP, 2006). While the geomorphology and ecology of estuarine beaches have not attracted the same attention as marine shores, estuarine nearshore habitats are dynamic environments structured by the interactions of wind, wave action, tidal and current movements, sediment transport and chemical conditions (Carter and others, 1986). They often show higher primary and secondary productivity than either terrestrial or marine habitats (McLusky, 1989; Heip and others, 1995; Kennish, 2002). Despite their steep environmental gradients, estuarine nearshore areas are home to a high abundance and biomass of macrobenthic invertebrates, as a result of the high concentrations of organic matter and nutrients retained in the system. This secondary productivity leads to complex and distinctive food webs, and is crucial to the life cycle of many fish and wildlife species (Simenstad and Kinney, 1978; Kozloff, 1983; Simenstad, 1983; Phillips, 1984; Wolff, 1987; McLusky, 1989; Kruckeberg, 1991; Defeo and others, 2009).

Human alteration of nearshore habitats is extensive, including disturbance from construction activities, geomorphologic changes, hydrologic modifications, water quality reduction, and light level alteration (Williams and Thom, 2001). Human activities disrupt or eliminate the natural processes that control the delivery and distribution of sediment, water, energy, organic matter, nutrients, and other chemicals (Gelfenbaum and others, 2006). Because assemblages in nearshore ecosystems are determined largely by light regime, hydrodynamics, and sediment characteristics (Thom, 2000; Martin and others, 2005), it is inevitable that human modification of these processes will affect nearshore ecology, but the ecological consequences of these alterations are not well documented (Rice, 2006). Existing literature on the impacts of shoreline modifications suggests that these have a high potential for severely impacting nearshore biological resources in Washington State (Williams and Thom, 2001), although there is limited local documentation of such effects. Known or hypothesized impacts of armoring on the biota of the nearshore environment are discussed in terms of the same five physical mechanisms discussed above.

Encroachment (placement loss) and land-beach disconnection are closely linked in terms of potential biotic impacts on nearshore ecosystems (fig. 1). Shoreline modifications can alter nearshore biology by being placed directly on top of vital habitats, by removing key riparian vegetation, and by disrupting flows of organic material. Riparian vegetation, that is, terrestrial plants closely associated with backshore environments, hosts a variety of insect species (Romanuk and Levings, 2003), some of which serve as a key food resource for juvenile fishes foraging nearshore at high tide (see below). Vegetation adjacent to the supratidal zone can also alter beach conditions by shading the substrate (Jedrzejczak, 2002), which helps maintain moisture and temperature thresholds essential for spawning forage fish (see below; also Penttila, 2000; Rice, 2006) as well as for marine crustaceans (Koch, 1989) and other beach dwelling invertebrates (Pennings and others, 2000). There are also likely terrestrial-marine linkages in terms of movement of organic matter; riparian vegetation adds carbon to the shore in the form of leaves and large woody debris, and marine-derived nutrients enter the terrestrial system through decomposition of deposited marine wrack (Polis and Hurd, 1996). Thus, decreased vegetation cover resulting from installation of shoreline modifications changes the physical and biological structure of the nearshore zone by creating hotter, drier habitats, and removing vegetation-dependent organisms. Unmodified shorelines are naturally buffered against such harsh physical conditions and are presumably more taxonomically diverse and productive (Webb and others, 1978). Exploration of these linkages in Puget Sound has been limited. Sobocinski and others (2010) examined 26 armored and unarmored beaches in Puget Sound. They found that at sites where the armoring was below Mean Higher High Water, the density and diversity of some beach-dwelling invertebrates were reduced, as was the abundance of organic debris such as driftwood, wrack and leaf litter. This debris may be an important part of nearshore detritus-based food webs. Riparian vegetation also had some influence on beach invertebrate communities as a whole, regardless of placement of armoring (Sobocinski, 2003).

Placement loss of upper-shore habitat may have indirect impacts on biota at higher trophic levels as well. Effects on higher-shore invertebrates and birds were studied at four beaches in southern Santa Barbara County, California (Dugan and Hubbard, 2006, 2010, and Dugan and others, 2008). All four beaches were narrow and backed by bluffs, much like the majority of Puget Sound beaches, but composed primarily of moderately fine grained sand rather than the coarser, mixed sediments typically found in Puget Sound. Each beach was divided into two segments: an established seawall section, and an adjacent unarmored section of the same length and orientation. Significant habitat reductions, including year-round loss of upper intertidal beach zones and narrowing of mid-intertidal zones, were observed on the sections of beach in front of seawalls. The abundance, biomass and species richness of upper shore macroinvertebrates, such as amphipods and isopods, was significantly higher at the unarmored beaches. These macroinvertebrate species are strongly associated with the availability of stranded macroalgal wrack (Dugan and others, 2003), which was significantly lower on the armored beaches (Dugan and Hubbard, 2006). Shorebirds, seabirds, herons, land birds and waders, all of which showed significantly reduced abundance and species richness on armored sections of beach, may respond to the combination of habitat loss and reduced prey availability resulting from armoring (Dugan and others, 2008). Habitat loss and decreased prey availability on altered shorelines forces coastal birds, many of which are threatened or declining, to relocate. The birds not only have to follow their prey, but look for new roosting locations as well (Dugan and others, 2008).

Herrera Environmental Consultants (2005) clearly demonstrated a case of placement loss in Puget Sound. They conducted an assessment of beach and sediment characteristics in Thurston County, Washington to evaluate the effects of armoring on fish spawning habitat due to altered beach morphology, substrate characteristics, and supply and transport of sediment. Reduced beach width and habitat area was found in front of armored structures, with the loss of upper beach habitat increasing as the percentage of shoreline armoring increased. Surf smelt and Pacific sand lance spawn on mixed sand and gravel beaches in the upper intertidal zone of Puget Sound; thus the reduction of this zone on armored shorelines decreased the area where these important forage fish can spawn.

Rice (2006) demonstrated an example of land-beach disconnection in a study on the northern end of Camano Island, Washington. He evaluated physical differences between adjacent natural and modified shorelines and the resultant effects on surf smelt. Removal of natural shoreline features, such as shade-providing terrestrial shoreline vegetation, can have dramatic effects on shoreline microclimate. Light intensity, substrate and air temperatures and humidity approximately 12 ft above mean lower low water (MLLW) were monitored on the beach, and substrate samples were collected. Altered beaches had higher daily light intensity, higher air and substrate temperatures, and lower relative humidity. In these harsher microclimates on the altered beach, the survival of surf smelt eggs was significantly reduced compared to the natural beach (Rice, 2006). Of all the factors that influence the development and survival of intertidal embryos, temperature is the most important (Frank and Leggett, 1981; DeMartini, 1999).

Effects of sediment impoundment and active and passive erosion on nearshore biota have been harder to demonstrate. As eroding beaches become narrower due to passive erosion and armoring, the reduced habitat extent can presumably lower the diversity and abundance of biota directly (Sobocinski, 2003; Dugan and Hubbard, 2006; Dugan and others, 2008), although this kind of study has not been done over long time scales. Broad surveys in the U.K. suggest that the intertidal profile along much of the coastline has gotten steeper in the last century, attributed to removal of sediment from the shore by rising sea level interacting with shoreline defense structures (Taylor and others, 2004). Steeper profiles may also be characterized by coarser sediments, and correlate with reduction in abundance of bivalves (Fujii and Raffaelli, 2008). Under circumstances where the intertidal does become steeper and narrower, via any of the mechanisms discussed above, there are likely to be impacts both on organisms that use the beach at low tide (such as birds, discussed above) and by infauna such as clams that may require finer sediments than those found on modified beaches (fig. 1).

A variety of studies in the U.S. suggest that use of the shoreline at high tide by mobile species such as fishes and crabs may be impacted by armoring, although the mechanisms of these effects are seldom clear. On the Gulf Coast of Mississippi, Peterson and others (2000) and Partyka and Peterson (2008) assessed the use of nearshore habitat by nekton (fishes and crustaceans). Nekton collections were done monthly for 2 years at 13 sites adjacent to natural marsh, sandy beach and altered marsh habitat types. The depth profile adjacent to altered marsh habitats was steeper than near unaltered sites, which in turn was steeper than near beach habitats. The deeper nearshore water may hinder the development of submerged aquatic vegetation (SAV) and eliminate the benefits of SAV to juvenile fish and crustaceans as a source of food and protection. Abundance and diversity of species examined in this study were lower in areas that had been altered by armoring (Peterson and others, 2000). The effects of development and bulkheading were manifested not only through changes of marsh, beach, and subtidal habitats, but by fragmenting of the landscape and severing terrestrial-aquatic linkages such as carbon input from the land to the nearshore (Bilkovic and Roggero, 2008, reviewed by Peterson and Lowe, 2009).

In Puget Sound, shoreline modifications may affect nearshore fish behavior in a variety of ways. Noise generated by bulkhead construction may affect distribution and behavior of young salmon species (Feist and others, 1996). Foraging of juvenile salmon in shallow water appears to be affected both in lakes as they migrate from their rearing grounds (Toft, 2001) and in Puget Sound proper as they migrate to the open ocean (Toft and others, 2007, 2010). Chinook salmon congregate in the littoral zone of lakes, and prefer shallow water with a gradual slope and small to fine substrate. In Lake Washington 70 percent of this shallow water zone has been modified with docks, marinas, and other hardening structures, which often steepen the slope. In the Sound, juvenile Chinook salmon consumed less terrestrial/riparian prey (insects) at sites with supratidal and intertidal retaining structures compared to those feeding at unarmored beaches (Toft and others, 2007). With a large proportion of the Sound's shorelines armored, especially on the east side, the cumulative impact on feeding of these endangered species could be substantial.

Marsh habitats in Puget Sound tend to be altered more by diking and filling in river deltas than by armoring along shorelines, but in other regions there have been severe impacts of armoring on marsh areas (for example, Currin and others, 2010). Marsh habitats are unique components of nearshore landscapes, vital to many ecologically and economically important fishes and crustaceans throughout their lives (Minello and others, 1994; Peterson and Turner, 1994; Currin and others, 2010).

Attempts to document armoring-related changes to subtidal habitats in Puget Sound, such as eelgrass beds, have yielded no clear links to date; Simenstad and others, 2008) found no relationships between patterns of armoring around Hood Canal and presence of eelgrass. However, in other estuarine systems there is some evidence that developed shorelines have negative impacts on the benthos in subtidal habitats adjacent to the shoreline, not just the shoreline habitats themselves (Carroll, 2003). In the Chesapeake Bay area, natural and anthropogenic drivers have led to habitat loss and degradation (Seneca and Broome, 1992; Thayer, 1992; Zedler, 1992; Zimmerman, 2000). Seitz and others (2006) studied the Elizabeth-Lafayette River system and the York River, two tributaries in the Chesapeake Bay, to evaluate the effects of shoreline armoring in shallow estuarine habitats. They compared the benthos of the subtidal areas adjacent to natural marsh, bulkhead, and rip-rap shorelines. In these habitats bivalves (various clam species) constitute up to 90 percent of the benthic community and prey biomass for higher trophic levels such as fishes and birds. Diversity, density and abundance of bivalves were higher at natural shorelines than at those that had been altered and over seven times higher in shallow than deep benthic environments. Predator abundance mirrored prey density, showing a ‘bottom-up control’ relationship in these nearshore food webs (Seitz and others, 2006).

In Washington State, most research on the effects of man-made shoreline structures on fishes has involved marinas, including bulkheads and overwater structure elements (Nightengale and Simenstad, 2001). One of the few studies documenting fish behavior in the presence of a bulkhead was done by Heiser and Finn, 1970), who found large concentrations of salmon fry in protected marinas in Puget Sound. From a boat they studied the activities of the small fish and noted that they seemed to be exhibiting predator avoidance behavior when in close proximity to the bulkhead. Fish were reluctant to enter deeper water by going around the structure. Salmon fry and fish schools often concentrate in higher densities behind breakwaters in marina basins as compared to natural nearshore areas (Heiser and Finn, 1970; Penttila and Aguero, 1978), but the degraded water quality in marinas may adversely affect these fish species (Williams and Thom, 2001).

Similarly, Able and others (1998) and Duffy-Anderson and Able (1999) studied the effects of piers on the distribution of juvenile fish species in the Lower Hudson River estuary. The 2-year seasonal study demonstrated that while shallow portions of the estuary are important nursery sites for juvenile fishes, species richness was decreased under piers, indicating poorer habitat quality. Piaskowski and Tabor (2001) found that retained shorelines and over-water structures create habitats that are avoided by juvenile Chinook salmon at night.

When armoring extends relatively low on the shore, these constructed hard surfaces become new habitat for intertidal biota. Around Sydney Harbor, Australia, approximately 50 percent of the shoreline has been altered with seawalls that have been colonized by benthic plants and animals. Chapman and Bulleri (2003) tested the hypothesis that seawalls support the same assemblages of plants and animals as natural rocky reefs. They found that not all organisms are able to adjust to the new habitat. Comparisons made at three different sites showed that organisms in the mid- and high-intertidal zones exhibited larger differences between seawalls and reefs than those in lower zones. At all heights, however, some species were missing and additional species were found, indicating that the two environments do not support exactly the same assemblages, and seawalls cannot be considered as surrogates for natural shorelines, even rocky ones (Chapman and Bulleri, 2003). Later studies (Chapman, 2006; and Moriera and others, 2007) found that while algae and sessile animals showed similar patterns across habitats, 50 percent of mobile animals were not present at seawalls, and rarer species tended to be absent. Vertical seawalls may lack microhabitats needed by mobile animals such as chitons, and in addition have a more compressed intertidal area, which may crowd species not adapted to living near one another (University of Sydney, 2008). To support a full suite of species, Chapman (2006) recommends that seawalls be built to: (1) include small cavities and crevices that will retain water even at low tides and (2) have a more gradual slope or a combination of surface gradient types. An additional concern is that artificial habitats such as breakwaters, and probably other armoring structures, can provide suitable habitat for invasive species and serve as corridors for their spread (Bulleri and Airoldi, 2005).

Although not directly relevant to Puget Sound, there is a substantial literature relating shoreline armoring to the ecology of sea turtles. Mosier and Witherington, 1999) evaluated the impact of armoring on sea turtle nesting behavior in a sandy environment on the southern Atlantic coast of Florida, which experiences a great deal of erosion and subsequent armoring (Clark, 1992). The beach studied has the densest population of loggerhead turtles in the state (Conley and Hoffman, 1986; Meylan and others, 1995). Results showed that fewer adult turtles emerged from the sea onto beaches in front of the various armoring structures than on adjacent, unarmored areas. Most of the turtles that did emerge in front of seawalls returned to the water without nesting. There were more emergences on beaches with dunes, showing that these may have been used as a visual clue. Reduction in habitat may cause the turtles to lay eggs lower down the beach where they can drown or wash away (Murphy, 1985).

An indirect impact of armoring can stem from the process of beach nourishment, which is often done to compensate for sediment depletion that can follow the reduction of natural sources, and to slow further beach erosion. Though nourishment is often perceived as preferable to shore hardening (Finkl and Walker, 2004), it has its own set of ecological effects (Blott and Pye, 2004; Peterson and others, 2006; Colosio and others, 2007). It does not provide a cost-effective solution in all situations, for example, if it needs to be repeated when erosion removes the recently introduced sediment. The frequency required depends on the physical setting of each beach, especially the energy to which it is exposed (Greene, 2002). Success of a nourishment project is affected by the timing, quality and quantity of new sediment used (Speybroeck and others, 2006), as well as the mechanics of nourishment itself. Some advantages of beach nourishment are the creation of a wider beach, allowing more recreational space; protection to shoreline structures; the use of dredged material for a constructive purpose; and the ability to change methods at any point if the practice becomes unsatisfactory or a better method is discovered. Nourishment also can restore habitat for some nearshore species. Negative effects can be direct, such as burying vegetation and animals when large quantities of sand are placed on the shoreline, or indirect as such as reduction in prey for larger animals or birds (Nelson, 1993; Bishop and others, 2006; Peterson and others, 2006; Colosio and others, 2007). The disruption to the natural shoreline may lead to emigration of nearshore species (Hayden and Dolan, 1974) and changes in beach morphology such as steepening of gradient and habitat reduction (Peterson and others, 2006; Fanini and others, 2007, 2009). Sediment that is vastly different in composition from the natural beach can further harm species and make full recovery of the beach unlikely (Goldberg, 1988; Peterson and others, 2000; Peterson and others, 2006). Data regarding the life history of affected species, their likely recovery rates and cumulative effects of repeated nourishment are limited (Speybroeck and others, 2006). Suggestions for reducing some of the ecological impacts of nourishment include: (1) avoiding sediment compaction; (2) timing the nourishment events to minimize impacts to biota, affording a higher possible chance of recovery; (3) selecting techniques appropriate for each different site; (4) implementing several small nourishment projects rather than one large one; (5) spreading the location of nourished areas out leaving undisturbed areas in between; and (6) importing sediment that closely matches the sediment type of the original beach (Speybroek and others, 2006; Defeo and others, 2009).

Engineering and Alternatives to Shoreline Armoring

A broad array of habitat protection and mitigation techniques (besides nourishment, discussed above) can reduce the need for shoreline modifications to estuarine and nearshore marine areas. These include land use management and alternative modification strategies (Williams and Thom, 2001). For example, bluff stability and nearshore water quality can be improved by better management practices in watersheds and upland habitats, including building setbacks, storm and groundwater management, and vegetation management (Downing, 1983; Cox and others, 1994; Macdonald and Witek, 1994; Zelo and Shipman, 2000). Setbacks simply involve building structures a safe distance from eroding shorelines or bluffs, and are considered the safest and least expensive alternative to avoiding erosion hazards along Washington's coastlines (Downing, 1983; Terich, 1987; Komar, 1998). Using aerial photographs, on-site surveys, property assessment records, and direct questioning of property owners, Gabriel and Terich, 2004) found that setbacks from the shoreline in Thurston County, Washington ranged from 6 to 432 m, demonstrating substantial inconsistencies in construction and policy regarding setbacks.

Surface and groundwater management is another way to reduce erosion around sensitive shoreline structures and property (Myers and others, 1995). When groundwater drainage is blocked or infiltration rates increase rapidly, hydrostatic pressure rises and increases the threat of landslides (Downing, 1983). If there is too much buildup of runoff during periods of heavy rainfall, channels will eventually downcut through the slope, creating severe slope stabilization problems as erosive forces increase. This threat can be mitigated by adding areas for groundwater pooling, discharging water at stable shoreline features (that is, rocky headlands), diverting runoff to inland waterways, or pumping the drainage offshore (Smith, 1997). Effective management practices to reduce direct water runoff as well as shoreline erosion include use of riparian vegetation; planting deep-rooted upland vegetation increases soil stability and reduces erosive hydrologic forces on shorelines (Menashe, 1993). Foliage and forest debris help buffer the rainfall, slow surface water runoff, and increase the absorptive capacity of soil. Roots create a complex underground system that stabilizes and anchors soil. Maintaining existing vegetation and adding plants to bare ground on bluffs can improve slope stability by trapping sediment and controlling surface runoff (Menashe, 1993; Cox and others, 1994). The use of non-native plants can affect the success of this process, if they are not adapted to withstand the local environment. Native plantings should be selected to be appropriate to each site, allowing the greatest potential for project success (Gerstel and Brown, 2006).

Other methods of minimizing ecological and physical degradation caused by shoreline modifications include the use of soft stabilization. This involves the incorporation of natural materials that can settle and distort over time, adjusting to changing shoreline conditions. Currin and others (2010) discusses "living shoreline" techniques in North Carolina that use marsh vegetation as the major component of shoreline stabilization. On any shore type, use of natural materials rather than hardened structures should result in reduced impacts to nearshore habitats (Cox and others, 1994; Macdonald and others, 1994; Zelo and Shipman, 2000). In Puget Sound, such methods include beach nourishment with sand and gravel, vegetation planting, and anchoring of large woody debris to the shoreline (Williams and Thom, 2001). Large woody debris (LWD: snags, stumps, driftwood) is a significant feature of Pacific Northwest beaches (Macdonald and others, 1994; Zelo and Shipman, 2000). LWD naturally accumulates in backshore areas at extreme high tides, and helps stabilize the shoreline (Macdonald and others, 1994; Zelo and Shipman, 2000). It can trap sediment to slow erosion, promoting vegetation on beaches (Downing, 1983) and absorbing wave energy (Zelo and Shipman, 2000). It also can provide roosting, nesting, refuge, and foraging opportunities for terrestrial wildlife, fishes, and aquatic invertebrates (Brennan and Culverwell, 2005). Artificial placement of LWD requires burial of concrete blocks below the beach surface to anchor the debris in place. This process involves excavation and removal of large amounts of sediment, which can interrupt or damage habitats, as well as creating temporary noise pollution (Gerstel and Brown, 2006). The long-term costs and benefits of use of LWD and other soft-stabilization methods have not yet been investigated. Barnard (2010) discusses current efforts in Washington State to compile information on alternatives to armoring in a "design guidance" manual.

Information/Research Needs

Numerous scientists familiar with the literature on armoring-beach interactions have noted the substantial need for more research to clarify impacts, both physical and biological (Pilkey and Wright, 1988; Kraus, 1988; Plant, 1990; Plant and Griggs, 1992; Kraus and McDougal, 1996; Griggs, 2005; Johannessen and MacLennan, 2007, summary of Discussions from Breakout Groups, 2010). Many caution that evaluating degradation can be a decades-long process and can vary dramatically from location to location. Suggested topics of additional research include the following:

- Undertake long-term profile surveys at sites with seawalls, quantifying seawall-wave interactions. Without sustained field studies at consistent sites, the role armoring structures play in active and passive erosion cannot be definitively determined. Such studies need to be done at sites differing in wave environments and in types (and elevations) of armoring to clarify the conditions under which active erosion does or does not occur.
- Develop physical models to assess scour effects on beach profiles; these models need to be tested at larger sizes than attempted to date, as small scale experiments may not accurately reflect reality.
- Develop numerical models of beach profile changes with ground-truthing done to accurately reflect starting profile shape, wave regime and sediment sizes.
- Conduct three-dimensional field experiments, looking at cross-shore transport, longshore transport, and sediment transport.
- Determine the influence of the water table on foreshore and swash zone sediment transport.
- Gather data on how benthic communities respond to armoring. Spatial variation in benthic communities has been related to temperature, salinity, sediment type and tidal regime (for example, Dethier and Schoch, 2005), but data on how communities respond to shoreline modifications are rare. Such data are critical for coastal planning in the face of rising sea levels (Fujii, 2007; Fujii and Raffaelli, 2008). Physical and biological responses to armoring need to be integrated.
- Quantify cumulative impacts (biological and physical) of armoring; is there a threshold, on the drift cell or larger scale, above which armoring impacts become particularly severe?

In Puget Sound in particular, the following issues have been culled out as needing more research (Johannessen and MacLennan, 2007): Net short-drift rates for sediment; long-term changes on the profiles of armored beaches, using historic data sources; quantitative sediment budgets, derived in part from long-term beach and bluff monitoring; and biological responses to beach nourishment.

Cumulative Impacts and Planning for the Future

Local-scale issues of a few bulkheads on a shoreline readily become regional issues as more bulkheads accumulate within a system (Peterson and Lowe, 2009). Odum (1970) warned that cumulative impacts and alterations to estuarine environments would hamper their productivity and sustainability, although as demonstrated in this review, little is actually known about the cumulative impacts of seawalls. Gabriel and Terich (2004) sought patterns of cumulative impacts of seawall construction in Thurston County, Washington, but were unable to state conclusively that seawall construction alone was strongly linked to geologic and physical changes or shoreline erosion rates. Cumulative effects of shoreline armoring are of great concern to shoreline administrators and resource managers and prompted the initial Coastal Erosion Management Strategy in 1992 (Canning and Shipman, 1995), but the science of understanding cumulative impacts of shoreline armoring is in its infancy. It is likely that impacts extend far beyond just a physical influence. They also include changes in geological, chemical, and biological systems within the nearshore region (Meadows and others, 2005), which must be integrated for successful shoreline management (Rice, 2006).

In the face of major potential environmental changes (such as increased coastal development and sea level rise), there is great need in conservation and management agencies for reliable predictive tools for planning the sustainable use of estuarine and coastal systems (Davis and others, 2002; Fujii, 2007). Fujii recommends the development of a model to make quantitative predictions about the interactions between intertidal habitats and how their biomass may change in response to environmental changes and subsequent sea level rise. This tool would help coastal managers adopt an approach that can sustain both conservation interests and socio-economic needs (Fujii, 2007). However, such a model will require large amounts of data from many different sites and over a wide range of habitats and species.

In the Puget Sound region, the process of advocating for, permitting, designing, and installing alternatives to traditional bulkheads would benefit from more coordinated objectives and guidelines from permitting agencies (Gerstel and Brown, 2006; also see Barnard, 2010). In North Carolina, it is still much faster and cheaper to get a permit for a traditional bulkhead than for a ‘living shoreline’ project (Currin and others, 2010). In general, shoreline planning and permitting processes need to be evaluated and potentially revised to encourage a more thorough characterization of regional and local geology and hydrology affecting each site. Additionally, providing more public education could reduce landowners’ concerns regarding potential risks to their property, resulting in fewer requests for shoreline modifications and, ultimately, less pressure on the already stressed environment (Gerstel and Brown, 2006).

Summary

Shoreline armoring is increasing worldwide with expanding coastal populations and development, especially in urban areas. Concerns about predicted sea level rise will increase the demand for coastal erosion-control, and thus the demand for more armoring. At the same time, sparse but increasing evidence suggests that armoring may have undesirable effects on nearshore ecosystems, on both geomorphological and ecological processes. On shorelines undergoing natural, long-term erosion (passive erosion), the presence of a seawall ultimately results in the narrowing and eventual loss of the beach in front of that seawall. More controversial are effects of seawalls on active erosion, that is, erosion below, at the end of, or downdrift of an armoring structure, resulting from wave reflection and/or loss of sediment supply. Extents, rates, and cumulative impacts of active-erosive effects need more documentation, especially in the relatively unstudied coarse-sediment beach types that characterize Puget Sound.

Ecological impacts of armoring are even less well documented. The most clear direct effects are the result of actual habitat loss when seawalls are emplaced over part of the beach (placement loss); this leads to loss of spawning area for forage fishes (and for sea turtles, in other systems), loss of accumulated organic debris and the organisms that consume it, and loss of coastal bird foraging and roosting area. Hypothesized indirect effects are diverse but there are few relevant studies, and they were often conducted on very small spatial and temporal scales. These indirect effects include: loss of area where drift algae and large woody debris accumulate, and thus loss of the food and microhabitats they supply; loss of backshore vegetation and the ‘services’ it supplies, such as shading of beach sediments and supply of insects to nearshore waters; loss of the shallow-water, low-slope regions on the upper shore used by fishes and perhaps crustaceans at high tide. If beaches in front of seawalls become narrower and steeper (which will depend on larger issues of sediment supply, wave energy, and regional changes in sea level and land subsidence), substrates may become coarser, and the communities inhabiting the whole intertidal zone may change. There is not yet any clear evidence for effects of armoring on lower-shore or subtidal ecology, for instance to eelgrass beds, although such effects may exist; it is very difficult to disentangle confounding factors, as well as to seek evidence on appropriate scales of space and time.

Alternatives to shoreline armoring are diverse, although their effectiveness over time remains untested. These include: increased building setbacks, to lessen the concern about bluff erosion; management of water and riparian vegetation to reduce the likelihood or rate of bluff erosion; nourishment of sediment-starved beaches (although this is not a self-sustaining or ecologically benign solution), and “soft-stabilization” techniques that use wood and vegetation, often combined with beach nourishment, to buffer wave impacts and reduce erosion.

Glossary

Accretion The buildup of a beach, by deposition of water- or airborne material.

Active Erosion A mechanism by which armoring accelerates beach erosion by reflecting wave energy and amplifying edge waves.

Alongshore Parallel to and close to the shoreline.

Amphipods Small crustaceans, common in many aquatic habitats, which are usually scavengers or decomposers .

Armoring Physical man-made modifications to the shoreline emplaced with the purpose of slowing erosion.

Assemblage Groups of species associated with a specific habitat type.

Backshore ~ supratidal zone. High-elevation area of the beach between the foreshore and bank, acted on by waves during storms.

Beach Gradient Angle of the beach down the profile, extending seaward.

Beach Profile Vertical cross-section of a beach measured perpendicular to the shoreline.

Benthos Organisms living on or in the sea bed.

Berm Flat or raised portion of the beach created by sediment deposition by waves.

Biota Animal and plant life in an ecosystem.

Bivalve Mollusks with two shells, such as clams and mussels.

Bulkhead Man-made vertical structure built parallel to the shoreline.

Cross-Shore Transport Sediment movement along a beach profile.

Dissipative Beach A wide, gently sloping beach where incoming waves break before reaching the beach face, thus losing most of their energy.

Downcut Large channel down the slope of a hill face, caused by runoff.

Downdrift Direction of predominant movement of littoral material.

Ecosystem Organization of all biotic and abiotic factors in a specific area, often within certain geographical barriers.

Eelgrass One of various species of vascular (flowering) plants living in the marine realm, usually in soft sediments.

erosion Wearing away of land by natural processes

Estuary Semi-enclosed coastal body of water with freshwater input and a connection to the open sea.

Fetch The distance over-water that wind blows and thus waves build.

Foreshore ~ intertidal zone; portion of the shore that is exposed to air at low tide and submerged at high tide.

Geomorphology Study of landforms and the processes by which they are created, or the shape of a natural surface or object.

Groin Rigid man-made structure built perpendicular to the shore with the function of trapping sediment.

Habitat An area inhabited by a particular animal or plant species, the natural environment in which an organism lives, or the physical environment that surrounds a species population.

Hydrology Dynamics of water movement through an area.

Impoundment Trapping of sediment in a certain location.

Intertidal Same as foreshore.

Jetty Man-made structure extending into a body of water to protect shoreline from effects of waves, tides, or storms.

LWD Large woody debris, that is, stumps, logs, driftwood.

Littoral Pertaining to the shore.

Littoral cell A sediment-transport sector of shoreline from source area to deposition area.

Macrofauna Animals visible to the naked eye.

Macroinvertebrates Invertebrates visible to the naked eye.

Marsh A type of wetland subject to frequent or continuous floods.

Mean High Water The average high water height at a particular point over a period of time (usually 19 years).

Mean Low Water The average low water height at a particular point over a period of time (usually 19 years).

Microclimate Local atmosphere where the climate differs from the surrounding area.

Nekton Aquatic animals able to actively swim against water currents.

Nourishment The process of adding sediment to a beach.

Ordinary High Water Mark (OHWM) Highest level reached by a body of water that has been maintained for a sufficient period of time to leave evidence on the landscape.

Overwater Structures Man-made structures, such as docks, that extend over a body of water.

Passive Erosion The process whereby an armored shoreline prevents natural erosion of the bank, so that new upper beach cannot form as a shoreline retreats.

Photic Zone Depth of water receiving sufficient light for photosynthesis to occur.

Placement Loss The covering of backshore or foreshore area by shoreline modifications so that habitat is lost.

Ponding Area built to trap water runoff and allow it to drain slowly.

Revetment Sloping structure built on banks or cliffs to absorb energy from incoming water and slow erosion.

Runup The rush of water up the beach when waves break.

Scour Removal of underwater material by waves, currents, and tides, usually at the base of a structure.

Seawall Man-made structure built parallel to the shoreline, designed to protect land from the water.

Sediment Transport Movement of solid particles and the processes that govern their motion.

Shoreline The line where water and ocean meet.

Spawning Production and deposition of eggs.

Species Richness The number of different species in a given area.

Substrate Material on which organisms live or are attached.

Subtidal Marine environment below low tide line, never exposed to the air.

Swash Zone The portion of the nearshore region where the beach face is alternately covered by the run-up of the wave swash and exposed by the backwash.

Toe Lowest part of a bank, bluff or shoreline structure, where the slope meets the beach.

Updrift Direction opposite of the predominant movement of littoral materials.

Uplands Land above a shoreline.

Wave Energy Force exhibited by waves impacting another object.

Wrack Piles of algae, eelgrass, and terrestrial plants that wash ashore, often after storms.

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