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Puget Sound Shorelines and the Impacts of Armoring—Proceedings of a State of the Science Workshop, May 2009

Scientific Investigations Report 2010–5254

U.S. Department of the Interior
U.S. Geological Survey

Cover: Photograph showing timber pile bulkheads built to protect residential property from erosion. Ledgewood Beach on the west side of Whidbey Island. Photograph taken by Hugh Shipman, Washington Department of Ecology.

Puget Sound Shorelines and the Impacts of Armoring—Proceedings of a State of the Science Workshop, May 2009

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Conversion Factors

Inch/Pound to SI

Multiply	By	To obtain
	Length	
inch (in.)	2.54	centimeter (cm)
inch (in.)	25.4	millimeter (mm)
foot (ft)	0.3048	meter (m)
mile (mi)	1.609	kilometer (km)
yard (yd)	0.9144	meter (m)
	Area	
square foot (ft^2)	0.09290	square meter (m^2)
	Flow rate	
foot per year (ft/yr)	0.3048	meter per year (m/yr)

SI to Inch/Pound

Multiply	By	To obtain
	Length	
centimeter (cm)	0.3937	inch (in.)
millimeter (mm)	0.03937	inch (in.)
meter (m)	3.281	foot (ft)
kilometer (km)	0.6214	mile (mi)
	Area	
hectare (ha)	2.471	acre
square meter (m^2)	10.76	square foot (ft^2)
hectare (ha)	0.003861	square mile (mi^2)
square kilometer (km^2)	0.3861	square mile (mi^2)
	Volume	
cubic meter (m^3)	0.0008107	acre-foot (acre-ft)
Flow rate		
cubic meter per year (m^3/yr)	0.000811	acre-foot per year (acre-ft/yr)
meter per second (m/s)	3.281	foot per second (ft/s)
meter per day (m/d)	3.281	foot per day (ft/d)
meter per year (m/yr)	3.281	foot per year ft/yr)
millimeter per year (mm/yr)	0.03937	inch per year (in/yr)

Temperature in degrees Celsius (°C) may be converted to degrees Fahrenheit (°F) as follows:

°F=(1.8×°C)+32.

Temperature in degrees Fahrenheit (°F) may be converted to degrees Celsius (°C) as follows:

°C=(°F-32)/1.8.

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Puget Sound Shoreline Armoring: State of the Science Workshop

Hugh Shipman[1], Guy Gelfenbaum[2], Megan N. Dethier[3], and Kurt L. Fresh[4]

Introduction

The widespread extent and continued construction of seawalls and bulkheads on Puget Sound's beaches has emerged as a significant issue in shoreline management and coastal restoration in the region. Concerns about the impacts of shoreline armoring and managing the potential risks to coastal property are in many ways similar to those in other places, but Puget Sound also poses unique challenges related to its sheltered setting, glacially formed geology, rich estuarine ecology, and historical development pattern.

The effects of armoring on shorelines are complex, involving both physical and biological science and requiring consideration of the cumulative impacts of small-scale activities over large scales of space and time. In addition, the issue is controversial, as it often places strongly held private interests in protecting shoreline property against broad public mandates to preserve shorelines for public uses and to protect environmental resources. Communities making difficult decisions about regulating shoreline activities and prioritizing restoration projects need to be informed by the best science available.

To address these issues, a scientific workshop was convened in May 2009, specifically to bring local and national experts together to review the state of the science regarding the physical and biological impacts of armoring on sheltered shorelines such as those of Puget Sound.

Coastal Armoring

Coastal armoring is the practice of constructing seawalls, bulkheads, and revetments along shorelines to prevent erosion and to stabilize areas for upland land uses. Armoring is widespread along developed coastlines around the world and is often viewed as both necessary and environmentally benign by its proponents, but it poses challenges for managers charged with protecting public shorelines and coastal habitats. In the United States, armoring has been an issue on the Atlantic, Gulf, and Pacific coasts (Griggs, 2005), on the Great Lakes and in Hawaii (Fletcher, 1997). Although the geographic settings vary dramatically, the concerns often are similar and include the effects on public access and beach recreation, the impacts on ecological resources, the balancing of public costs and private benefits in managing erosion, and the specter of the long-term loss of beaches in front of seawalls (Beatley and others, 2002). The issue is complicated by the long-term and cumulative nature of the impacts, the vulnerability of the coast to natural hazards, and the political and legal complexities of zoning and regulating private property.

Specific concerns about the impacts of armoring include its direct impact on the beach where it is constructed, the effect on access both to and along the beach, the loss of terrestrial sediment supply to the beach system, and localized erosion or changes to sediment transport caused by wave interaction with structures (Woodroffe, 2002; Griggs, 2005). Geologists also point to the progressive loss of the beach that occurs when a fixed structure is built on an eroding shoreline (passive erosion), particularly in light of ongoing and future rates of sea level rise. Many of these physical changes associated with armoring have consequences for nearshore ecosystems and their functions, including the direct burial and isolation of habitats and the introduction of fill or new substrates.

Scientific information becomes critical for informing regional and local decisions about armoring. Knowledge of erosion rates and mechanisms helps define the risk to coastal development, assess the rate of change of the natural environment, and quantify sediment budgets. Studies of the relationship between geomorphic and biological processes helps scientists understand the sensitivity or resilience of coastal ecosystems to anthropogenic modifications. Evaluation of erosion control methods helps to assess the efficacy and relative impacts of alternative measures (beach nourishment, for example) and to identify appropriate means of minimizing or mitigating impacts of structures.

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Much of the scientific research on beaches and armoring has been focused on sandy, open-ocean shorelines, particularly the barrier islands of the U.S. Atlantic and Gulf Coasts (see Krauss, 1988; Kraus and McDougal, 1996). This reflects the dense coastal development and high recreational and tourism value of those regions, the vulnerability and repeated damages from tropical storms and hurricanes, and the abundance of large-scale, often publicly funded coastal engineering projects. These projects include large community-scale seawalls, beach nourishment, and the maintenance of tidal inlets (dredging and jetty construction).

Armoring on sheltered coasts and estuarine beaches has received much less scientific attention, although many of the technical and policy issues are similar. Sheltered coasts are shorelines protected from open-ocean wave conditions, typically associated with large bays and estuaries. They represent a majority of the U.S. coastline length, and include large back-barrier systems such as Pamlico Sound and Mobile Bay and large estuaries and bays such as Chesapeake Bay, Long Island Sound, San Francisco Bay, and Puget Sound. They are characterized by lower wave energy and slower erosion rates, an irregular coastline comprised of smaller beaches and sediment compartments, a large diversity of coastal landforms, and productive, complex ecology typical of estuarine environments (Nordstrom, 1992; National Research Council, 2007). They often lie in close proximity to major urban areas, are heavily impacted by human development, often bear the legacy of historical modifications, and typically have different land development patterns and recreational uses than ocean beaches (Nordstrom, 1992).

The National Research Council recently examined the complex issues associated with managing erosion on sheltered coasts (National Research Council, 2007). As with the science, policy development on these shorelines has not kept pace with similar efforts on exposed shorelines (Nordstrom, 1992). Even in states where armoring is strongly scrutinized on ocean beaches, armoring of estuarine shorelines often receives little attention. In its findings, the National Research Council (2007) stressed the importance of understanding cumulative impacts, the need for regional planning that takes into account sediment considerations, and the importance of better protecting a full suite of ecosystem services. The report also emphasized the need for better scientific understanding of shoreline processes and of alternative approaches to managing eroding coastlines.

Puget Sound

Puget Sound, the second largest estuary in United States, has roughly 4,000 km of sheltered coastline, much of it consisting of eroding bluffs, narrow mixed sand and gravel beaches, and heavily modified urban and industrial shorelines. Approximately one-third of this shoreline has been armored and the expectation is that this will continue, particularly in the face of regional population trends and potentially increased rates of sea level rise. Armoring has been suggested to alter physical processes such as coastal sediment supply and transport, the interaction of waves with beaches, and groundwater flows to the beach, as well as impacting ecological functions, such as spawning, detritus production and food web processes, and the maintenance of beach and nearshore habitats.

Relatively little field research and predictive modeling have been carried out on Puget Sound beach environments, related to either geomorphic or ecologic processes. Numerous technical reports have been produced and numerous reviews have been done of relevant research from both this and from other regions, but there remains a great need for more extensive and more rigorous scientific research into the behavior of the Puget Sound nearshore system and the impact of human activities on its future condition.

Several major initiatives have recently increased the need for better scientific understanding of Puget Sound shorelines and of the impacts of armoring, in particular. The Puget Sound Nearshore Ecosystem Restoration Project (PSNERP) has developed strategies for restoring coastal habitats, with an emphasis on protecting and re-establishing key ecosystem processes such as sediment delivery. The Puget Sound Partnership (PSP), a new state agency as of 2006, is actively prioritizing scientific studies, restoration objectives, and policy changes aimed at improvements to the entire Puget Sound basin, including coastal environments. The Washington Department of Ecology is working with local governments across Puget Sound to update existing Shoreline Master Programs to conform to new state guidelines that mandate the protection of ecological functions along Puget Sound's shoreline and that generally demand closer scrutiny of shoreline armoring.

These state-wide efforts require more scientific information and more technical guidance related to shoreline armoring and the restoration of degraded shorelines. Recognizing this need, scientists and technical staff from the U.S. Geological Survey, the Corps of Engineers, state and federal agencies, and the University of Washington secured funding to host a scientific workshop on the subject of shoreline armoring.

Ultimately, a better understanding of the impacts of armoring on sheltered and estuarine shorelines will provide the scientific basis for guiding principles and recommendations that lead to better decisions related to locating and regulating shoreline armoring. Specific objectives of the workshop were to:

- Summarize the state of science regarding physical and biological impacts of armoring on estuarine shorelines like those of Puget Sound;

- Inform conceptual models that integrate physical and biological knowledge and assess levels of certainty of knowledge;
- Identify and prioritize information and data needs that will advance our understanding of the impacts of armoring on Puget Sound beaches.

The workshop was held on May 16–19, 2009, at Alderbrook on Hood Canal, Washington. Workshop participants mostly were scientists from physical and biological disciplines, including experts from other regions with experience in shoreline geology, coastal ecology, and the specific issue of shoreline armoring. Of the 38 participants, 23 delivered presentations and 22 contributed papers to these Proceedings. In addition to the technical presentations, the workshop included a poster session, a half-day field trip, and a summary discussion employing breakout groups. A literature review also was prepared in conjunction with the workshop (Coyle and Dethier, 2010, this volume). In addition, the Puget Sound Partnership organized a separate forum for shoreline planners and resource managers on the day following the workshop in which several speakers summarized the important conclusions from the workshop.

Summary of the Papers

The 22 publications in these Proceedings are organized into five categories:

- Puget Sound Setting and Context
- National Perspective and Human Dimensions
- Coastal Geologic and Oceanographic Processes
- Beach Processes and Ecological Response
- Management Needs

Puget Sound Setting and Context

The paper by Quinn (2010, this volume) describes Puget Sound as a large, productive estuary shaped by complex geological forces and surrounded by numerous watersheds, including some in Canada. Over the last 200 years, human impacts have changed from dispersed influence of local native tribes to the results of occupation by millions of people and diverse extractive activities (for example, logging and fishing) and development patterns (dense urban and extensive residential development). Quinn (2010, this volume) describes the complex jurisdictional issues in the nearshore, making regulation and protection of shorelines difficult.

Shipman (2010, this volume) describes Puget Sound's shoreline as strongly influenced by its glacial history and characterized by a steep bluff-dominated coastline with narrow mixed sand and gravel beaches, a coastal sediment system largely fed by bluff erosion, and an irregular coastline divided into hundreds of individual littoral cells. Approximately one-third of the shoreline is armored, much of it in the form of bulkheads and seawalls associated with residential construction.

Dethier (2010, this volume) discusses beach types in Puget Sound as diverse in terms of wave exposure and therefore sediment types, with corresponding variation in biological communities. Beaches range from soft mud with eelgrass, clams, and oysters to "mixed-coarse" substrates with cobbles and sand, which have high plant and animal biodiversity and productivity. Sandy and pebbly beaches are common and tend to have simpler biotic communities because of the instability of the substrate. These varied beach communities link to adjacent terrestrial and marine ecosystems in a variety of ways, some of which are disrupted by armoring.

Myers (2010, this volume) describes how the Puget Sound Nearshore Ecosystem Restoration Project conducted an analysis of change in nearshore ecosystems from the mid-1880s to present in order to identify what anthropogenic drivers have changed Puget Sound's nearshore since European settlement of the region, and where those changes occurred. The key elements of this analysis are that it is documented comprehensively over the entire Puget Sound basin, directly related to physical and ecological change in ecosystem-scale processes, spatially explicit, and integrated within the framework of a geomorphic classification system. Shoreline armoring is one of the stressors considered in this analysis; armoring occurs along 27 percent of Puget Sound. The percent of armored shoreline varies considerably (9.8–62.8 percent) across the major sub-basin regions of Puget Sound. The South-Central Puget Sound sub-basin (area around the city of Seattle) is the most heavily armored of the sub-basins, with 63.0 percent of the shoreline armored.

Carman and others (2010, this volume) explain that regulation of shoreline armoring on Puget Sound primarily occurs through the Hydraulics Act, which is administered by the Washington Department of Fish and Wildlife, and the Shoreline Management Act, which is administered by the Washington Department of Ecology and local governments. These laws guide how and where structures are built, but both include constraints that limit their ability to strictly regulate armoring on residential property. The paper also notes that most new armoring structures are associated with residential development.

National Perspective and Human Dimensions

The paper by Nordstrom and others (2010, this volume) describes plans to monitor a beach-feeding project on the bay shoreline of Fire Island, New York. Existing armoring has impacted sediment transport and increased erosion on natural portions of this low energy shoreline, and feeding is intended to restore beach processes and habitat without the excessive offshore sedimentation and habitat disruption that might accompany conventional beach nourishment. The monitoring study will employ instrumentation and frequent measurements during the storm season to evaluate sediment transport rates and pathways, beach morphologic changes, and impacts on biota.

O'Connell (2010, this volume) describes several beneficial and adverse effects of shoreline armoring, utilizing experience from coastal zone management in the states of Massachusetts and Hawaii. Shoreline armoring can protect valuable waterfront real estate, maintain home values, and reduce loss of private and public infrastructure. Adversely, armoring can result in the loss or alteration of important coastal habitat, or in some cases hasten the loss of beach sediments. Data are presented from the diverse perspectives of Massachusetts and Hawaii, providing examples of the importance of this issue to state and local economies.

Griggs (2010, this volume) describes the status of shoreline armoring in the state of California, which has over 100 mi of coastal protection. In California, armoring issues include limitations of beach access, visual impacts, loss of beach as a result of the placement of the structure, loss of sand supply from eroding bluffs, and passive erosion, or loss of beach fronting a seawall as sea-level rises. Long-term beach monitoring data along the coast in Monterey Bay suggest that shoreline armoring there did not cause additional active erosion of beach sand, possibly a result of the high littoral or longshore transport rates in the area. In California, the use of soil-nail walls or sprayed concrete, which is colored and textured to match native rocks and cliffs, has become more popular. These structures may reduce negative visual impacts, but do not minimize other negative impacts of shoreline armoring.

Roberts (2010, this volume) describes a 2007 report by the National Research Council that examined the impacts of shoreline management, especially stabilization, on sheltered coastal environments. Many of the conclusions of that report are relevant to Puget Sound, especially the importance of considering cumulative impacts and of changing the regulatory environment to make it simpler to install non-structural solutions to shoreline erosion problems.

Currin and others (2010, this volume) discuss how North Carolina shorelines are experiencing rapid erosion, making efforts to stabilize the shoreline common. Alternatives to armoring that are currently being promoted include several "living shoreline" techniques that incorporate use of natural shoreline vegetation, especially salt marshes; these not only reduce erosion but provide a variety of other ecosystem services. Like Roberts (2010, this volume), this paper discusses how the current system for permitting shoreline stabilization projects does not favor these living shoreline methods.

Leschine (2010, this volume) discusses the implications of the lack of human dimensions research on the interactions of people with seawalls and other engineered features and how this may relate to restoration of nearshore ecosystems. Such engineered features represent a dilemma because they protect property from erosion or wave attack and thus can make a positive contribution to human well being. Conversely, they also can negatively affect a variety of other ecosystems goods and services. However, we currently lack an understanding of how people in the region value the numerous tradeoffs across ecosystem functions, goods, and services associated with armoring Puget Sound's shores. Integrating human-dimensions and natural scientific research can help expand scientific understanding relevant to nearshore ecosystem restoration.

Coastal Geologic and Oceanographic Processes

Komar and Allan (2010, this volume) discuss "build with nature" alternatives to shoreline armoring. They provide details from a case example at Cape Lookout State Park on the Oregon coast. They first describe the nature of the erosion problem, then the design, construction, and monitoring of a cobble berm as natural shoreline protection.

Osborne and others (2010, this volume) describe direct measurements and observations of gravel transport, beach sediment characteristics, beach erosion and accretion, and forcing mechanisms along a mixed-sand-gravel beach on Bainbridge Island, Puget Sound, Washington. The beach at this study site is backed by shoreline armoring structures and has been exposed to waves from storms and passenger-only fast ferries. The long term observations of changes in beach morphology, transport patterns, and sediment size and volume variations are consistent with the observation that this site is sediment-supply limited. It is undergoing long term passive erosion, most likely as a result of construction of bulkheads along the length of the study area.

Johannessen (2010, this volume) describes how sediment eroded from coastal bluffs is the primary source of sediment for many Puget Sound beaches, leading to concerns about the impact of shoreline armoring on sediment budgets and beach sediment supply. This paper describes a field-based methodology developed on Puget Sound to identify both historic and existing bluff sediment sources (locally referred to as "feeder bluffs"). This work has been carried out in portions of Puget Sound and confirms a substantial loss of historical sediment supply. The mapping is being used by local and state agencies and other organizations to identify shorelines for protection and restoration actions.

Beach Processes and Ecological Response

Rice (2010, this volume) argues that some of the clearest impacts of shoreline modifications on biota in Puget Sound are reduced survival of embryos of forage fish on upper beaches, as well as loss of high-shore invertebrates. Broad marine bird surveys also suggest a negative correlation with human development patterns. However, few studies are explicitly designed to address biotic patterns associated with human impact; such directed studies are needed to improve our understanding and management of the biological effects of shoreline armoring in Puget Sound.

Toft and others (2010, this volume) discuss how careful studies of restoration actions involving removal of shoreline armoring, with controls, can inform our understanding of armoring impacts. Two such case studies suggested that key links between terrestrial and marine systems that may be disrupted by armoring include the availability of habitat and food items for juvenile salmon; these prefer to forage in gently sloping shallow water and consume insects that drop from riparian vegetation, both of which tend to be absent on armored shores. High-shore invertebrates also return fairly quickly once armoring has been removed. The authors list suggestions for key further research.

Krueger and others (2010, this volume) describe how surf smelt and Pacific sand lance are key parts of the Puget Sound food web, providing food for many sea birds, marine mammals and fishes. Shoreline armoring might be the greatest threat to surf smelt and sand lance spawning habitat, as armoring affects beach morphology and results in the direct loss of spawning habitat. In addition to shoreline armoring, sea level rise is likely to cause widespread loss of spawning habitat for these two species. The discontinuous geographic distribution of spawning occurrence and egg abundance suggest that loss of a relatively small number of spawning beaches might have a large detrimental effect on egg abundance. Although some regulatory protection of surf smelt and sand lance spawning habitat currently exists, they fail to take expected environmental change and spatio-temporal variation in spawning into account.

Ruggiero (2010, this volume) reviews various published studies exploring seawall impacts on sediment dynamics. The effect of seawalls on beaches has been found to be most sensitive to the position of the seawall within the surf zone, the beach slope, and the reflection coefficient. However, it has not been conclusively confirmed in the field or the laboratory whether currents and sediment transport rates will increase or decrease in front of a hardened shoreline, as compared to a non-armored section of beach, and whether the sedimentary environment will be significantly modified. This paper suggests pilot investigations specific to the Puget Sound consisting of beach monitoring, field experiments, and modeling efforts that could help improve understanding of these processes and the effects of shoreline armoring on beaches.

Dugan and Hubbard (2010, this volume) describe how on Southern California sandy beaches, armoring of eroding bluffs substantially reduces beach width, abundances of invertebrates, and numbers of foraging and roosting shorebirds, gulls, and seabirds. Predicted sea level rise will further reduce this critical habitat area and the food it contains for birds and other vulnerable species.

Jackson and others (2010, this volume) describe how alteration of estuarine shores to increase their economic value is a long practiced tradition in the United States. Recent attention in Delaware Bay has focused on natural and human-induced changes occurring to sandy landward-migrating barriers that front marsh systems. These changes are important for the American horseshoe crab that annually spawn in the foreshores of these barriers. Erosion of the foreshore during storms can result in either the removal of sediment from the upper foreshore and deposition on the lower foreshore or the horizontal landward displacement of the foreshore. Beach nourishment may be a preferable alternative over building bulkheads for preserving habitat value for the horseshoe crab, but nourishment can decrease habitat value as well as enhance it, depending on morphology and sediment characteristics of the pre-nourished beach.

Management Needs

Barnard (2010, this volume) describes how documents that provide “design guidance,” such as those summarizing the best available science related to methods for streambank protection, can be critical to help managers and engineers create environmentally sound projects. No such guidance document is available for shoreline armoring projects except for the Corps of Engineers’ Coastal Engineering Manual, which emphasizes open-coast sandy beaches and thus is not entirely relevant to Puget Sound conditions. A “Marine Shorelines Design Guidance” document is being planned for Puget Sound; it will consider unique local conditions including the importance of drift cells and sediment supply, and discuss benefits and impacts of different techniques for stabilizing eroding shorelines.

Cereghino (2010, this volume) describes how protecting private property from erosion is in direct conflict with protecting the “public trust resource” of sediment supply to beaches. Restoration programs struggle with trying to solve a large-scale, cumulative problem with piecemeal small-scale projects on individual parcels. Restoration “systems” that span organizational boundaries may have greater success; these integrate planning, learning, land stewardship, and communication among stakeholders into the more traditional restoration activities of project development and funding.

Summary

The papers in this proceedings volume reflect the geological, ecological, and regulatory complexities of shoreline armoring issues. The Discussion Summary at the end of this volume begins to explore some of the research that workshop participants felt would improve understanding of armoring impacts. This report only touches on the human dimensions of shoreline armoring, such as historical and cultural values, public use and access, and property rights, and these would be highly appropriate topics for another workshop. In addition, these papers do not examine in detail the design and engineering aspects of erosion control methods and the development of "greener" or "softer" alternatives to conventional armoring, topics also worthy of further exploration.

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Puget Sound Setting and Context

Point Wilson Lighthouse in Fort Worden State Park, Port Townsend. Photograph taken by Hugh Shipman, Washington Department of Ecology.

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An Environmental and Historical Overview of the Puget Sound Ecosystem

Timothy Quinn[1]

Introduction: The Physical and Biological Setting

The Puget Sound ecosystem corresponds to the southern (U.S.) portion of the Strait of Georgia (aka Georgia Basin)–Puget Sound ecosystem (fig. 1). Collectively, these areas are sometimes referred to as the Salish Sea ecosystem, which straddles the United States and Canada border, and includes approximately 18,000 km^2 of water and 110,000 km^2 of land area (excluding the upper Fraser River watershed but including 419 islands) and some 7,500 km of marine shoreline, including islands (fig. 1; SeaDoc Society, 2009). The Salish Sea ecosystem is a fjord with flooded glacial valleys and is classified as a large estuary, or system of estuaries, fed by highly seasonal freshwater from the surrounding basins. The largest input of freshwater comes from the Fraser River, which drains a large part of British Columbia, Canada. Other important sources of fresh water are the Campbell, Powell, Cedar, Duwamish/Green, Elwha, Nisqually, Nooksack, Puyallup, Skagit, Skokomish, Snohomish, and Stillaguamish Rivers. This paper focuses on the Puget Sound portion of the ecosystem, despite its obvious connection to the larger system, because political boundaries tend to govern the way information is collected and summarized. Where possible, information about the Salish Sea ecosystem is included.

Much of the Salish Sea ecosystem has been shaped by similar geologic forces, including plate tectonics, volcanism, and glaciation. The topography and bathymetry of the ecosystem was most recently transformed during the Wisconsin Glacial Episode. This Episode included three major continental glaciations, starting about 70,000 years ago, separated by relatively warm interglacial periods, such as we are experiencing today. The last of these glaciations began about 30,000 years ago, reached its greatest advance 21,000 years ago near the southern edge of Puget Sound marine waters, and ended about 10,000 years ago. At the height of the most recent glaciation, sometime between 16,500 and 15,000 years ago, mammals such as humans migrated to North America from Siberia across the Bering Land Bridge (Goebel and others, 2008).

Soils of the ecosystem are derived from a complex mix of glacial and volcanic (lahar) deposits at lower elevations and in many of the major river valleys, to volcanic and marine rock at higher elevations. The character of the marine nearshore area is a function of the complex shape and geology of the coastline and the glacial deposits that have been redistributed by waves, tides and rivers (Shipman, 2008). In general, southern Puget Sound is shallower with finer grained sediments than areas to the north. Water depth in Puget Sound increases rapidly with distance from the shore. The mean water depth is 62 m, with a maximum of 370 m (Burns, 1985), and it takes approximately 5 months to completely exchange Puget Sound water with Pacific Ocean water. The weather and climate of the Puget Sound ecosystem are dominated by two main elements: winds typically blowing from west to east across the Pacific Ocean bring mild, moisture-laden air to the region throughout much of the year; mountain ranges deflect low-level air coming from the ocean, and during winter block colder air from the interior U.S. (Mass, 2008). The resulting general pattern of wet, mild winters and dry, cool summers is superimposed on complex regional topography, which ranges in elevation from 4,270 m to sea level. The western slopes of the Olympic and Cascade Mountains (fig. 1) receive enormous quantities of rain and snow during the winter. Other areas, such as the northeastern tip of the Olympic peninsula and the San Juan Island archipelago, remain relatively dry because they lie in the rainshadow of the Olympic Mountains. The maritime climate supplies water to more than ten thousand rivers and streams.

Characteristics of the watersheds that make up the Puget Sound ecosystem vary dramatically across the region. Sharp topographic relief creates highly variable local-scale climate, and in combination with diverse soil types, results in a wide variety of environmental conditions. This range in conditions supports high levels of biodiversity and other important biological phenomena. The terrestrial landscape is dominated by some of the most productive coniferous forest communities in the world, where many of the conifer species reach their maximum growth potential for height and diameter (Franklin and Dyrness, 1988). Douglas-fir forest communities dominate the lowlands of Puget Sound by virtue of their tolerance to well-drained, glacially derived soils, while hemlock and true fir (genus Abies) communities dominate wetter areas in the foothills and more mountainous regions (Franklin and Dyrness, 1988). Interspersed among the forests, particularly at lower elevations, are other notable features, such as prairie, madrone forest, oak woodland, and wetland and bog

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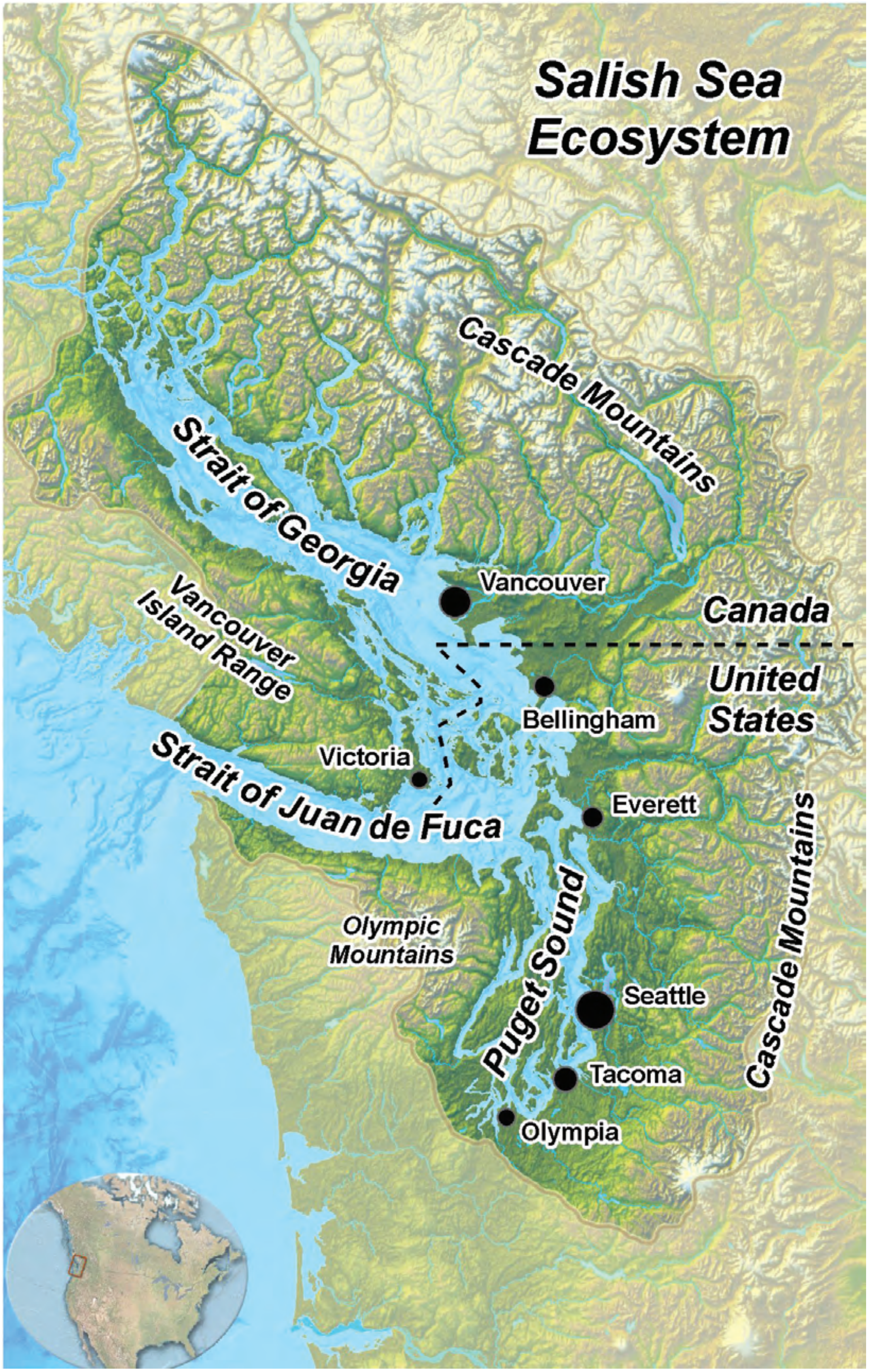

Figure 1. The Salish Sea Ecosystem showing marine waters in the Straits of Georgia and Juan de Fuca, and Puget Sound, and the surrounding watersheds. (Adapted from Stefan Freelan; accessed November 2009, at http://myweb.facstaff.wwu.edu/~stefan/SalishSea.htm).

ecosystems. While acknowledging that many taxonomic groups have not been well studied, the Center for Biological Diversity (2005) recognized about 7,000 species of organisms that occur in the Puget Sound Basin, including 4,248 animals, 1,504 plants, 851 fungi, and 392 algae, and ranks the Puget Sound Basin as a “hot spot” for biodiversity nationally. The World Wildlife Fund includes the Puget Sound Basin (along with Northeast Pacific Coast) as one of 200 priority ecoregions for protecting biodiversity worldwide (Ricketts and others, 1999). Lombard (2006) suggests that the Puget Sound Basin also is unique by virtue of both high salmon species richness and high natural salmon productivity, making this one of the most productive salmon areas along the Pacific Coast. This productivity is not limited to salmon. Washington State supports the second largest oyster production in the nation and the most important clam fishery (geoduck) on the west coast of North America (Puget Sound Action Team, 2007).

The Growing Human Influence

Shortly after sailing into the southern portion of the inland waters of the Pacific Northwest in 1792, George Vancouver claimed the area for Great Britain and named it after his Lieutenant, Peter Puget. Most if not all inhabitants of the Puget Sound region were Native Americans commonly referred to as Coast Salish people, who took their principal identity from permanent villages where they lived during the rainy winter months (Drucker, 1963; 1965). Villages along the coast and in major river valleys were supported by the region’s abundant natural resources, primarily salmon, smelt, eulachon, herring (roe), and shellfish. Western Red Cedar was used as a building material for longhouses and canoes and as a source of material for clothing (Boas, 1992). Up until 4 to 6 thousand years ago, Native Americans were likely hunter-fisher-gatherers; however, by the time Vancouver visited the region, most coastal Native Americans lived in permanent villages and relied on specific high-productivity resource areas. The transition from hunter-gatherer to more sedentary lifestyles was related to a number of factors: exploitation of the region’s abundant food resources, particularly salmon, which were increasing with the expansion of estuaries as sea level stabilized following the last glaciation (Mitchell, 1983); improved technology for fishing, hunting, and food storage; and increasing social complexity and organization (Deur, 1999).

Explorers and sea otter and beaver trappers arrived in Washington via ship or the Oregon Trail during the early 19th century. The first European settlement was established in 1846 at New Market, or Tumwater (near Olympia, fig. 1), as it currently known. In 1853, the Washington Territory was formed from part of the Oregon Territory. Logging started as early as the 1850s and quickly became a focal point of economic activity for the growing population. Forests were first harvested by axe and horse teams along marine shorelines, which also helped to open ports and facilitate shipping trade up and down the Pacific Coast (Chasan, 1981). Henry Yesler started the first steam-powered sawmill in the region, which was quickly followed by Pope and Talbot’s mill at Port Gamble. By the 1870s, fueled by the California Gold Rush, San Francisco became a major market of Puget Sound Basin timber. In the 1890s, about a decade after the arrival of the transcontinental railroad, Washington State was one of the top five producers of timber in the United States, had increased salmon landings by 2,000 percent over catches two decades earlier, and was attracting adventuresome entrepreneurs from around the country (Center for the Study of the Pacific Northwest, 2009). In short, the industrial revolution that brought railroads to Washington ushered in the mechanized era of natural resource extraction on par with the scale of the region’s natural resource bounty. However, the effects of the industrial revolution were not consistent across the Pacific Northwest. Oregon, which was founded by farmers, had a different land-use philosophy. This theme was touched on by Ivan Doig (1982): “Even what I have been calling the Pacific Northwest is a multiple. A basic division begins at the Columbian River; south of it, in Oregon, they have been the sounder citizens, we in Washington the sharper strivers. Transport fifty from each state as a colony on Mars and by nightfall the Oregonians will put up a school and a city hall, the Washingtonians will establish a bank and a union.”

A Changing Landscape

Washington achieved statehood in 1889 and its constitution reflects the Progressive Era’s heightened concern over the powers of central government (Lombard, 2006), and the belief in private property ownership in combination with untapped natural resources as the economic engine of the region (Conte, 1982). To disperse central government powers, the constitution provided substantial authority to local governments (counties, cities, and towns) to make and enforce regulations that do not conflict with general law, a legacy that continues to this day. For example, there are 2 countries, 100 cities, 12 counties, 12 conservation districts, 12 local health authorities, 3 regional councils, 22 Indian Tribes, 14 state agencies, 9 federal agencies, and 22 port districts that have some jurisdiction in Puget Sound environmental issues. As stated by Lombard (2006): “Power sharing reduces opportunities for abuse and pushes decision makers closer to the level of citizens most affected, but it also results in the fragmentation of authority of over key issues for ecosystems …”. Less than 1 year after the State Constitution was adopted in 1889, the legislature authorized the sale of land between the high and low tides (Washington Department of Natural

Resources, 2000) in an act entitled “Tide and Shoreland; Appraisement and Disposal of ” (Conte, 1982). By 1971, when the legislature prohibited such sales, only 40 percent of the tidelands in the Puget Sound Basin area remained in state ownership (Bish, 1982). Sale of tidelands was consistent with other Progressive Era and pro-growth agendas since most of the local commerce and industry were centered on marine harbors that provided access to deep-water shipping lanes. Although the issue was contentious at the time, ultimately selling of these tidal lands was viewed as a necessary precursor to timely port development (Conte, 1982).

The era of unmitigated ecosystem provisioning (exploitation) would come to a familiar conclusion. The peak of the salmon pack occurred in the decade from 1910 to 1919, while lumber production in the 12 counties surrounding Puget Sound declined from about 6 million board feet in 1926 to about 2 million by 1951 (Chasen, 1981). Throughout the 1920s, shellfish production declined, a fact that oysterman blamed on water pollution associated with the wood pulp industry. The economy would gradually become increasingly diversified and less dependent on natural resource extraction, particularly after the Second World War. By the mid-20th century, people of the region were coming to value Puget Sound and surrounding forests “as amenities, as objects of contemplation, and settings for avocational activities” (Chasen, 1981).

An Ecosystem in Decline

The Puget Sound Basin, like many coastal ecosystems worldwide, is in serious decline (U.S. Commission on Ocean Policy, 2004; Ruckelshaus and McClure, 2007; Heinz Center, 2008). Human population growth in the Puget Sound region has increased from about 1.29 million people in 1950 to about 4.22 million in 2005, and is expected to reach 5.36 million by 2025 (Puget Sound Regional Council, 2010; fig. 2). Much of the ecological capital (large salmon runs, mature forests, coastal wetlands, clean water) that supported extractive industries in the late 19th century has been exploited and degraded. Over the last 100 years, more than 60 percent of the State’s old-growth forest has been harvested, and much of the remaining old-growth remnants are limited to relatively high elevation public land (Washington Department of Natural Resources, 1998). Approximately 23 percent of Puget Sound Basin forestland has been converted to human-dominated uses, including agriculture and urban lands (Washington Department of Natural Resources, 1998). Tidal marsh and other river estuarine ecosystem types declined by 80 percent in the last 150 years through a process of diking and draining. Much of this loss occurred prior to statehood (Bortleson and others, 1980) as early farmers took advantage of flat and fertile, relatively treeless ground near river estuaries and flood plains. Currently, about a third of the Puget Sound shoreline has been modified by the construction of seawalls, docks, and other structures (Berry, 2000). Some of this shoreline modification and the pattern of coastal land use resulted from development of major ports in the late 1800s along with connecting rail lines, especially those running along the central eastern Puget Sound shoreline. However, Puget Sound is experiencing a relatively new (beginning around 1970) round of shoreline modifications related to residential (re)development. In the process of upgrading small vacation cabins and summer homes to larger, more expensive structures, many landowners are adding seawalls to protect their investments against threat of shoreline erosion (Small and Carman, 2005). Rivers and streams have been modified by dams and water withdrawals. Nearly one-fourth of the watersheds in Puget Sound basin are over-appropriated, that is, there is not enough water to supply granted water rights and also support fish and water quality (Washington Department of Natural Resources, 2000).
In 12 of 19 basins in the Puget Sound ecosystem for which data were available, a limiting factors analysis (Smith, 2005) rated water availability as poor, where a poor rating was associated with one or more of the following problems: 303(d) listing for low flow, known salmon mortality due to low flow or other studies documenting low flow problems, and prohibition to additional water allocation due to over appropriation. Point sources of water pollution have been effectively controlled even as their legacy remains, for example, the state identified 115 sites in 2008 representing more than 3,900 acres of contaminated sediments in Puget Sound (Washington Department of Ecology, 2008). Approximately 50 percent of this contamination results from readily indentified point sources including pulp, paper, and chemical production; and petroleum refining, transport, and storage. Water quality is increasingly threatened by nonpoint sources of contamination such as urban runoff from an extensive transportation network, and by new classes of chemicals such as endocrine disrupters and fire retardants that pervade our homes and businesses. The Center for Biological Diversity (2005) identified nearly 1,000 imperiled species in the region. A more recent assessment (Brown and Gaydos, 2007) noted that the number of marine related species of concern in the Salish Sea ecosystem had increased from 60 species in 2002 to 64 species in 2006. Although many species in these assessments use areas outside of the Puget Sound Basin, some iconic species or subpopulations, including Puget Sound Chinook Salmon, Steelhead Salmon, and the Southern (Puget Sound) Resident Killer Whale, are among those imperiled mostly by human related activities in the region.

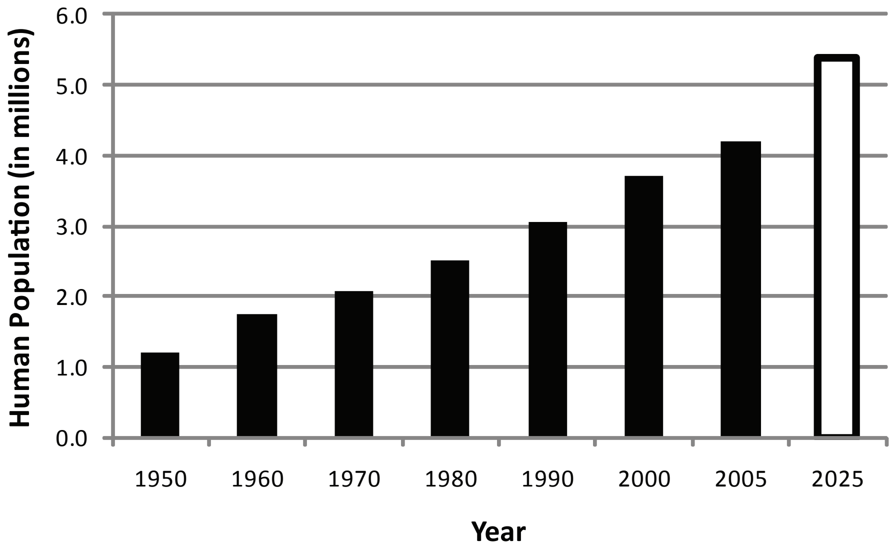

Figure 2. Human population estimates from 1950 to 2005 and projections to 2025 for the Puget Sound area of Washington State (Puget Sound Regional Council, 2010).

New Efforts to Protect Puget Sound

Many aspects of environmental issues today can be traced to land-use policy decisions made early in the history of the State, which makes the challenge of protecting and restoring the ecosystem that much more difficult. Nonetheless, Washington State and other entities are responding to the challenges of protecting and restoring the Sound in the face of increasingly important threats such as human population growth and climate change. Two new programs, the Puget Sound Nearshore Restoration Project (a joint effort sponsored by the Washington Department of Fish and Wildlife and U.S. Army Corps of Engineers) and the Puget Sound Partnership (a new state agency) are particularly promising. While details about these organizations are beyond the scope of this overview paper, both science-based programs recognize the need for a systems view of the issues (Millennium Ecosystem Assessment, 2005), the role humans play in the ecosystem, and the importance of addressing ecosystem process, structure, and function as part of the problem identification and solution.

In order to save Puget Sound, the same forces that shaped its early history, that is, the reliance on natural resource extraction, and the dispersed governance structure, must now realign. Benefits provided by a functioning ecosystem should be (re)defined in terms of ecosystem services that provide for both extractive industries (and the jobs they create) and other less visible but no less important benefits such as clean water, flood control, carbon sequestration, recreation, and fish and wildlife habitat. We must give clearer voice to the value of aesthetic, cultural, and spiritual ecosystem services, since they are difficult to quantify in traditional economic terms. Local government officials, who have been granted substantial power by the state, must recognize our inherent dependence on the ecosystem. Leaders must create a vision of the future that both supports functioning ecosystems and, in turn, is supported by the citizens they serve.

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The Geomorphic Setting of Puget Sound: Implications for Shoreline Erosion and the Impacts of Erosion Control Structures

Hugh Shipman[1]

Abstract. Puget Sound occupies a complex glacial landscape dominated by a steep, irregular coastline, eroding bluffs, and mixed sand and gravel beaches. The wave environment is fetch-limited and wave action is often oblique to the shoreline, emphasizing the role of longshore sediment transport in shaping coastal landforms and controlling erosion patterns. Beaches are laterally heterogeneous, reflecting the variable wave environment, differences in coastal geologic units, variability in the abundance and texture of local sediment sources, and the diverse assemblage of geomorphic features. Much of the shoreline is subject to erosion, although its rate and character varies with the complex coastal geomorphic setting. Long-term erosion rates are relatively slow, but also tend to be highly episodic, driven by storm events.

Approximately one-third of the Puget Sound shoreline is armored, although at a local scale this proportion varies significantly across the region. Historically, armoring occurred primarily along the margins of the large urban and industrial bays and river deltas, but most of the new armoring is in the form of seawalls and bulkheads associated with residential construction in less developed areas. Concerns about the potential impacts of armoring have increased in recent years, in part due to a greater awareness of the role of beaches and riparian zones in the greater Puget Sound ecosystem. Possible impacts include burial and modification of back beach areas, changes in delivery and transport of beach sediment, loss of ecological connectivity between terrestrial and aquatic environments, and beach changes due to the interaction of waves with structures. These concerns have led to increased scrutiny of armoring proposals and growing interest in alternative technologies to control erosion, including beach nourishment and hybrid structures employing vegetation or large woody debris. They also underscore the need for better information about erosion rates and sediment budgets, linkages between geomorphic processes and ecological functions, and the efficacy and environmental impacts of different erosion control approaches.

Introduction

Puget Sound has approximately 4,000 km of shoreline, much of it consisting of beaches and coastal bluffs subject to chronic erosion. Many segments of this shoreline are heavily developed, with roads, homes, and industry along the water's edge, particularly along the Sound's urbanized eastern shore. Other shoreline areas remain relatively unaltered, but are under increasing pressure as demand for coastal property rises within the rapidly growing urban region. This increased development of shorelines, and the attendant desire to protect and improve property, has resulted in the widespread construction of seawalls, revetments, and other forms of armoring.

These efforts, however, have raised concerns about the long-term impact of erosion control practices on shoreline dynamics, coastal ecosystems, and public responsibilities for managing the coast (Macdonald and others, 1994; Broadhurst, 1998). Shorelines by their nature lie on a narrow boundary between the terrestrial and aquatic landscapes, are ecologically important, and are managed under a complex suite of regulations (Carman and others, 2010). To make matters more challenging, erosion is not just a threat to shoreline property but is also an important natural geomorphic process that builds beaches and maintains coastal habitats (Johannessen and MacLennan, 2007).

Understanding the effectiveness of armoring and its potential environmental impacts requires an improved knowledge of the factors that influence erosion, the movement of sediment, and the complex contribution of erosion to the long-term maintenance of shorelines and coastal ecosystems. The purpose of this paper is to review the geology and coastal processes that shape Puget Sound shorelines and to summarize the issues that have emerged regarding the management of erosion on the region's beaches.

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Geologic Setting

The Puget Lowland occupies a north-south trough between the Cascade Mountains on the east and the Olympic Peninsula on the west (fig. 1). This depression is a major geologic feature resulting from the subduction of the Juan de Fuca Plate beneath the western edge of North America. Besides creating the broad physiographic setting of Puget Sound, tectonic processes have led to a complex distribution of older bedrock (Burns, 1985; Shipman, 2008). In much of the region, this bedrock is deeply buried under Pleistocene sediments and is not exposed at the shore, but in some areas, such as in the San Juan Archipelago, rocky shores are common.

The modern landscape of the Puget Lowland is largely a legacy of the Vashon glaciation (15,000–20,000 years BP), the most recent of several glaciations that have shaped the region (Easterbrook, 1986). This glacial history has influenced both the configuration of Puget Sound's shoreline and the sedimentary composition of its bluffs and coastal watersheds. Meltwater flowing southward beneath the ice is believed to have scoured the major troughs that define Puget Sound today (Burns, 1985; Booth, 1994). The glacier left a distinct north-south grain to the region's hills and valleys, which are superimposed on a broad outwash plain about 100 m above modern sea level (Booth, 1994). Much of the sediment exposed on the edges of river valleys and along the coastal bluffs is glacially derived, consisting of a diverse suite of lake-bed clays, outwash sands and gravels, coarse-grained till and glacial marine drift, and interglacial fluvial deposits.

Oceanographic Setting

Puget Sound, together with the Strait of Georgia to the north, form an inland sea connected to the Pacific Ocean through the Straits of Juan de Fuca. The Sound consists of a complex network of deep glacial channels and basins. The nearshore zone is typically restricted to a narrow platform, confined between a steep terrestrial landscape and deeper water offshore.

Sea-level history exerts an important influence over shoreline evolution. Post-glacial isostatic rebound had different effects in northern and southern Puget Sound, but occurred rapidly and was generally over by 8,000 years ago (Finlayson, 2006). During the late Holocene (the last 5,000 years), most regional shorelines have generally experienced gradual submergence similar to the global eustatic trend – tide gauge records in Seattle indicate an annual submergence of about 2 mm/yr (Mote and others, 2008). Tide gauges and leveling indicate that Washington's Pacific Coast and western portions of the Olympic Peninsula are emerging, but that this pattern does not extend into the Puget Lowland (Mote and others, 2008). There is also local evidence of abrupt co-seismic subsidence and emergence associated with Holocene faulting, which has profoundly affected shorelines near the faults, but that has not had regional-scale influence (Bucknam and others, 1992).

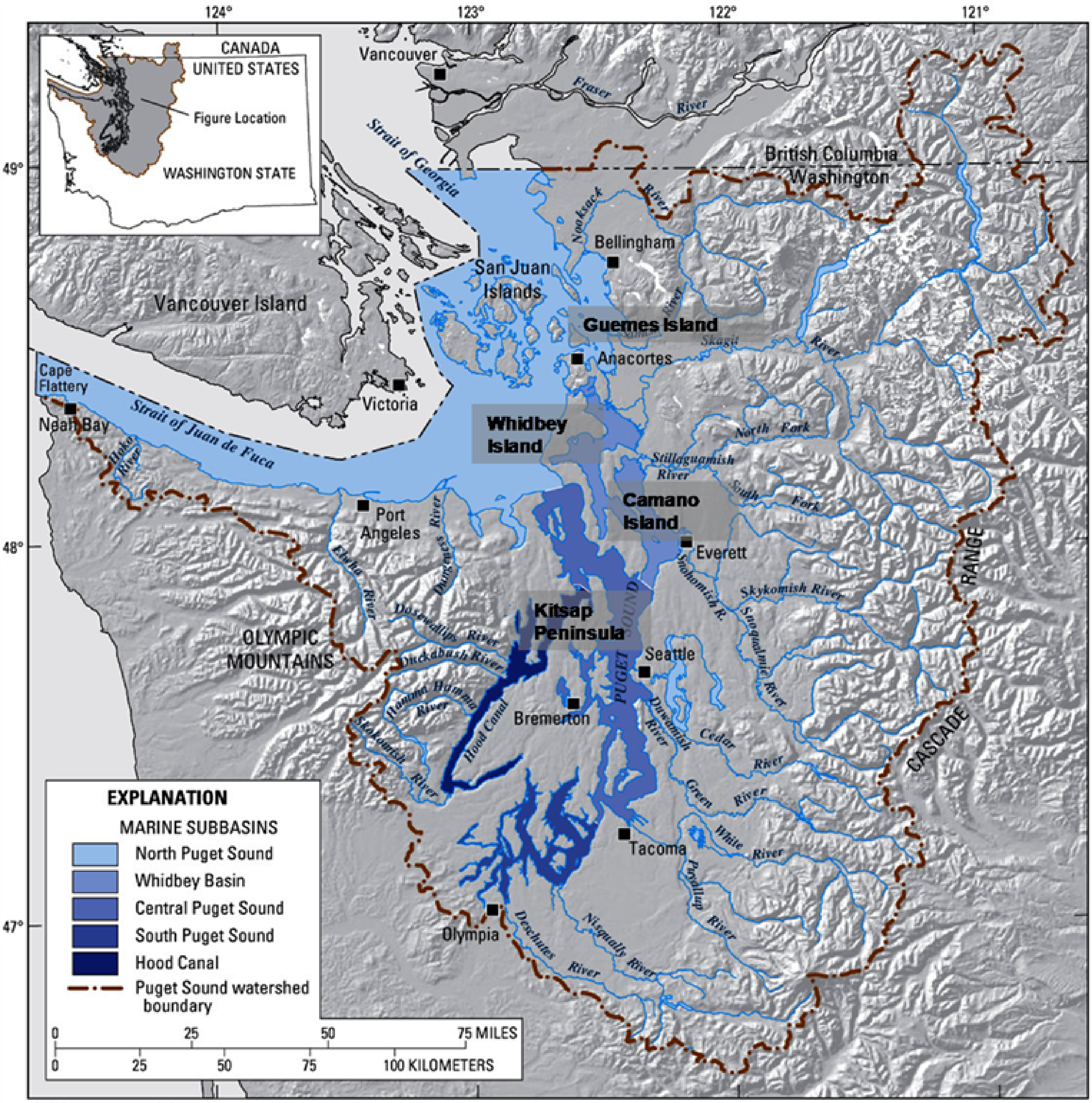
Puget Sound experiences mixed semi-diurnal tides, with the diurnal range increasing from about 2 m on the Strait of Juan de Fuca to more than 4 m in southern Puget Sound. The mixed tides are skewed towards the upper half of the tidal range, so waves most commonly interact with the upper portion of the foreshore (Finlayson, 2006). Although tidal currents may influence the evolution of the shoreline, they are not generally believed to be a major factor in shoreline erosion when compared to waves. Atmospheric pressure and other meteorological conditions contribute to local tidal surge, which can elevate water levels more than 0.5 m above normal levels during low-pressure winter storms. Annual sea level is subject to variability as a result of periodic El Nino events, which may result in sea level 20–30 cm higher along the west coast (Mofjeld, 1992; Subbotina and others, 2001).

Pacific Ocean waves and swell have little influence on Puget Sound except near the entrance, so wave generation is directly linked to local wind conditions. Because of the relatively small bodies of water, waves are fetch-limited and rarely exceed significant heights of 1–2 m or periods of greater than 3 seconds during storms (Downing, 1983; Finlayson, 2006). The fetch-limited conditions do not just result in smaller waves, but lead to significant longshore variability in the wave environment due to local variation in the orientation and length of fetch (Finlayson and Shipman, 2003; National Research Council, 2007).

Coastal Processes

The modern shoreline of Puget Sound developed as rates of global sea-level rise began to slow during the last 5,000–6,000 years. Rivers have continued to deliver sediment to the coast, building large estuarine deltas at their mouths. Streams have carried sediment from small coastal watersheds to the shore, contributing to the gradual evolution of small estuaries. Wave action has eroded the coastline and transported sediment, forming beaches and leading to the evolution of a wide variety of coastal landforms (Downing, 1983; Shipman, 2008). Of the Sound's 4,000 km of coastline, about half consists of bluffs and small barriers, with the remainder comprising bedrock shores, several large river deltas, and hundreds of sheltered estuaries and back-barrier lagoons.

Beaches on the Sound consist of a wide mixture of sediment sizes, dominated by coarse sand and gravel. Composition varies rapidly alongshore, reflecting heterogeneity of sediment sources, changes in the wave environment, and complex transport dynamics (Finlayson, 2006). Beaches are typically composed of a steep, coarse-grained beach face and gently-sloped, sandy low tide terrace.



PSNERP base map from U.S. Geological Survey digital data 1:2,000,000, 1972
Albers Equal-Area Conic Projection
Standard parallels 47° and 49°, central meridian 122°
Washington shaded relief, USGS, 30 meter DEM
British Columbia shaded relief, NASA, SRTM 90 meter

Figure 1. The Puget Sound basin, showing major rivers, oceanographic subbasins, and selected locations referred to in this paper.

Mixed grain-size beaches, such as those on Puget Sound, exhibit complex patterns of both crosshore and longshore sediment transport (Adams and others, 2007; Curtiss and others, 2008; Warrick and others, 2009). Like other estuarine beaches, those on Puget Sound are characterized by a veneer of mobile beach sediment, low longshore transport rates, and strong segregation of the shoreline into discrete littoral cells (Nordstrom, 1992; National Research Council, 2007). The beach face often exhibits a gravel surface layer overlying a more heterogeneous mix of gravel, sand, and shell fragments (Finlayson, 2006). Typical of beaches on other glacially influenced coastlines, coastal processes on Puget Sound are strongly controlled by the inherited glacial topography, the compartmentalization of beaches by resistant headlands, and an abundance of coarse-grained and varied sediment sources (Ballantyne, 2002).

Ultimately, beach behavior is not simply a function of wave environment and sediment size, but is a complex function of geologic controls, such as sediment supply, resistance to erosion, and antecedent topography and bathymetry (accommodation space). Local features such as cobble lags, stream mouth deltas, and historical landslides may exert significant influence over beach processes. Seasonal fluctuations in elevation and grain size occur on some beaches, but may be as much due to changes in dominant local direction of longshore transport as to cross-shore transport related to cyclical changes in storm waves and swell. Puget Sound resembles other relatively low-energy systems lacking swell components in that beach profiles may represent a persistent response to larger storms and storms may tend to generate a shore-parallel retreat of the beach face (Nordstrom and Jackson, 1992; Finlayson, 2006).

The largest waves on Puget Sound are generated by winds that are topographically channeled along the north-south water bodies, leading to wave action that is often highly oblique to the shore, strengthening the role of longshore sediment transport in shaping the shoreline (Finlayson and Shipman, 2003). Redistribution of coastal sediment has resulted in the widespread occurrence of spits, cuspate forelands, and other types of barrier beaches (fig. 2).

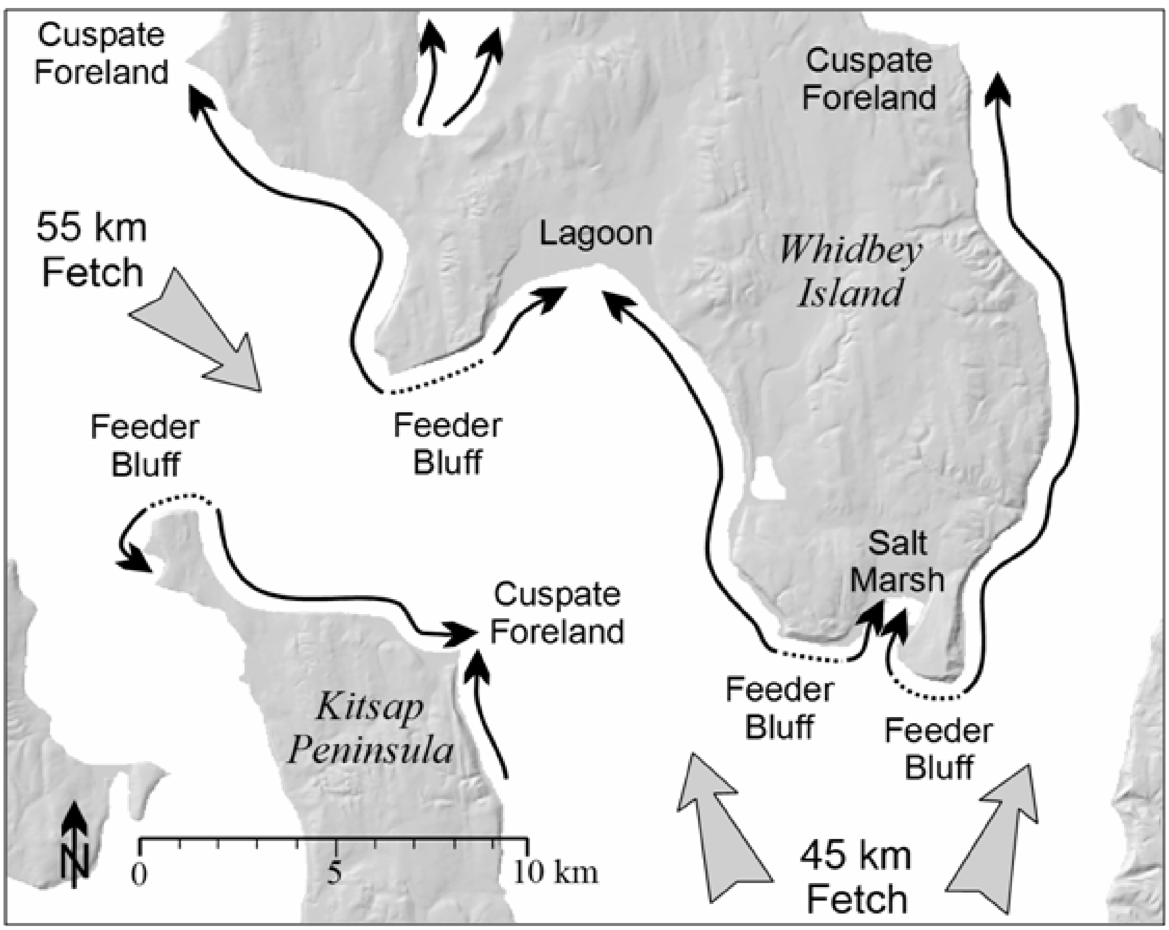


Figure 2. The complex pattern of longshore sediment transport (black arrows) and littoral cells in north central Puget Sound (from Finlayson and Shipman, 2003). Net transport patterns reflect the combination of maximum fetch (large arrows) and the predominance of southerly storm waves.

The strength and direction of wave action can vary significantly in the longshore direction, leading to significant changes in potential sediment transport. This may contribute to both complex evolution of shoreline landforms (Ashton and Murray, 2006) as well as to local variability in erosion patterns. The irregular shape of the shoreline, combined with the fetch-limited wave environment, leads to the division of the coast into hundreds of discrete littoral cells, each with its own sources and sinks of sediment (Schwartz and others, 1989). Transport rates are orders of magnitude smaller than those typically found on ocean coasts (Wallace, 1988) in part due to the lower wave energy, but also due to the coarse-grained material and the fact that some beaches may be sediment-limited (the capacity of waves to move sediment may exceed the amount of sediment available).

Eroding coastal bluffs are the primary source of beach sediment on most Puget Sound beaches (Keuler, 1988; Johannessen and MacLennan, 2007), although sediment abundance and size varies significantly, even over short reaches (fig. 3). Small streams may be a source of sediment on some shorelines where coastal drainages yield large amounts of sediment and where the configuration of the stream mouth allows transfer of sediment out of the estuary into the beach system. Conversely, larger rivers such as the Skagit, Nooksack, or Nisqually carry large volumes of material into Puget Sound (Downing, 1983), but are not considered major sources of beach sediment, as most empty into the heads of bays, where the coarser grained sediment is retained within the river delta. The Elwha River is a notable exception, as its configuration and location along the Strait of Juan de Fuca make it a significant element of the local coastal sediment budget (Galster and Schwartz, 1990).

Figure 3. Eroding bluff on Guemes Island. 30-40-m high bluff consists of a diverse assemblage of Pleistocene glacial and glaciofluvial units and a wide range of sediment types, from silt to coarse gravel and boulders.

Shoreline Erosion

Much of Puget Sound's shoreline is subject to erosion and retreat, as demonstrated by the widespread occurrence of steep coastal bluffs and eroding barrier beaches. Mechanisms and rates vary significantly from one location to another and are influenced by the wave environment, the resistance of coastal materials to erosion, the nature of the landform (bluff, barrier beach, or artificially filled shoreline), and the character of the adjacent beach. Patterns of erosion reflect the complex geologic and wave environment and therefore vary significantly from one location to another. Erosion mechanisms differ among landforms. Erosion is most often associated with coastal bluffs, spits and other barrier beaches, and with anthropogenically-modified shorelines.

Erosion and retreat of coastal bluffs is a complex function of wave-induced toe erosion, driven by major storms coupled with high water levels, and hillslope mass-wasting, typically triggered by heavy rainfall and elevated groundwater levels (Gerstel and others, 1997; Hampton and others, 2004). The rates and mechanisms of bluff erosion vary significantly due to differences in bluff height, geology and hydrology, wave exposure, and other factors (fig. 4). Bluff erosion is highly episodic and usually occurs as discrete slope failures (Shipman, 2004; Johannessen and MacLennan, 2007), although mass-wasting events can range from shallow debris avalanches to large, deep-seated landslides subject to periodic reactivation. Bluff erosion also has a complicated relationship with beach condition, since beaches on Puget Sound derive much of their sediment from bluff erosion and a broad beach or high storm berm can provide substantial protection to the bluff toe from wave action. Long-term bluff erosion depends on both the ability of wave action to erode the toe of the bluff and the capacity of waves to transport eroded sediment away from the site so that direct erosion of the bluff toe can continue (Keuler, 1988).

Barrier beaches are classified as depositional landforms, and on Puget Sound these beaches are often locally referred to as *accretion beaches*. This terminology derives from the long-term constructional nature of these landforms, but can lead to confusion, since barriers are often subject to erosion and can be highly dynamic landforms. Barriers erode either by thinning and narrowing due to transport of sediment away from the site (offshore or alongshore) or by overwash and landward migration, examples of both of which can be observed on Puget Sound. Erosion typically occurs during major storms, when waves can erode the beach face or overwash the berm (fig. 5). Barrier landforms often have complex configurations, and it is common for some portions to erode while others remain stable or accrete. In addition, barriers are often associated with stream mouths or tidal inlets where additions of sediment or currents can complicate erosion patterns. Barrier erosion and landward migration is an inherent aspect of long-term coastal retreat, but it can be aggravated by changes to local sediment budgets due to anthropogenic activities (Komar, 2000). This may be most notable adjacent to jetties and large groins where sediment transport is blocked, but can also result from the armoring of updrift bluffs and the loss of sediment supply, as has occurred at Ediz Hook near Port Angeles (Galster and Schwartz, 1990; Komar, 2000).

Although erosion is most widely associated with bluffs and barrier beaches, it can occur in other settings as well. Bedrock shorelines may erode, although rates are low or negligible in more resistant lithologies. Marshy shorelines, typical of deltas and estuaries, can also erode, although forcing mechanisms may be very different than on beaches, relating to changes in fluvial sedimentation patterns and tidal channel evolution. Some of the most significant erosion on Puget Sound occurs along historically filled shorelines where armoring is lacking or is poorly maintained – such as on old, inactive industrial sites. Fill materials are often easily erodible and have, by definition, been placed seaward of the original shoreline, steepening the profile and increasing exposure to wave action during a greater range of tides.

Few studies of erosion rates have been carried out on Puget Sound, in part because determining reliable long-term rates is made difficult by the generally slow and highly episodic nature of erosion and the lack of reliable historical data on shoreline position. Shipman (1995) summarized data on erosion rates from numerous studies in the region and found they generally ranged from a few centimeters to several tens of centimeters per year. These studies were largely of coastal bluffs and may have been biased to sites with high erosion rates. Erosion typically occurs in pulses, associated with rainfall-induced landslides or with large storms during very high tides, and commonly are separated by long intervals of relatively little change (Johannessen and MacLennan, 2007). Given the variability of rates from year to year, Keuler (1988) suggested that at least 20 years of record were necessary to establish a reliable long-term average. A general observation on many Puget Sound bluffs is that a bluff may retreat approximately 1 m in a typical landslide, and that such slides might occur every 40 years. This corresponds to a rate of 2.5 cm/yr, or 2.5 m in a century.

Rates of erosion can also vary spatially, even over short distances, due to changes in geologic conditions, variation in wave exposure, differing human activities, or variability in the local availability of beach sediment (Komar, 2000). Even along coastal reaches with similar wave energy and geology, bluff retreat rates can vary significantly due to differences in the character of the beach (Keuler, 1988; Shipman, 2004) and its ability to protect the coast from wave action.

Figure 4. Contrasting examples of bluff erosion in Kitsap County. (*A*) Low bluff of glacial till subject to wave-induced erosion. (*B*) Large deep-seated landslide.

Figure 5. Examples of barrier beach erosion. (*A*) Barrier beach on Camano Island. Gravel deposits on the landward side of the berm (arrows) are recent overwash from a major high tide storm. (*B*) Eroding barrier and dunes on northwestern Whidbey Island, indicated by fresh scarp and fallen trees.

Armoring on Puget Sound

Seawalls, bulkheads, and revetments have been constructed on approximately one third of Puget Sound's shoreline, although on a local scale the proportion varies regionally due to differences in development patterns and shoreline type (Berry and others, 2001). Armoring is most extensive on the heavily developed eastern shore between Everett and Tacoma and generally less pervasive along portions of northern and western Puget Sound, where development levels are lower and bedrock shorelines more common. Historically, most armoring was associated with the protection of agricultural dikes and levees in river deltas, the construction of railroads and roads along the shore (fig. 6), and the reclamation of intertidal and low-lying areas for industrial development (Macdonald and others, 1994). Much of this type of development occurred in the 19th and early 20th centuries. In the 1950s, coastal development activities had shifted to larger shoreline residential communities, many with elaborate canal configurations. This often involved large-scale dredging and filling of coastal wetlands and was largely ended by the adoption of environmental regulations of the early 1970s. Most new armoring on Puget Sound takes the form of seawalls and bulkheads in conjunction with residential development, along with ongoing repair and replacement of older structures. The high value of coastal property, the widespread occurrence of eroding shorelines, and the relatively mild wave environment make armoring both desirable and effective.

Figure 6. Railroad along the shoreline between Seattle and Everett. The seawall was constructed in the early 1900s to protect the railroad, which had been built on the beach below the high bluffs. The upper beach is buried by the railroad grade. This photograph was taken at an extreme low tide; a normal high tide would extend to the seawall, leaving no beach exposed.

Although armoring activities are more tightly regulated than they were historically, the practice remains common (Carman and others, 2010).

Erosion control structures on Puget Sound differ widely in design and construction, reflecting not just site conditions and cost, but also historical practice and local contractor expertise (Downing, 1983; Terich, 1989). Vertical bulkheads (the terms bulkhead and seawall are often used interchangeably on Puget Sound) are standard practice on residential sites and may be constructed of rock, concrete, wood, or other materials (fig. 7). Currently, the most widely used technique is a near-vertical placed-rock wall (locally called a rockery or a rock seawall). Sheet-pile walls and riprap revetments are commonly employed in industrial and urban settings, particularly where structures were built farther seaward and at lower tidal elevations.

There have been significant changes in armoring practice over time, reflecting increased regulation of shoreline activities and a shift from large-scale reclamation of intertidal areas to more conventional erosion control on naturally eroding shorelines. Whereas historically, structures were often built in conjunction with extensive intertidal fill, new structures are usually required to be kept as high on the shore as feasible. Much new armoring is either replacement of older structures in heavily developed areas or the construction of new structures on less developed rural and suburban shorelines.

The role of armoring varies among sites. On bluffs, armoring may be designed to reduce toe erosion or be part of a more complex slope stabilization effort. On low-lying shorelines, armoring may be intended primarily to reduce overtopping and flooding or to minimize storm damage from waves and drift logs. On historically filled sites, armoring is necessary to retain fill material and may also support marine activities such as boat moorage and freight handling. Armor is often placed to protect other shoreline structures such as pier abutments, stair landings, boat houses, stormwater outfalls, and utility infrastructure. The widespread use of armoring on residential shorelines is attributable not just to its need for protecting upland structures from erosion, but to its role in site planning and landscaping, creating safe and convenient access to the water, improving recreational use of the shoreline, and to its contribution to both perceived and real property value.

Figure 7. Typical examples of residential erosion control on Puget Sound. In each case, high tides would reach the seawall. (*A*) Rock seawall in Kitsap County. (*B*) Timber pile bulkhead on Camano Island. (*C*) Concrete bulkhead on a barrier spit in Anacortes.

Impacts of Armoring

Concerns about the potential adverse impacts of erosion control structures on Puget Sound have risen in recent years due to a greater awareness of the role of beaches and riparian zones in the greater Puget Sound ecosystem (Gelfenbaum and others, 2006; Quinn, 2010), new studies from other regions suggesting a range of environmental problems associated with hardened shorelines (National Research Council, 2007), and the continuing local trends in new seawall construction.

The effects of armoring on Puget Sound shorelines are strongly related to the geologic processes that shape the shoreline and maintain beaches and coastal habitats. Successful control of erosion of coastal bluffs removes an important source of beach-forming sediment. It may also reduce the natural supply of large wood and detritus to the shoreline ecosystem that accompanies natural erosion events. The significant role of longshore sediment transport on Puget Sound increases the likelihood that alterations to sediment processes in one location may eventually impact shoreline conditions elsewhere within a littoral cell. The construction of seawalls and bulkheads on eroding coastlines may effectively protect upland areas, but does not prevent continued retreat of the beach itself, with the result being the gradual narrowing of the upper beach and loss of upper intertidal habitats. The lateral heterogeneity of Puget Sound beaches means that the effects of armoring may vary considerably from one location to another and that long-term trends in shoreline condition may be difficult to separate from natural variability in short-term investigations.

Several reviews of the impacts of armoring on Puget Sound have been undertaken, examining relevant local and national research on both physical and biological processes (Macdonald and others, 1994; Thom and others, 1994; Williams and Thom, 2001). In addition, assessments of armoring have been made within specific geographic regions of the Sound, such as Thurston County (Herrera Environmental Consultants, 2005) and King and Snohomish Counties (Johannessen and others, 2005). More focused studies of beaches have looked at biological responses to armoring and altered riparian connections (Sobocinski, 2003; Rice, 2006) and the geological responses of shorelines to changes in the delivery and the transport of beach sediment within the littoral system (Galster and Schwartz, 1990).

These regional studies suggest a broad range of potential effects of erosion control structures on Puget Sound shorelines. In general, these can be categorized as follows:

- *Loss of upper beach and backshore*. Even when built high on the beach profile, seawalls typically eliminate a narrow zone of the high tide beach. On Puget Sound, this may result in the absence of accumulated drift logs and beach wrack and the loss of dry beach at high tides, which may in turn reduce the area available for forage fish spawning (Penttila, 2007) and for recreation.

- *Aquatic-terrestrial connectivity*. Armoring modifies the natural transition between terrestrial and aquatic ecosystems. This can affect movement of materials and organisms between systems, reduce the quality of riparian functions, and introduce discontinuities to this narrow ecotone and ecological corridor. Structures also tend to result in alterations to the pattern of natural drainage to the beach.

- *Passive erosion*. Most shorelines in Puget Sound are naturally eroding. A seawall or revetment may effectively stabilize the area landward of the structure, but does nothing to address the underlying retreat of the beach face or shoreline, which will continue on the seaward side of the structure (Fletcher and others, 1997; Griggs, 2005). With time this results in narrowing of the remaining beach, the loss of the upper beach, and increased interaction of the structure with waves. This is a significant impact of armoring, but one that may take many decades to appear.

- *Sediment delivery and transport*. Seawalls on coastal bluffs stop the natural erosion of the bluffs, thereby reducing the delivery of sediment to the littoral system and reducing the overall budget of the local littoral cell. Seawalls that encroach across the beach, either because of their original construction, or because of subsequent erosion of adjacent shorelines (passive erosion), may act as groins, impeding longshore transport of sediment and leading to localized erosion on downdrift properties.

- *Altered wave action*. At higher water levels, waves can reflect off of structures, possibly increasing erosion and scour and in some case influencing longshore sediment transport patterns (Griggs, 2010; Ruggiero, 2010). Engineers have long been aware of localized end effects associated with seawalls and other coastal structures (Kraus and McDougal, 1996).

Documenting the impacts of armoring is challenging due to the significant spatial and temporal variability associated with beach systems, the long-term nature of some of the responses, and the cumulative impact of shoreline modifications. In addition, separating the effects of armoring from the effects of other shoreline activities can be difficult. Examples include increased stormwater runoff, loss of forest cover, modification of natural drainages, and construction of other marine facilities such as piers, access stairs, outfalls, and boat launches. In some cases, seawalls can facilitate development closer to the water than might otherwise occur, increasing the likelihood and magnitude of these other impacts.

Increasing concerns among regulators about the possible impacts of armoring have led to closer examination of proposed projects, including requirements that proponents more rigorously demonstrate the threat from erosion and demonstrate that they have considered alternative designs

(Carman and others, 2010). Within the Puget Sound region, interest has grown in "softer" approaches to erosion control, such as beach nourishment, biotechnical methods (erosion control and slope stabilization using vegetation), and structures employing natural elements such as cobble and large wood (Zelo and others, 2000; Shipman, 2001; Barnard, 2010). In addition, the restoration community has taken an active interest in opportunities to remove or modify existing armoring as a way of restoring natural shoreline ecological functions and improving beach-oriented recreational opportunities (Hummel and others, 2005; Cereghino, 2010).

Summary

Shoreline erosion will remain a major issue on Puget Sound during coming decades. Regional population growth will lead to more development along the coastline, and the prospect of higher sea levels raises the possibility of faster erosion and increased storm damage. At the same time, concerns about protecting and restoring the Puget Sound environment, including its coastlines and beaches, will increase attention on activities such as armoring that have long-term impacts on shoreline functions. Making decisions about how, where, and whether to armor the shoreline will be important to addressing this potential conflict, but will require better understanding of both the processes that shape Puget Sound's coastline and the range of strategies that can be employed to reduce both hazards and loss of natural resources.

A number of areas of scientific inquiry would contribute to improving the science related to erosion and the impacts of shoreline armoring on Puget Sound. These include:

- Better information about erosion rates, sediment budgets, and patterns of shoreline change. Some of this information can be derived from local studies, but some may come from careful application of work done in other regions that is applicable to the unique conditions of Puget Sound (for example mixed sediment beaches, bluff-dominated systems, and fetch-limited shorelines, including lakes).

- Improved understanding of the factors influencing erosion and the sensitivity of beaches and shorelines to changes in sediment supply and to long-term changes in water levels.

- Interdisciplinary efforts among geologists, biologists, and engineers. Many of the most damaging impacts of armoring may be related to the response of ecological systems to changes in physical and geomorphic characteristics of the shoreline. Evaluation of short-term effects of structures and of alternative methods of controlling erosion involves engineering and design skills, as well as better biological and geological understanding.

- Well-designed empirical studies comparing armored and unarmored sites. These will benefit from collection of environmental data (waves and water levels), coordinated physical and biological measurements, and judicious selection of both spatial and temporal sampling intervals. Long-term studies will be particularly valuable.

- Development of long-term, placed-based studies of longer shoreline reaches, where investigations of environmental conditions, sediment processes, and biological responses can be carried out simultaneously. In the absence of such work, it may be difficult to gain understanding into the complex relationships between geological, oceanographic, and ecological processes.

- Evaluations of the geomorphic and engineering response of shorelines to a variety of conventional and alternative stabilization measures and the effectiveness of these methods in controlling erosion. Care will need to be taken in assuring comparable conditions between sites.

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Overview of the Ecology of Puget Sound Beaches

Megan N. Dethier[1]

Introduction

As described elsewhere in this Proceedings (Shipman, 2010), shorelines in Puget Sound are diverse in terms of geomorphology and corresponding biotic communities. In marine and estuarine ecosystems, a limited set of physical parameters – substrate type, depth or elevation, and wave or current energy – strongly constrain the distributions of organisms (Dethier, 1990; Kozloff, 1993; Dethier and Schoch, 2005); this linkage is now acknowledged in national systems for classifying marine habitats, which rely in large part on these physical factors (for example, Allee and others, 2000; Madden and others, 2009). In estuaries, patterns of variation in salinity and temperature also contribute to the character of the biota, but because these often co-vary with other physical parameters, it is difficult to tease out critical forcing factors (Dethier and Schoch, 2005). For example, moving from the mouth to the head of an estuary usually involves gradients in sediment type (sand to mud), wave energy (high to low), salinity (marine to fresh, or less variable to more variable), and temperature (usually more stable to less stable). These gradients exist even in deep, well-mixed fjordal estuaries like Puget Sound, although ranges in salinity and temperature are much less than in drowned-river estuaries like the Chesapeake (Dethier and others, 2010). There salinities range from pure fresh to pure marine along the gradient, whereas in Puget Sound salinity seldom drops below 25 practical salinity units (psu) except directly in front of river mouths. As a result of this relative uniformity in water characteristics, the primary factors controlling the ecology of Puget Sound beaches are likely to be substrate type and wave energy, which also co-vary (for example, mud is not found in areas of high waves or currents). The following discussion of the ecology of Puget Sound beaches thus focuses on the plants and animals characteristic of the various beach types, as defined largely by substrate type.

Shoreline Types

The complex coastline of Puget Sound consists of a large proportion of linear, relatively open shorelines plus small to large embayments and several large river deltas. No beaches in the Sound are exposed to oceanic swells, and thus none would be classified as Exposed or High Energy in various classification systems (Dethier, 1990; Washington State Department of Natural Resources, 2001). There is, however, a range of energies from moderately exposed, on beaches open to long north-south wave fetches, to very protected in shallow embayments, such as those common in south Sound. The range of wave and current energies results in a range of unconsolidated sediment types that comprise the beaches, from coarse gravel-cobble to very fine, organic-rich silts.

Several attempts have been made to quantify the relative abundance of different beach-sediment types within the Sound. Figure 1 shows one such effort, derived from the DNR data, based on the simple length of shorelines categorized into particular substrate types (but ignoring the width of the intertidal zone or polygonal areas such as deltas). This system places every shore 'unit' into one substrate category, even though a given stretch of shore may have (for example) coarse gravel on the upper shore and fine mud on the lower shore. Another effort (Bailey and others, 1998) used shoreline area rather than length, classifying each polygon (including one zone of a complex beach) into a substrate category. Despite these differences, the data on relative proportions of different substrate types are surprisingly similar. Puget Sound beaches are dominated by pebbles, sand, and mud (fig. 1), commonly in combination; a frequent pattern on beaches open to the Sound is a coarse pebble-sand mix on the upper shore and cleaner sand on the lower shore. Upper-shore communities are discussed separately below; it is at these higher levels where shoreline armoring (hardening with seawalls, riprap, or other solid structures) generally occurs. Larger size sediments and consolidated (rocky) shorelines are uncommon, although an ecologically important beach type (see below) is the mixed-coarse or rock-gravel-sand type that is scattered throughout the Sound. The dearth of bedrock shores and preponderance of erodible beach types leads to the high demand for armoring for shoreline protection. The different beach types vary dramatically in the productivity and diversity of their biota, and in their perceived "value" to humans; these factors are discussed below.

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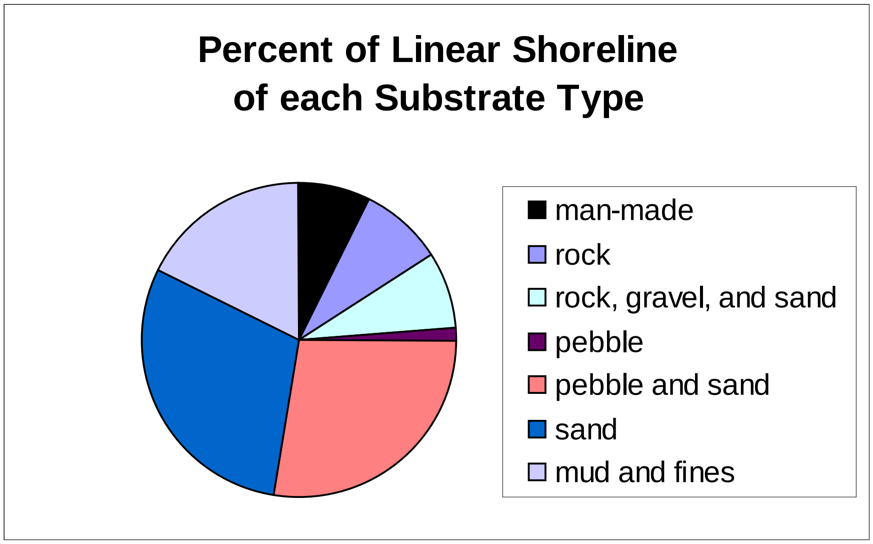

Figure 1. Percent of linear extent of shoreline (not area) in Puget Sound estimated for each substrate type. Substrate types are categorized on the basis of aerial observations and thus do not comprise particular grain sizes. The "rock, sand, gravel" type is similar to the "mixed coarse" in other classifications. From Washington State DNR data, 2001. http://www.dnr.wa.gov/Publications/aqr_nrsh_shrzne_sum_find.pdf.

Biotic Communities

Mud Habitats

The material on muddy beaches in Puget Sound ranges from extremely soft and anoxic muds to firmer sandy mud, sometimes called "mixed fines" (table 1). Primary producers in these habitats consist mostly of benthic diatoms, which sometimes form a thin brown coating on the sediment surface; these are actually highly productive organisms despite their very limited biomass (Thom, 1989; Thom and Albright, 1990). Green algal blades ("ulvoids," of several species) may be present, either attached to pebbles, bits of shell, or worm tubes, or free-floating; these too are highly productive (Thom, 1984). If dense mats develop in one location, they may kill beach infauna because they prevent feeding and oxygenation of the sediment below them, and rotting mats add a huge biological oxygen demand (Bolam and others, 2000; Auffrey and others, 2004). Eelgrass (*Zostera marina*: see below) is found in sandier areas in the low intertidal zone, although not in bays in southernmost Puget Sound (Washington State Department of Natural Resources, 2001).

Mud shores, as well as mixed-fine shores, are often dominated by burrowing mud shrimp (*Upogebia pugettensis*) or ghost shrimp (*Neotrypaea californiensis*), which aerate but further soften the sediment with their extensive burrow systems (Dumbauld and Wyllie-Echeverria, 2003). Some broad muddy tide flats in protected coves have thousands of characteristic mounds from these species. Other common occupants of mud are deposit-feeding clams (especially *Macoma nasuta* and *M. balthica*), some polychaetes (especially spionids and capitellids), and amphipod crustaceans (especially corophiids). Until the early 1900s, many muddy shores in Puget Sound, especially in southern bays, had dense populations of the Olympia oyster, *Ostreola conchaphila*; however, a combination of overharvesting, pollution, and introduced predators reduced their populations to very small levels (McKernan and others, 1949). Another commercial shellfish species, the geoduck clam *Panopea generosa*, can be found very low on muddy shores but it is more common in higher-energy and subtidal habitats (Dethier, 2006).

Mixed-Fine Habitats

Many open shorelines in Puget Sound have mid-low shore areas characterized by a mix of sand and mud, often referred to as "mixed-fines." This substrate may be optimal for eelgrass (Mumford, 2007), both the native *Zostera marina* and the introduced *Z. japonica*. The native eelgrass lives low on the shore and in the shallow subtidal zone, while the Asian species tends to inhabit slightly higher zones. Both are highly productive species that also stabilize the substrate, and create refuge habitat and feeding grounds for juvenile fishes, crabs, and other species (reviewed in Mumford, 2007). They are critical habitat for juvenile salmon migrating along the shoreline. Co-occurring with eelgrass, or in areas between eelgrass patches, are a variety of infaunal species characteristic of either mud and sand habitats, such as amphipods, *Macoma* clams, horse clams (*Tresus* spp.), geoducks, burrowing sea cucumbers and anemones, and a variety of tube-building and mobile polychaete worms.

Table 1. Summary of key ecological features of different shoreline habitats in Puget Sound.

[Species richness data come from identical 50-m transects at different areas around the Puget Sound (Dethier and Schoch, 2005; Dethier and Berry, 2009). N.D., not determined]

Habitat	Primary producers	Dominant species	Species richness	"Valued" species
Mud and mixed-fine sediments	Diatoms, ulvoids, eelgrass	Ghost and mud shrimp, bent-nose clams, polychaete worms, amphipods	15–30	Olympia oysters, shorebirds, geoduck clams, juvenile salmon, Great Blue Heron
Sand	Very few, sometimes eelgrass	Sand dollars, cockles, horse clams, polychaetes	5–25	Shorebirds, geoduck clams, human recreation
Mixed-coarse	Green, red and brown macroalgae including some kelps	Ulvoids, barnacles, anemones, crabs, snails, clams, seastars, polychaetes	25–75	Hardshell clams, Cancer crabs, Pacific oysters
Bedrock or Artificial	Green, red and brown macroalgae including some kelps	Rockweed, ulvoids, mussels, barnacles, snails, seastars	N.D.	Some shorebirds, Pacific oysters
High-Shore (sand and pebbles)	Very few intrinsic	Amphipods, isopods	N.D.	Forage fish (spawning), juvenile salmon (feeding), shorebirds, human recreation

Sand Habitats

Moderate-energy, open sand beaches and embayments often have extensive eelgrass beds; only in the areas of greatest wave fetch does the substrate become too unstable for eelgrass to remain rooted. Certain beaches in Puget Sound without eelgrass have beds of sand dollars (*Dendraster excentricus*), which live primarily subtidally but extend up into the low or even mid-shore. When present, they tend to be very dense (reaching densities of >1,000/m^2) and exclude other biota via bioturbation (Schoch and Dethier, 1997). The relative instability of the sediment in these higher-energy beaches reduces the density and diversity of occupants. Beaches without eelgrass or sand dollars have sparse clam populations (including *Macoma secta*, horse clams and *Clinocardium* cockles), and a different array of sparse polychaete species than in mud. Commercially valuable geoduck clams can be found naturally or cultured on sandy shorelines. Upper shore areas, as in mixed-fine habitats, tend to be composed of depauperate steep gravel-sand sediments.

Mixed-Coarse Habitats

In areas where cobbles (>~10 cm diam.) are abundant on the low shore, the substrate is stabilized into a complex mix of cobbles, pebbles, and sand; these habitats harbor a rich flora (on the cobbles) and fauna (both on the cobbles and infauna) (Dethier and Schoch, 2005). These are by far the richest intertidal habitats in Puget Sound, and probably have the highest primary and secondary productivity (table 1). Ulvoid algae often cover the cobbles, especially in the summer, and there are smaller amounts of diverse red, brown, and additional green algae. In areas rarely uncovered by the tide, large amounts of kelp (as well as the invasive brown alga *Sargassum muticum*) are present. Animals living attached to or hiding under the cobbles include barnacles, anemones, crabs (including recreationally important *Cancer* spp.) and smaller crustaceans, and snails of many types. The infauna living in the sediment beneath the cobbles is likewise diverse, with many more species and higher biomass than in sand or mud habitats. These include a wide diversity of polychaetes and other worms, small crustaceans, and other invertebrates.

Recreationally and commercially harvested clam species are abundant; these include hardshell clams such as littlenecks (*Protothaca* spp. and *Venerupis*), butter clams (*Saxidomus* spp.), and others (for example, *Macoma inquinat*a, cockles). Predators on these clams include seastars, moonsnails, dogwhelks, Cancer crabs, marine birds, and humans. While most of these clam species can be found in other habitats, they reach highest abundances in this mixed sediment, probably because individuals of all sizes are hard for predators and wave energy to reach; digging in the substrate is difficult, even for humans with shovels. The importance of cobble for successful survival of these clams was found long ago, when beach owners and aquaculturists began adding gravel or cobble to sandy beaches to enhance clam abundance and growth (Glude, 1978; Schink and others, 1983; Thom and others, 1994). In some areas, for example throughout Hood Canal, introduced Pacific oysters (*Crassostrea gigas*) are common on the mid and low shore, attached to cobbles or to each other.

Bedrock Habitats

Bedrock shorelines are quite uncommon in the Sound proper (fig. 1), although they dominate the shore in the San Juan Islands. Artificial “shorelines”, such as riprap around marinas, may contain similar biota to bedrock shores (Pister, 2009), although these similarities have not been studied in Puget Sound. Patches of hardpan (resistant basal till) are present on some beaches, but their biota has not been surveyed extensively. In general, the plants and animals seen on these hard substrates are an estuarine-tolerant subset of those seen on more-marine shores such as in the San Juans. *Fucus* (brown rockweed) is the dominant primary producer. Other common species include barnacles, blue mussels (*Mytilus trossulus*), various small snails and limpets, small crabs, chitons, and seastars. Areas where silt settles on the rock have even lower diversity.

High-Shore Habitats

Although mid- and low-shore beach substrates and biota vary widely around Puget Sound, the upper-shore areas of many beach types are similar; frequently, beaches that have sand, cobble, or even mud in the low shore have very different sediment at higher elevations. Mid-shore beaches tend to be steeper and often coarser than the low shore, characterized by pebbles, small cobbles, and sand. They are physically unstable and biologically relatively depauperate in marine species, with sparse populations of worms and small crustaceans (amphipods and isopods). At the highest shore level, however, the beach is often less steep and more stable, creating a zone that fills several key ecological functions (Rice, 2010; Toft and others, 2010). Areas at or above Ordinary High Water are often either sandy or have sand mixed with pebbles, and are the site of accumulation of driftwood and detritus from both terrestrial and marine sources. They can be densely occupied by talitrid (“beach hopper”) amphipods, which are important decomposers and are prey for some shorebirds (Dugan and others, 2008). This is also the habitat used for spawning by several species of forage fishes that are central to Puget Sound food webs (especially surf smelt (*Hypomesus pretiosus*) and sand lance (*Ammodytes hexapterus*): see Penttila, 2007 and Rice, 2010). However, this supratidal zone is often covered by armoring, which effectively eliminates all these ecological functions unless it is built well above the zone of the highest high tides.

Marsh Habitats

Marshes in Puget Sound range from areas encompassing many square miles of vegetation (for example, rushes, sedges, grasses) on the large river deltas to narrow strips of marsh plants (for example, pickleweed *Salicornia*) in the supratidal zone of low-energy linear beaches (usually those without armoring, although found sometimes in front of high-shore seawalls). Characteristic marsh types are controlled by substrate and wave energy, as with the communities described above, but also by degree of freshwater influence from rivers or streams. Diagnostic marsh species and associates for marsh types found in Puget Sound are described in Dethier (1990). The human modifications most often seen in marsh habitats are not armoring, as with the other habitats described above, but diking and filling. They will not be discussed further here.

Links to Other Ecosystem Components

Puget Sound beaches are very much “in the middle” of nearshore ecosystems, with organisms and processes on the shore providing key linkages between terrestrial and marine food webs (see Toft and others, 2010). At low tide, a variety of birds use the beaches, include Great Blue Herons (*Ardea herodias*), gulls, Dunlin (*Calidris alpina*), and other shorebirds; they feed, roost, and in some cases nest there (reviewed in Buchanan, 2006; Eissinger, 2007). At high tide, species such as cormorants (*Phalacrocorax* spp.), grebes (numerous species), mergansers (*Mergus* spp.), and scoters (*Melanitta* spp.) feed near shore. On unaltered shorelines, overhanging vegetation links to the marine realm by dropping both detritus and insects onto the shore (Brennan, 2007). This detritus (plus that from the sea) is broken down by high-shore amphipods and eventually supplies detritus-based food webs in nearshore ecosystems. Insects are important to fishes such as juvenile salmon that forage on the shore at high tide as they migrate out of the Sound; complex marine habitats such as those provided by eelgrass beds are also critical for these species (reviewed in Fresh, 2006). Other animals (for example, other fishes) from nearshore waters probably use the beach at high tide, although these linkages have had little documentation. Nearshore waters are critical to the beach, in turn, by bringing food for the abundant suspension feeders, as well as larvae, spores, and seeds of shoreline organisms, nearly all of which have dispersive propagules. Finally, humans use the shore of Puget Sound extensively, for both extractive (harvesting of clams and other shellfish, as well as algae) and non-extractive (education, birdwatching, walking) activities (Leschine and Petersen, 2007).

Armoring on Puget Sound Beaches

As mentioned above and elsewhere in this volume, a large proportion of the shoreline of Puget Sound, approximately 25–30 percent, is armored (Strategic Needs Assessment Report, 2009). The proportion is much higher in the south-central Sound, around 63 percent, than further north. In some cases armoring is installed primarily as a landscaping feature; this is especially true on muddy shores, which (as low-energy environments) are vulnerable to much less erosion than more open beaches in Puget Sound. In other environments, especially the high shore above mixed-fine, sand, and cobble beaches, armoring is used to protect property from erosion or perceived risk of erosion. A variety of studies (mentioned above, and see review by Coyle and Dethier, 2010) have demonstrated ecological impacts of armoring on high-shore processes, especially when the armoring is emplaced below Ordinary High Water such that it covers the supratidal zone and interrupts terrestrial-marine linkages. In other parts of the world, armoring has been demonstrated to cause local beaches to become steeper and coarser; if that occurs in Puget Sound, this change in substrate type would be expected to have an impact on the local flora and fauna. However, this effect has not been demonstrated locally, and we do not know how far across the shore (for example, into the low intertidal) or along the shore (that is, down-drift) such impacts might occur. Substantial research that spans various spatial and temporal scales is needed to understand these impacts.

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Shoreline Development on Puget Sound

Doug Myers[1]

Introduction

Conceptual models are emerging for the links between shoreline armoring and disruption of natural sediment transport processes as well as the support functions for nearshore biota in Puget Sound. To identify what anthropogenic drivers changed the nearshore since European settlement of the Puget Sound region, and where those changes occurred, the Puget Sound Nearshore Ecosystem Restoration Project's (PSNERP) Nearshore Science Team (NST) conducted an analysis of change in nearshore ecosystems (Simenstad and others, 2010). The key elements of this analysis were that it be: (1) documented comprehensively over the entire Puget Sound basin; (2) directly related to physical and ecological change in ecosystem-scale processes; (3) spatially explicit; and (4) integrated within the NST's development of a geomorphic classification system of Puget Sound's shoreline features (Shipman, 2008).

For purposes of dividing Puget Sound's 2,500-plus miles of diverse shorelines into quantifiable units, drift cells mapped by Schwartz and others (1989) were "snapped" to the coastal drainage basins that directly drain to those mapped segments, using a 30-m resolution digital elevation model created by Finlayson (2006). The result was a comprehensive Puget Sound-wide geodatabase (Simenstad and others, 2010) of more than 828 "process units" corresponding largely to littoral drift cells and large deltas. Shipman (2008) lists the following Puget Sound rivers as having "large" deltas: Nooksack, Skagit, Stillagumaish, Snohomish, Duwamish, Puyallup, Nisqually, Skokomish, Elwha, and Dungeness. In addition, for purposes of the Change Analysis, PSNERP included the Deschutes, Samish, Hamma Hamma, Quilcene, Dosewallips, and Duckabush Rivers in the "large" river delta category. Geomorphic segments, or shoreforms, and shoreline drainage units are embedded within these process units, allowing for several spatial scales of analysis. Puget Sound also was divided into seven distinct subbasins that primarily reflect differences in oceanography and geomorphology (see Simenstad and others, 2010) for a description of subbasins). A Strategic Needs Assessment process interpreted change analysis summary data as a critical component of a Puget Sound scale nearshore restoration feasibility study being prepared by the U.S. Army Corps of Engineers (COE) as part of the General Investigation of the Puget Sound Nearshore under a cost-share agreement with Washington Department of Fish and Wildlife. A feasibly study is being prepared by the COE to determine whether there is a compelling national need for a particular suite of restoration projects and whether the COE can provide a solution.

Shoreline armoring represents one of the shoreline alterations or stressors analyzed in the PSNERP geodatabase. Armoring has varying degrees of impact generally related to the type of shoreform that is being altered, location on the beach, and the degree to which the structure interacts with wave energy. Coastal processes adversely impacted by the presence of shore armoring include reduced sediment supply, increased sediment transport rates and volumes, and reduced depositional processes largely resulting from reduced wave dissipation or increase wave reflectivity, which in turn reduces the deposition of fine sediment, driftwood or Large Woody Debris (LWD) and other organic material, such as beach wrack. Some shoreline armoring also can change the patterns of freshwater seepage onto the beach (Washington Department of Ecology, 1994). The most extreme example of this process disruption would be recorded in the geodatabase as a shoreform transition. A shoreform transition represents a change between historical and current shoreform types, including the transition to an artificial shoreline (fig. 1). Armoring tends to co-occur with other shoreline development components that also have adverse impacts on shoreline processes and functions, such as the removal of shoreline vegetation, increased impervious surfaces, septic system inputs and disturbance of riparian wildlife. When associated with artificial shoreforms, the disruption of processes from armoring may be less important than the alteration that destroyed the shoreform in the first place. In many cases, this alteration involves the filling or dredging of the shoreline to create deepwater access. Figures 2 and 3 below show different ways to express the co-occurrence of shoreline armoring and nearshore fill.

[1] People for Puget Sound.

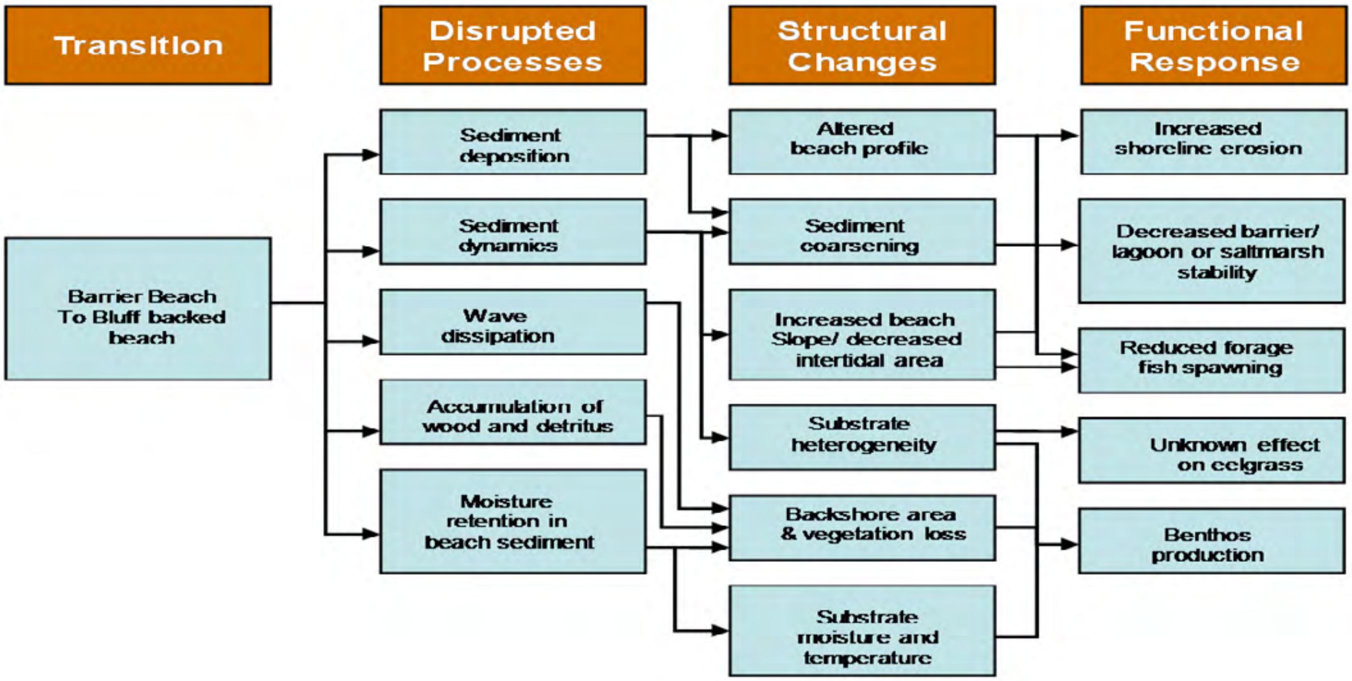

Figure 1. Conceptual model describing some of the implications of changing a barrier beach to a bluff backed beach.

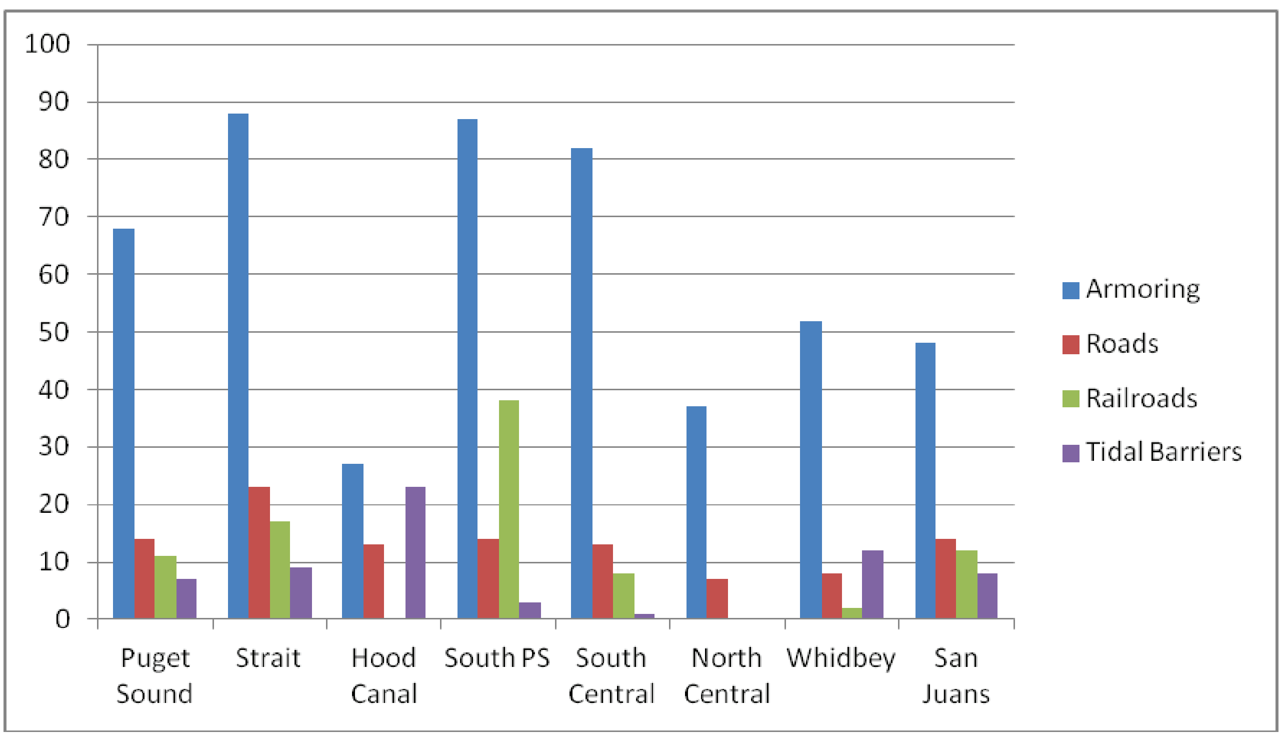

Figure 2. Presence of different stressors along mapped fill shoreline for Puget Sound and subbasins, expressed as a percentage (%) of fill length that stressors occupied (for example, Armoring was present along 68 percent of filled shoreline length in Puget Sound as a whole) (Strait, Strait of Juan de Fuca; PS, Puget Sound; Whidbey, Whidbey Basin).

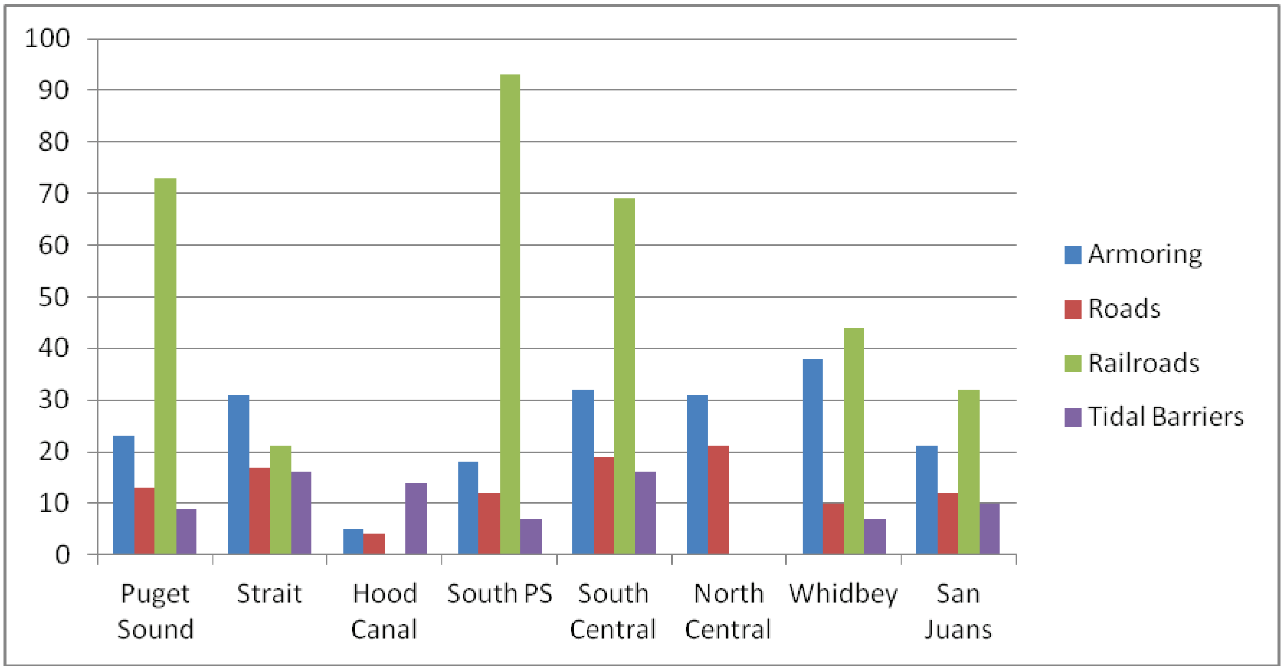

Figure 3. Presence of mapped nearshore fill along shorelines with other stressors, expressed as a percentage (%) of stressor length that fill occupied (for example, fill occurred along 23 percent of armored shoreline length in Puget Sound as a whole). (Strait, Strait of Juan de Fuca; PS, Puget Sound; Whidbey, Whidbey Basin.)

Results of the PSNERP Change Analysis show that shoreline armoring occurred along 27 percent of Puget Sound. The percent of armored shoreline varied considerably (9.8–62.8 percent) across the subbasins that comprise the study area. The South-Central Puget Sound subbasin had the most armoring, accounting for close to 63.0 percent of the subbasin's shoreline. Other subbasins with considerable shoreline armoring include: South Puget Sound (34.5 percent), Whidbey Basin (22.5 percent), and Hood Canal (21.2 percent). The subbasins with the least amount of shore armoring include North Central Puget Sound (9.8 percent), San Juan Islands–Strait of Georgia (14.0 percent), and the Strait of Juan de Fuca (16.1 percent). The average length of armoring across all process units in the Sound was 29.5 percent. Twenty-five percent of all process units in the Puget Sound basin had armoring more than 50.0 percent of the shoreline length. The average percent armoring within process units was as low as 7.8 percent in the North Central Basin and only 11.8 percent in the San Juan Islands-Strait of Juan de Fuca subbasin. Subbasins with the highest average percent armoring among process units include the South Central Puget Sound (56.6 percent) and South Puget Sound (45.5 percent) subbasins. Different shoreforms had varying degrees of armoring (table 1).

Table 1. The amount of armoring (percentage) by shoreform type as defined by Shipman (2008).

[km, kilometer]

Current shoreform type	Armored length (km)	Total length (km)	Percent armored
Artificial	244.1	325.2	75
Barrier Beach	119.9	440.2	27
Barrier Estuary	11.2	163.6	7
Barrier Lagoon	9.2	60.8	15
Bluff Backed Beach	511.3	1,529.2	33
Closed Lagoon Marsh	0	4.0	0
Delta	51.5	310.3	17
Plunging Rocky	0.9	185.5	0
Rocky Platform	21.5	503.9	4

Case Study: Beach Transitions

Because of site-scale findings and anecdotal information, a major premise of the Corps of Engineers General Investigation was that the change analysis data would point specifically to transitions empirically linked to certain stressors, such as loss of barrier beaches linked to armoring. One particular change analysis output of interest to this phenomenon is the transition of beaches from one type to another. As predicted by the geomorphic classification system (Shipman, 2008), we expect real transitions from one geomorphic type to another to be rather rare. Throughout Puget Sound, 42 barrier beaches were lost, but 29 new bluff-backed beaches appeared on the landscape. This would suggest an overall loss of depositional beaches, which we expect from our conceptual model linking armoring to disruption of sediment transport processes. However, both beach types lost shoreline length, 7.7 percent for bluff-backed beaches and nearly 12.0 percent for barrier beaches, as many transitioned to artificial shorelines.

Conceptually, the mechanisms that could cause transitions from a barrier beach to a bluff-backed beach include loss of significant sediment budget as a consequence of armoring and the trapping of sediments updrift of overwater structures that would make the downdrift beach more erodible. Likewise, the updrift beaches that are now trapping sediment would be mapped as barrier beaches by the change analysis methodology. Massive landslides within the period of analysis could also transform a bluff-backed beach to a barrier beach.

Because of the dynamic, directional nature of drift cells, we should expect that barrier beach shoreforms could move from one place to another over time. This would register in the change analysis methodology as two transitions: from barrier beach to bluff-backed beach at the historic location of the barrier beach and from bluff-backed beach to barrier beach directly adjacent and down drift. If that is the case with any of these transitions, we would expect an equal number of each kind of transition to explain this phenomenon.

Many of these transitions are small (< 1 km in length). Thus, the probability of mapping registration errors between the two time periods used in the change analysis causing a “false positive” is high. However, where mapping confidence is higher, we can extrapolate the relative rate at which sediments moved from one position to the next. Each transition must, therefore, be looked at individually in this way and in the context of how stressors like overwater structures and armoring could affect sediment budget and movement (see examples, figs. 4 and 5).

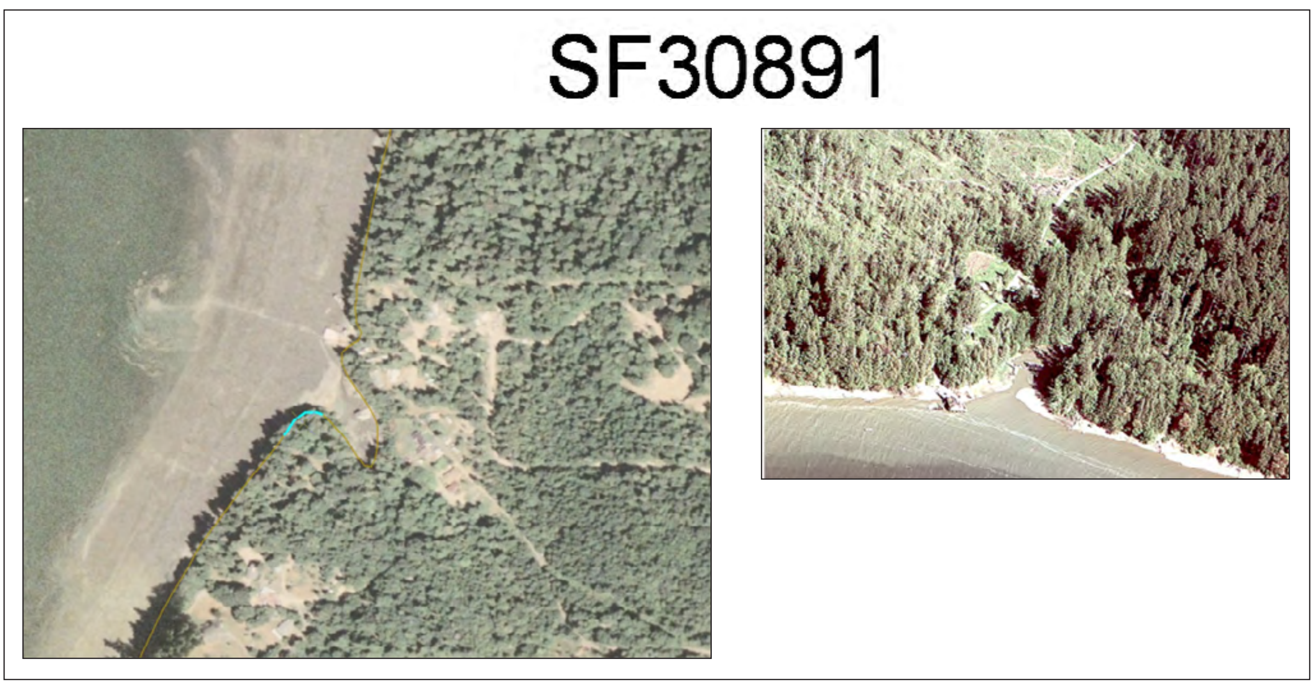

Figure 4. Example data source discrepancy due to shorezone mapping of current shoreline being landward of barrier.

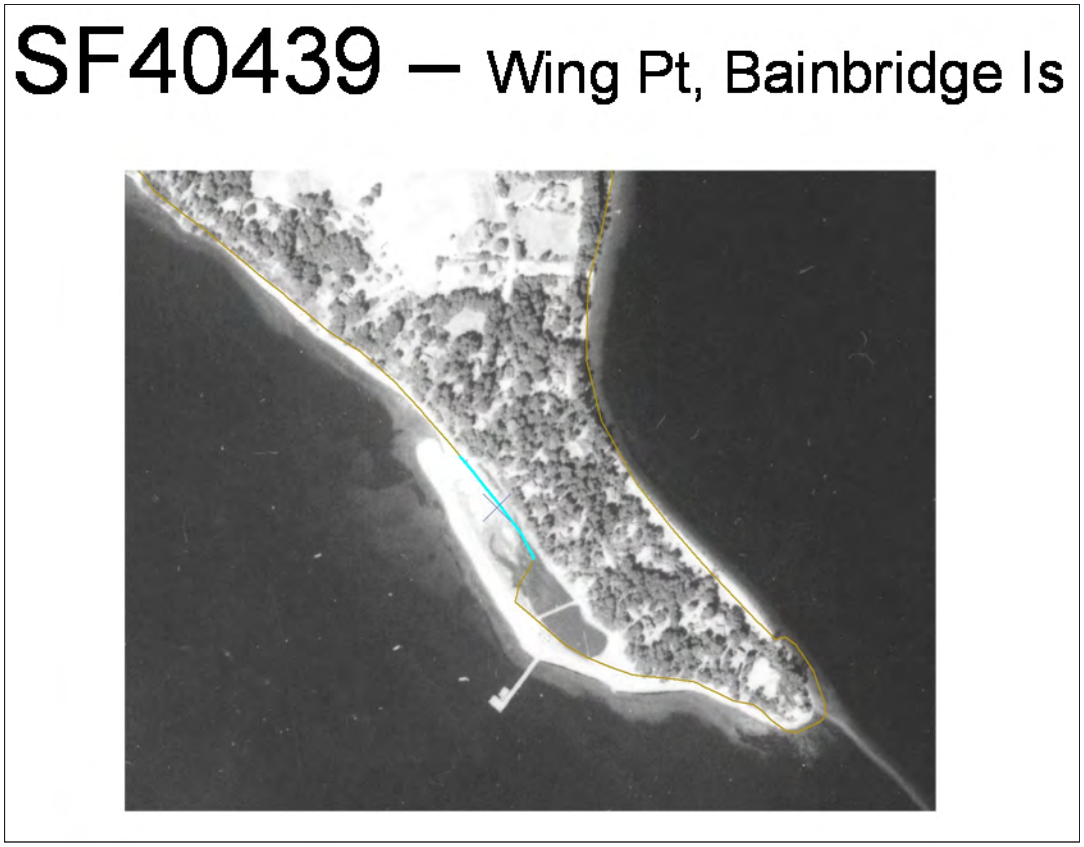

Figure 5. Example real transition with barrier apparent in this 1945 image.

In the South Central Puget Sound Subbasin, 10 such transitions were investigated in a case study comparing the transitions signaled in the change analysis geodatabase with ancillary aerial photographs of interim time periods between the historical and current endpoints to reveal that 5 were likely to be real transitions or loss of barrier beach and the other 5 were mapping discrepancies. At the scale of a subbasin restoration strategy, this information would be useful to screen potential locations for the bulkhead removal or beach nourishment management measures. Once a “real transition” is detected, additional information, such as the co-occurrence and adjacency of certain stressors with the observed shoreform transition, can be consulted. For example, armoring co-occurs on 33 percent of bluff-backed beaches by length, representing the most common co-occurrence with a natural shoreform. If armoring conceptually linked to the disruption of sediment supply and transport) is commonly found adjacent to and updrift of a shoreform transition, it could be thought to have a role in that transition happening.

Conclusion

The PSNERP Change Analysis and Strategic Needs Assessment begins to put the driver of nearshore armoring into context with the landscape disruptions it causes and in relation to other stressors. These diagnostic tools will inform restoration strategies to maximize the benefits of armoring removal as a restoration management measure.

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Regulating Shoreline Armoring in Puget Sound

Randy Carman[1], Kathy Taylor[2], and Peter Skowlund[2]

Introduction

Bordered by approximately 2,500 mi of shoreline, Puget Sound contains a rich array of marine habitats that support diverse populations of fish, shellfish, birds, marine mammals and other wildlife. For humans, Puget Sound provides a recreational playground, support for waterborne commerce, and outstanding waterfront properties for residential development. Concurrent with increasing population levels in Puget Sound, shoreline development for single-family residences has substantially increased. Moreover, approximately half of the shoreline modifications on saltwater shorelines are associated with single-family residences (Berry and Kazakov, 2004). In addition, single-family residential development on Puget Sound shorelines commonly involves the installation of some form of shoreline armoring.

Armoring of marine shorelines is not unique to Puget Sound. In California for example, 10 percent, or 110 miles of the coastline, has now been armored. In the State's most developed counties (Ventura, Los Angeles, Orange, and San Diego), approximately 33 percent of the shoreline is armored with seawalls or riprap (Griggs, 2010).

Locally, Morrison (2001) estimated that 36.6 percent of the marine shoreline in Thurston County, WA had been armored. His analysis, however, indicated that the rate of new armoring declined between 1995 and 1999, from 874 ft to 29 ft/yr.

More recent data based on Hydraulic Project Approvals (HPAs) issued by the Washington Department of Fish and Wildlife (WDFW) indicate that construction of bulkheads in Puget Sound is occurring at a brisk pace. These data indicate that 233 new bulkheads were constructed on Puget Sound shorelines between January 2005 and December 2007 (Brian Benson, Washington Department of Fish and Wildlife, unpub. data). Assuming a hypothetical average length of 100 ft, this equates to approximately 4.4 mi of new shoreline armoring over this 3-year period, or slightly less than 1.5 mi/yr. During this same timeframe, a total of 389 existing bulkheads were replaced on Puget Sound shorelines due primarily to deterioration of the structures. On the plus side of the equation, 11 bulkheads were removed over the three years, primarily as components of shoreline restoration projects incorporating beach contour and riparian vegetation rehabilitation.

Regulation of shoreline modifications in Puget Sound, including armoring installation, is administered primarily through two state laws, due in large part to the fact that the U.S. Army Corps of Engineers (COE) does not assert regulatory authority above Mean Higher High Water (MHHW) in marine waters in Washington State (Jeffrey Dillon, U.S. Army Corps of Engineers, oral commun., January 15, 2010). Because most new shoreline armoring takes place above MHHW in Puget Sound, the Hydraulic Code (Code) administered by WDFW and the Shoreline Management Act (SMA) administered by the Washington Department of Ecology (Ecology) are the two principal regulatory authorities for shoreline armoring in the state.

Washington Hydraulic Code

The Hydraulic Code (RCW 77.55.100), established in 1943 by the Washington Legislature, was originally a simple, one-paragraph law that focused on protection of fish life from impacts resulting from in-water construction activities. It required that any person that desires to conduct a "…project that will use, divert, obstruct, or change the natural flow or bed of any river or stream, or that will utilize any of the waters of the state…", must submit plans to the Departments of Fisheries (WDF) and Game (now merged into WDFW) for approval prior to commencing construction. Permits issued for such in-water work are referred to as Hydraulic Project Approvals. The Code has undergone many changes through the years, in both substance and length; the Revised Code of Washington (RCW) for WDFW now contains 23 pages (http://apps.leg.wa.gov/RCW/default.aspx?cite=77.55), and the Washington Administrative Code (WAC) contains 78 pages of implementing language (http://apps.leg.wa.gov/WAC/default.aspx?cite=220-110).

Bulkhead criteria for projects in Puget Sound were originally developed by WDF in 1971, and subsequently revised in 1974 to address the need for protection of surf smelt spawning areas in the upper intertidal zone. The WDF, however, did not exert regulatory authority in marine waters until March of 1977, following a decision by the Pollution Control Hearings Board that ruled in favor of the agency in its issuance of a permit for the East Bay Marina in Olympia (PCHB No. 1032). In subsequent years, WDFW sought to

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[1] Washington Department of Fish and Wildlife.

[2] Washington Department of Ecology.

minimize impacts from bulkheads by requiring placement as near to the bankline or Ordinary High Water (OHW) as possible. Some bulkheads, however, encroached up to 10 ft horizontally onto the beach below OHW, resulting in substantial loss of upper beach area and function. Improved understanding of the importance of marine shorelines for juvenile salmon and other species of fishes during the mid to late 1980s led to more (resource) protective approaches by WDFW during the review and permitting of marine shoreline bulkheads (Small and Carman, 2005).

In 1991, at the request of a lobbyist hired by a local bulkhead contractor, the Washington Legislature passed the Marine Beach Front Protective Bulkhead law (RCW 75.20.160, now RCW 77.55.141). This new law severely restricted the ability of WDFW to deny permits for single-family residential bulkheads by stating "…the department shall issue a permit…". The law also allowed for protection of marine waterfront "property," indicating that the presence of a structure was not necessary to justify the need for a bulkhead. At the request of WDF, some specific language was included regarding: (a) how far waterward from OHW a new bulkhead could be placed, (b) the location for replacement bulkheads, and (c) prohibition of "…permanent loss of critical foodfish or shellfish habitat" (for example, forage fish spawning areas, eelgrass, juvenile salmon migration corridors).

Following passage of the marine bulkhead law, issuance of permits by WDFW frequently became highly politicized, and attempts to rigorously apply existing regulations often resulted in legislative scrutiny and actions to diminish regulatory authority. In addition, contractors were frequently successful in arguing that, due to geological, engineering, or safety issues, 6 ft of encroachment waterward of OHW (the maximum allowed under the law) was necessary for bulkhead construction. Construction of a 100-ft bulkhead could therefore result in the unmitigated loss of 600 ft^2 of upper beach area. The difficulty in preventing this type of beach loss arises, in large part, from an inherent conflict between protecting shoreline habitat while still allowing for the protection of shoreline property and human safety. In essence, WDFW faces conflicting mandates: to ensure no net loss of habitat function and value (WDFW POL – M5002) while issuing approvals for marine bulkheads without the authority to examine need, request an alternatives analysis, or require adequate mitigation for adverse impacts (site specific or cumulative).

WDFW recently conducted a pilot study of the effectiveness of HPAs at achieving no net loss of fish habitat (Quinn and others, 2007). The study reviewed a total of 58 recently issued HPAs, 14 of which were for marine bank protection. Individual projects were reviewed for compliance with permit provisions and permits were judged qualitatively according to three measures of effectiveness (ability of the permit to protect public resources, to meet no net loss, and to mitigate impacts). Among all project types reviewed, HPAs for marine bank protection contained the highest number of protective provisions, had relatively high compliance rates (a measure of how well applicants/contractors followed provision language), and had relatively high implementation rates (a measure of outcomes against a hypothetical permit that contained all appropriate provisions).

Overall permit compliance was judged relatively high for marine bank protection projects, yet there was a large disparity between overall permit compliance and ability of the permit to achieve high effectiveness (fig. 1). More than 50 percent of the permits reviewed received less than a medium score for ability to meet no net loss. Similarly, scores for the permit's ability to mitigate impacts were clustered in the low to medium range.

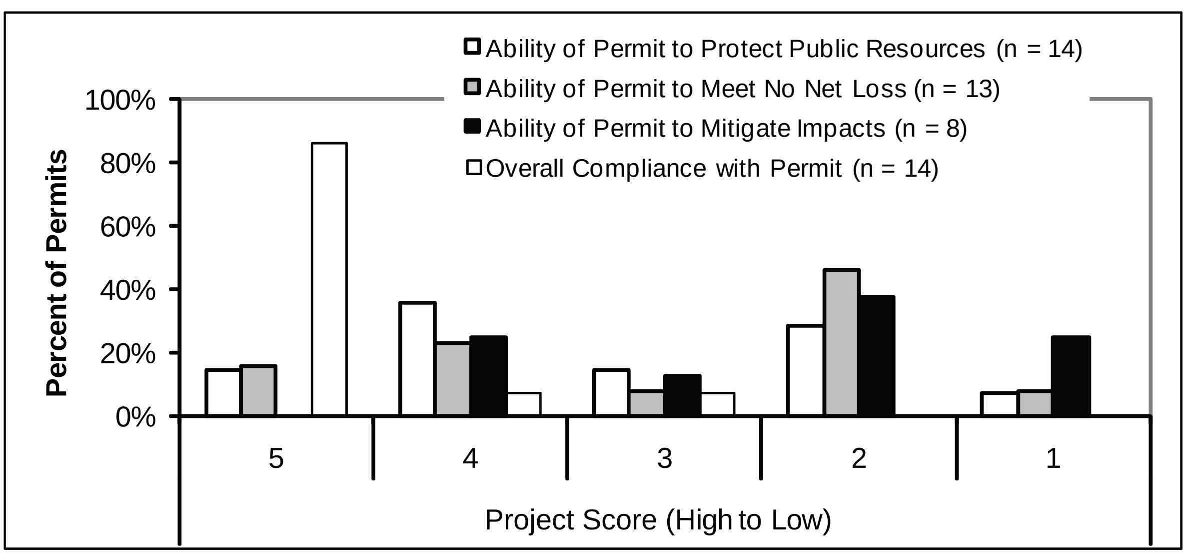

Figure 1. Three qualitative measures of HPA permit effectiveness (protect public resources, meet no net loss and mitigate impacts) and overall permit compliance for marine bank protection (from Quinn and others, 2007).

The report concluded "…achieving no net loss standards was difficult probably because of the nature of the HPA projects. Even when well-implemented (high provision, compliance, and implementation rates), projects were often judged to decrease fish habitat function, albeit in small quantities. Part of our inability to meet "no net loss" is undoubtedly related to the dual nature of the Hydraulic Code (Chapter 77.55 RCW), to protect fish life while allowing for the protection of personal property and human health." The report also concludes "…without the HPA program, we would see substantially more loss of fish life or habitat associated with the 4,000 projects permitted annually. However, the agency's goal of achieving no net loss of habitat function and values (WDFW POL-M5002) is difficult to attain solely through the HPA permit process."

A number of issues continue to limit the effectiveness of the HPA at protecting shorelines within the context of shoreline armoring. WDFW currently lacks regulatory authority to: (1) address the "need" for a bulkhead (that is, perceived need for armoring continues to supersede protection of shoreline functions); (2) require alternatives to traditional bulkheads, even in low-energy environments; and (3) address cumulative impacts or impacts that continue beyond the longevity of the permit (typically 5 years). Protection of personal property continues to supersede protection of shoreline processes and function along marine shorelines. The political will to implement a balanced approach to shoreline management is sorely needed to protect and perpetuate natural shoreline functions. For example, WDFW needs to develop alternative shoreline protection techniques appropriate for specific types of shorelines and wave environments that protect private property while minimizing the negative impacts of armoring. Finally, existing WDFW regulations are "reactive" and apply to individual project sites, which makes it difficult to address shoreline problems at larger spatial scales (for example, at the drift cell scale). Cumulative and ecosystem impacts (for example, downdrift loss of sediment supply) typically occur at this larger spatial scale and therefore cannot be adequately addressed on a site-by-site basis. Local assessment and planning efforts could prove valuable to addressing this need.

Some improvements to the Code and implementation of shoreline protection may be realized in the near future. WDFW is currently working on the preparation of a Habitat Conservation Plan (HCP) for the HPA program. Current work on the HCP includes compilation of the scientific literature on several topics, including shoreline armoring. The process is scheduled to be completed in 2011 and could lead to important changes in the Code that will afford increased protection for aquatic resources and habitats in Puget Sound. WDFW is also providing technical assistance to local jurisdictions in cooperation with the Aquatic Habitat Guidelines workgroup (http://wdfw.wa.gov/hab/ahg/index.htm).

A recent publication: "Protecting Nearshore Habitat and Functions in Puget Sound, An Interim Guide" (http://wdfw.wa.gov/hab/ahg/), provides an analysis of impacts from shoreline armoring as well as recommendations for minimizing impacts through alternative design and construction techniques.

In addition, executive level management and scientific staff from WDFW have discussed the results of the pilot study on HPA effectiveness with legislative representatives. To improve effectiveness of the Code and outcomes for fish and their habitat, WDFW provided three specific recommendations:

- Provide funding to WDFW to conduct compliance and effectiveness monitoring wherein projects are followed through completion to determine if permit conditions are sufficiently protecting fish habitat;
- Provide WDFW civil authority for HPA violations, as opposed to the current system of jurisdiction within county courts as criminal offenses, to improve follow through and outcomes for violations; and
- Investigate WDFW statutory authority under RCW 77.55 to determine which statutes restrict the department's authority to meet the "no net loss" goal (since the passage of 77.55 RCW in 2000, numerous statutory changes have weakened the department's ability to protect fish life.

More recent discussions have included the need to require long term mitigation that remains in effect for the duration of the project impacts.

Numerous improvements to the Code will obviously be necessary to move toward meeting goals such as no net loss of shoreline habitat function. Clearly, actions including implementing permit compliance and effectiveness monitoring, increasing enforcement authority, and reducing impediments to effective regulation of impacts are needed in the near future. It is unfortunately true, however, that positive movement on these issues faces many challenges. As noted, changes to the Code by the legislature have historically tended to be regressive.

Shoreline Management Act

The Washington Hydraulic Code is not the only authority by which shoreline armoring is regulated. Washington's Shoreline Management Act (SMA) was approved by the public in a 1972 referendum "*to prevent the inherent harm in an uncoordinated and piecemeal development of the state's shorelines.*" The SMA has three broad policies: (1) encourage water-dependent uses, (2) protect shoreline natural resources, and (3) promote public access (RCW 90.58.020). The SMA establishes a balance of authority between local and state government (RCW 90.58.050). Cities and counties are the primary regulators but the Washington Department of Ecology has authority to approve local Shoreline Master Programs (SMPs) and some permits.

The SMPs are based on the SMA and state guidelines (WAC 173-26 Part III) and are tailored to the specific needs of the community. More than 200 cities and all 39 counties in the state of Washington have SMPs. Local SMPs include both plans and regulations. The plans constitute a comprehensive vision of how shoreline areas will be used and developed over time and the regulations are the standards that shoreline projects and uses must meet.

The SMA establishes a system of permitting for shoreline development (RCW 90.58.140). Substantial Development Permits are needed for many projects costing more than $5,718, or those interfering with the public's use of the waters. Many common shoreline uses are exempt from obtaining a Substantial Development Permit, including bulkheads necessary to protect existing single-family residences, normal maintenance and repair of existing structures, and emergency construction needed to protect property.

Even if a bulkhead project meets the criteria for exemption, it must still comply with the SMA and all applicable regulations and design standards contained in the local SMP. The local SMP may require conditional use permits for bulkheads, soft approaches as an alternative to hard armoring, or may prohibit bulkheads entirely.

Existing structures may be replaced if there is a demonstrated need to protect principal uses or structures from erosion. However, these must be designed, located, sized, and constructed to assure no net loss of shoreline ecological functions and cannot encroach waterward of the Ordinary High Water Mark (OHWM) unless the single-family residence it protects was built prior to 1992, and only if there are overriding safety concerns. If leaving an existing structure in place would cause net loss of shoreline ecological functions, it must be removed as part of the replacement. Additions or increases to an existing bulkhead are considered new structures.

Comprehensive updates of local SMPs are required of all Puget Sound jurisdictions by 2012. Currently, 36 cities and counties with Puget Sound marine shorelines are in the process of updating their SMPs. An additional 71 Puget Sound jurisdictions will be updating their SMPs this biennium. These comprehensive updates must:

1. Be based on local inventory and characterization of shoreline ecological processes and functions.
2. Identify location of existing land uses, including structures, bulkheads, and shoreline modifications.
3. Identify shoreline areas with degraded ecological functions and sites with restoration potential.
4. Determine that new SMP regulations, including those relating to bulkheads, "assure that shoreline modifications individually and cumulatively do not result in a net loss of ecological functions."
5. Limit the size of new shoreline stabilization structures to the minimum necessary and apply soft approaches unless demonstrated not to be sufficient to protect primary structures.
6. Ensure publicly financed erosion control structures incorporate public access improvements and ecological restoration into project design.
7. Mitigate new erosion control measures, including replacement structures on feeder bluffs that affect sediment producing functions.
8. Where beach erosion is threatening existing development, adopt provisions for a beach management district to provide comprehensive mitigation for adverse impacts.
9. Prepare a shoreline restoration plan with policies, priorities, and actions for ecological restoration. This may include removal of armoring.

Regarding Shoreline Stabilization, SMP updates must (WAC 173-26-231(2):

1. Allow structural shoreline modifications only where they are demonstrated to be necessary to protect a primary structure.
2. Reduce the adverse effects of new shoreline modifications as much as possible, limiting their number and extent.
3. Give preference to types of shoreline modifications that have a "lesser impact on ecological functions" and require mitigation of identified impacts resulting from shoreline modifications. Impacts may include:
    a. beach starvation,
    b. habitat degradation,
    c. sediment impoundment,
    d. exacerbation of erosion,
    e. hydraulic impacts,
    f. loss of vegetation,
    g. loss of large woody debris, and
    h. restriction of channel movement.
4. Where justified, give priority to "soft" over "hard" shoreline modifications, starting with:
    a. vegetation enhancement,
    b. upland drainage control,
    c. biotechnical measures,
    d. beach enhancement,
    e. anchor trees,
    r. gravel placement,
    g. rock revetments,
    h. gabions,
    i. concrete groins,
    j. retaining wall and bluff walls,
    k. bulkheads, and
    l. seawalls.

New shoreline development is addressed in (WAC 171-26-231(3)(a)(III). To summarize, new development should be located and designed to avoid the need for future shoreline stabilization based on “geotechnical analysis”, new subdivisions of land must assure that the lots created will not require shoreline stabilization during the life of the development, and new or enlarged structural stabilization shall not be allowed except in cases meeting specific criteria. Replacement of erosion control structures must be designed, located, sized, and constructed to assure no net loss of shoreline ecological functions. Replacement erosion control structures cannot encroach waterward of the Ordinary High Water Mark, unless is it protecting a single-family residence built prior to 1992, and only if there are overriding safety concerns.

Most of the cities and counties in Puget Sound are in the process of updating their SMP regulations. Whatcom County is one of the few Puget Sound jurisdictions to have completed an SMP update. The 2008 Whatcom County SMP sets clear policies and regulations limiting new or expanded structural shore stabilization. As more cities and counties complete SMP updates, there will be more regulation of erosion control structures on Puget Sound shorelines. This sets in motion a more systematic approach to analyzing existing shoreline conditions and emphasizes a set of priorities to avoid interruption of processes that may be caused by armoring, unless it can be demonstrated that armoring is necessary to protect a primary structure. This, in turn, should limit the number and extent of future shoreline modifications. It is premature to arrive at any conclusion regarding the success of these efforts until the process is complete and the results have been evaluated.

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National Perspective and Human Dimensions

Under winter beach conditions, lateral access is significantly reduced due to the encroachment of these temporary protection structures onto the beach at Malibu. Photograph taken by Gary Griggs, Institute of Marine Sciences, University of California, Santa Cruz.

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Mitigating the Effects of Bulkheads on the Bay Shore of Fire Island National Seashore

Karl F. Nordstrom[1], Nancy L. Jackson[2], and Patricia Rafferty[3]

Abstract. The National Park Service is constructing a feeder beach to restore sediment to the eroding bay shore adjacent to a marina bulkhead using sand removed from a navigation channel. An important goal of this project is to evaluate its feasibility in reducing erosion caused by shoreline armoring while ensuring that it does not (1) create an intervening environment between the active beach and upland; (2) result in excessive sedimentation offshore; or (3) result in sediment being re-deposited in the navigation channel. Semi-annual topographic surveys will be made before, during, and after placement of the fill to reveal how the shore evolves through time. A process explanation will be provided in a 28-day instrumented time series study, using sand traps and dyed sand tracer to determine rates and pathways of sediment transport. The results will identify how much fill is needed, how the volume and frequency of emplacement relate to dredging needs, and whether feeder beaches can be used in other bay shore locations.

Introduction

Shore parallel walls, such as bulkheads, are commonly used to protect estuarine shores because they are affordable, provide protection in limited space, and need not alter the bay bottom (Nordstrom, 1992; Shipman and Canning, 1993; Macdonald and others, 1994; Douglass and Pickel, 1999; Taborda and others, 2009). Information about effects of shore parallel structures is based largely on studies on ocean beaches (Plant and Griggs, 1992; Griggs and others, 1994; Kraus and McDougal, 1996; Basco and others, 1997) and reviewed by Kraus (1988) and Kraus and McDougal (1996). In contrast, information about armoring on estuarine beaches is sparse (Jackson and Nordstrom, 1994; Macdonald and others, 1994).

Shore parallel walls alter shore processes and responses in several ways. Vertical structures increase wave reflection (Miles and others, 2001), which can cause greater turbulence and scour seaward and at the ends of the structures. More sediment can be mobilized at vertical structures than on beaches without structures (Silvester, 1977; Griggs and others, 1994; Miles and others, 2001; Jaramillo and others, 2002), but it is not clear whether this mobility is accompanied by increased erosion rates (Kraus, 1988; Basco and others, 1997). Shore parallel structures do contribute to local sand starvation by preventing erosion of the upland that would otherwise provide sediment to the longshore transport system (Kraus, 1988). If placed across the active beach, these structures can become sediment traps and cause local accretion updrift and erosion downdrift (Kraus, 1988). They can alter beach habitat by contributing to changes in sediment size, replacing the beach during construction, or preventing new beach from forming as the shore is displaced landward through erosion and sea-level rise (Canning and Shipman, 1995; Spalding and Jackson, 2001; Dugan and Hubbard, 2008; Dugan and others, 2008). They can also create exotic habitat as newly introduced hard structures in formerly sandy environments (Chapman and Bulleri, 2003), and act as barriers to movement of fauna between water and land. These ecological effects greatly reduce the value of using artificial structures to protect land managed for natural values. As a result, more innovative “soft” solutions to shoreline armoring (beach nourishment, vegetation plantings) are being sought in estuarine environments (Macdonald and others, 1994; Zelo and others, 2000).

The National Park Service is now examining ways to minimize the detrimental effects of shore parallel walls within Fire Island National Seashore (fig. 1), where 17 communities remain as developed enclaves. Nearly all of these locations are protected by shore parallel walls. These walls are primarily bulkheads, so this term is used when referring to them.

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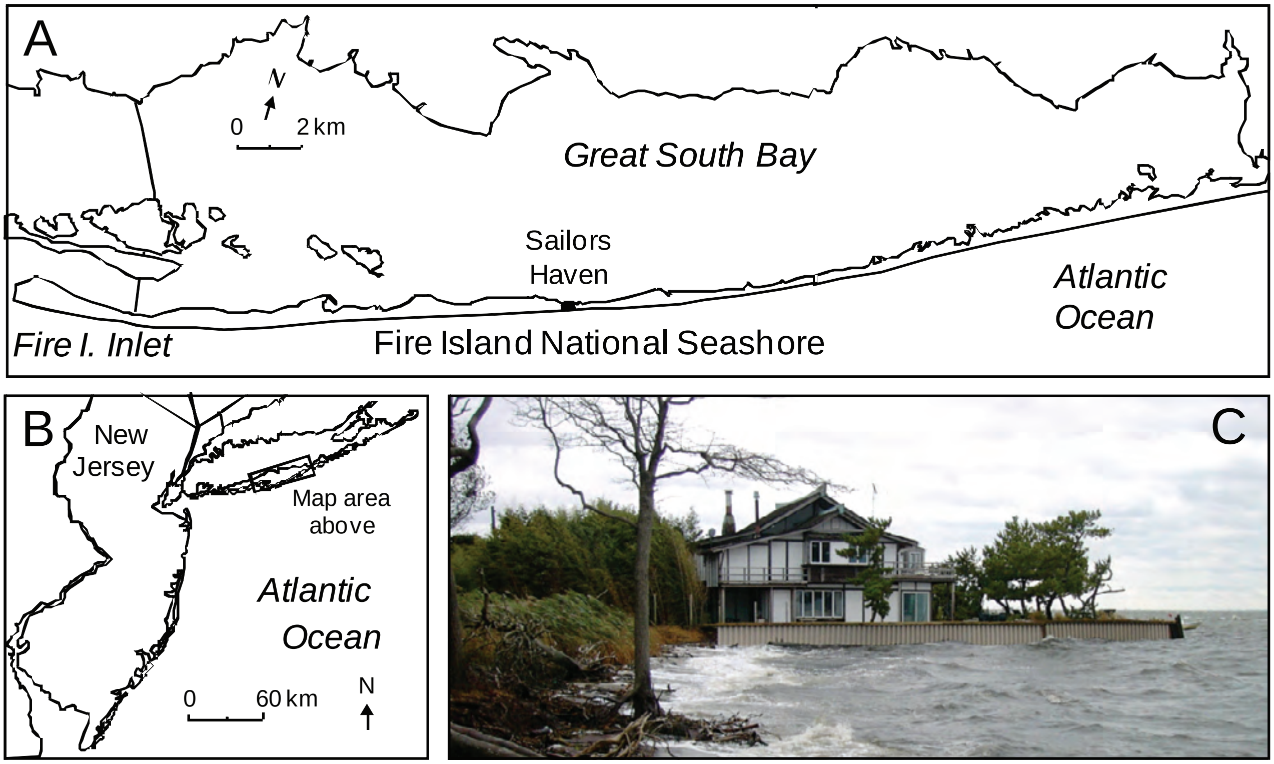

Figure 1. (*A*) and (*B*) are the Fire Island setting. The photograph (*C*) was taken at time of high water on the east side of the community of Cherry Grove, just east of Sailors Haven. The narrow beach and eroding upland are characteristic of much of the bay shore, including sites far from bulkheads.

Bulkheads were often installed prior to the establishment of the national seashore. Others were constructed subsequently, without permission of National Park Service managers or under the issuance of park special use permits, for repair or replacement with little or no change in location, capacity, or appearance. Determining the effect of bulkheads on adjacent unprotected land and identifying alternative strategies for managing these areas are critical research needs for the park.

Many bulkheads have been in place so long that the foreshores fronting them have been eliminated, leaving the structures on the low tide terrace. These structures act as sediment traps for alongshore sediment transport on the foreshore, causing the beach to accrete on the updrift side and erode on the downdrift side. The bulkheads on private land terminate at National Park Service property, resulting in accelerated erosion of park land (fig. 1*C*). Erosion adjacent to some of the bulkheads is threatening fresh water wetland systems as well as beach and upland habitat, and exposing utility lines that service the island.

The purpose of this paper is to identify how beach nourishment can be used as an alternative to construction or extension of bulkheads to protect the eroding bay shore of Fire Island. Nourishment has not been used there in the past, and the acceptability of this option requires conducting a feasibility study to document that a feeder beach can restore the sediment budget interrupted by bulkheads without creating undesirable beach habitat or excessive sedimentation offshore. Documentation of the effects of nourishment will be provided by gathering data in the field over a 2-year period at a demonstration site at Sailors Haven Marina (figs. 1 and 2). The rationale and methods for this data-gathering program are identified here, as well as the perceived benefits of the project in addressing environmental issues.

Characteristics of the Bay Shore of Fire Island

Waves causing beach change on the bay shore are generated in Great South Bay (fig.1*A*). This basin is narrow and shallow, and fetch distances for waves breaking on the middle section of the shoreline are less than 15 km in the direction of the dominant northeasterly and northwesterly winds (Sherman and others, 1994). Wave heights are low (<0.3 m) and wave periods are short (<3 s) during moderately strong onshore winds of 6-7 m s^{-1}. Mean tidal range on the mid-island bay shore is 0.21 m; spring tidal range is 0.24 m (National Oceanic and Atmospheric Administration, 1995). Beaches are low and narrow (fig. 1*C*). Where beaches are

Figure 2. Sailors Haven study area, showing projected location of feeder beach. Source: New York District Engineer photograph taken after Hurricane Isabel in autumn 2003.

limited in size, small changes in sediment input and output can cause high rates of shoreline change (Nordstrom, 1992; Freire and others, 2007). Much of the bay shoreline of Fire Island is eroding, with an average long term rate of about 0.3 m yr^{-1} and a maximum long term rate over 1.0 m yr^{-1} Leatherman and Allen (1985). Rates in a given year can be up to 3 m yr^{-1} (Nordstrom and others, 2009).

The shallow low tide terrace is characterized in many locations by a series of transverse bars that are generally oriented southwest to northeast, indicating that sediments comprising them are driven primarily by northwest winds when water is blown out of the bay and spilling waves break frequently across the low tide terrace. Sediments on the foreshore, in contrast, appear to be driven primarily by northeast winds that are accompanied by raised water levels and plunging waves that break directly on the foreshore, although easterly transport can occur on the foreshores at times of high water during northwest winds as well.

The bay shore of Fire Island consists of numerous segments of land managed by the National Park Service alternating with land in developed communities. About 18 percent of the 67.3 km-long shore is protected by 43 bulkhead segments. Most bulkheads are sheet-pile structures (fig. 1*C*). The longest extent of bulkhead is 1.85 km (Nordstrom and others, 2009). Access to the developed communities and intensively used areas of the Seashore is primarily by ferry, so most communities have a marina and access channel that requires periodic maintenance dredging.

An Alternative to Bulkheads

The existing regulatory framework promotes replacement of existing structures over implementation of alternative designs for erosion mitigation. An owner with an existing bulkhead can easily obtain a permit from the New York State Department of Conservation (NYSDEC) for its replacement. If an owner proposes an alternative method of shoreline protection that requires placing sediment in the intertidal zone, such as beach fill or a vegetated shore, the application is presumptively incompatible with NYSDEC regulations. If a permit could be granted under state regulations, greater review, monitoring, and pre-construction documentation would be required, increasing the time and cost to implement the project or action. The National Research Council (2007) identified regulatory policies as a major impediment to implementing alternatives to shoreline armoring to minimize the negative impacts on coastal resources. That report called for the implementation of demonstration projects to evaluate alternatives and to provide monitoring data that regulatory agencies can use to evaluate these alternatives.

Beach nourishment is the most widely used response to shoreline erosion in the USA (Valverde and others, 1999) and is generally considered more benign than use of hard structures (Speybroek and others, 2006). Vegetation alternatives can be used in estuarine environments but not on sandy substrate subject to reworking by energetic bay waves (Nordstrom, 1992), such as most of the bay shore of Fire Island. By protecting eroding shores, vegetation has the disadvantage of reducing sediment inputs to downdrift areas (Macdonald and others, 1994).

Placing beach fill on the low tide terrace would cover benthic habitat. This is a special concern on estuarine beaches, where fauna are not acclimated to the rapid surface change and burial occurring on ocean beaches. The perceived losses are often cited as the primary reason for lack of acceptability of nourishment projects in estuaries (U.S. Army Corps of Engineers Baltimore, 1980; U.S. Army Corps of Engineers Seattle, 1986; Nordstrom, 1992; Shipman, 2001). The NYSDEC policy against use of beach fill on the low tide terrace has contributed to the lack of impetus to use nourishment projects on Fire Island. Another problem is that the State requires that shore protection efforts attempt to achieve a permanent solution to local erosion.

The Feeder Beach Concept as a Form of Restoration

The inherent dynamic nature of beach systems and the adaptation of species to geomorphic change prevent the possibility of finding a permanent solution by restoring landforms or habitats to specific target states and maintaining existing inventories in a stable shoreline condition in perpetuity, but the processes whereby these resources evolve can be maintained. The term “restoration” can be applied to a process, such as sediment transport, just as it can to a stage in landform evolution (for example, a marsh or upland). Thus reestablishing the sediment budget using a feeder beach (to protect the upland next to a bulkhead and supply sediment to the system in a natural way) can be considered restoration, and the concept of permanence transfers to the issue of maintaining sediment inputs.

Introducing sediment at the eroding ends of bulkheads would help overcome the site-specific impacts of these structures while allowing adjacent natural areas to be nourished at a rate corresponding to natural sediment transport rates. Large-scale nourishment projects, while economically efficient, may be less desirable than small projects on estuarine shorelines because they would bury too much existing habitat and create an intervening environment between the active beach and upland. Use of sediment dredged from nearby navigation channels provides suitable source materials that can be delivered relatively cheaply and at a rate that can more nearly approximate natural losses.

The demonstration project at Sailors Haven Marina (fig. 2) will provide an initial template for restoring sediment to the transport system at hard structures interrupting longshore transport at other locations on Fire Island. The plan is to place sand dredged from the navigation channel over a portion of the low tide terrace and foreshore west of the marina to protect the upland and create a feeder beach that will supply sediment to the longshore transport system and compensate for the losses caused by the marina bulkhead. Long-term success of a feeder beach requires periodic renourishment. At Sailors Haven Marina, this will be done in conjunction with dredging of the navigation channel, where dredging is required every 2 to 4 years.

The project is not intended to totally prevent coastal erosion. The National Park Service policy is to allow natural processes to occur to the extent possible and only intervene to redress accelerated erosion caused by human actions (National Park Service, 2006). Evolution of estuarine beaches in areas subject to human alterations is now often related mainly to human activity (Taborda and others, 2009), and it seems appropriate to use human action to restore sand to the system where human actions accelerated past losses.

NYSDEC has agreed to the demonstration project and has issued a permit for construction and monitoring. Results of the project will allow NYSDEC to determine if this is an appropriate technique for application at other hard structures. Dredging within the Seashore requires issuance of a Special Use Permit. Pending successful completion of this demonstration project and NYSDEC approval of the technique, park managers can use this permit process to require communities to beneficially use sand from channel dredging to construct and periodically create feeder beaches where appropriate. In December 2005, park managers implemented new polices for the issuance of Special Use Permits for private bulkheads that are designed to minimize impacts from replacement of existing bulkheads and facilitate implementation of more ecologically sensitive designs in the future.

The beach fill should mimic the natural configuration of the shore by being at the height of the natural formations and relatively narrow, and it should be close to the bulkhead ends (fig. 2) to compensate for the sediment deficit at the location most adversely affected. The width of the fill must reflect a compromise between the need to minimize the footprint of the fill on the landscape and the need to prevent the upland from eroding at an accelerated rate. On an ocean shore, a wide fill is desirable to provide space for new dunes with complete environmental gradients to form, but the natural profile along most of the Fire Island bay shore consists of an eroding foreshore in direct contact with the upland or marsh. One purpose of the study is to determine a design height and width for the fill that will not create an intervening sub-environment. Periodic wave overwash of the fill and delivery of wrack to the wider backshore created by the fill are important in providing the habitat and nutrients representative of a natural estuarine backshore. Evaluation of the naturalization process requires examining effects of specific storms and longer term changes in topography related to cumulative storm effects as identified below.

Characteristics of the Demonstration Project

Sand for the demonstration project will be available from maintenance dredging that will occur in 2011–2012 (estimated to yield 2,500 m^3). It is assumed that the length of the initial fill will be at least 200 m, the backshore width no greater than 4 m and the height no greater than 1.5 m above the height of the low tide terrace. Placement of fill must occur between November 2011 and January 2012 to avoid impacts on sea turtles, essential fish habitat, and breeding birds and avoid interference with park visitation.

Studies of beach processes in low-microtidal estuaries and studies of bulkheads and nourishment projects in these environments are underrepresented in the scientific and management literature (Nordstrom and others, 2009; Jackson and others, 2010). Accordingly, a major portion of the evaluation will be devoted to a field study of the evolution of the fill. Steps will include identifying (1) the rate of sediment transport alongshore and the likelihood that sediment will move out of the fill area and nourish downdrift areas; (2) the likelihood that sediment will move from the foreshore to the bars on the low tide terrace and then to the navigation channel; (3) the likelihood that periodic nourishment will re-establish the sediment budget altered by the marina; and (4) the impacts on biota. These study components require evaluation of beach processes and shoreline changes in the short term (daily and storm-related cycles) and medium term (seasonal and annual effects).

Rate of Transport Alongshore

A feeder beach is not like a traditional beach nourishment project in that it is designed to allow sediment to leave the fill area to nourish adjacent beaches. Peat outcrops, fallen trees and root masses protruding from uplands protect the shore in places and create sediment traps. These features, and breaks in shoreline orientation, may create isolated longshore drift cells, so it is important to identify the extent to which sediment can bypass them. Longshore transport rates should be determined by conducting sediment tracer and sand-trapping experiments and using beach volume changes revealed in topographic differences in the fill area and downdrift.

Movement of Sediment to the Bars and Navigation Channel

A previous tracer study of the inner transverse bars west of the marina (Nordstrom and others, 1996) indicates that the bars provide a mechanism for movement of sediment offshore. The amount of sediment delivered appears small under natural conditions, but the amounts that would be delivered from a newly placed fill are unknown. Topographic profiles must extend offshore and onto the bars to identify changes in sediment volume, and a tracer study should include sampling offshore to determine pathways of sediment from the foreshore to the bars and intervening portions of the low tide terrace. The apparent eastward movement of the bars indicates the potential for delivery of sediment to the navigation channel. Sediments on the low tide terrace are similar to sediments in the eroding formations, the foreshore and the navigation channel (Nordstrom and others, 2009), indicating that these environments may not be mutually exclusive in terms of sediment exchange. The dredged sediment is compatible with placement on the beach, but there is the potential for this sediment to be recycled to the navigation channel.

Implications for the Sediment Budget

The optimum way to determine the amount of sediment required in the feeder beach is to (1) determine the rate of erosion of a natural headland uninterrupted by shoreline armoring; (2) determine how the marina alters that rate; (3) determine the rate that sediment from the feeder beach is delivered to downdrift beaches; and (4) evaluate whether the rate of transport from the feeder beach is compatible with the natural rate in the absence of the structure. The natural rate cannot be determined because of lack of data collection before the structure was built and lack of a control site in a different location that is assumed to be affected by the same processes. A practical estimate of the role of the feeder beach in reestablishing the sediment budget is the degree to which the volume of sediment moving out of the fill area matches the volume emplaced during renourishment intervals without increasing beach width in the long term, while allowing for some interaction between the waves and wave formed features on the beach and upland or marsh on the landward side. The landforms in the fill area and downdrift of it should mimic the form and function of the presently eroding segments along the bay shore removed from the bulkheads.

Impacts on Biota

The shallow waters of Great South Bay have been designated essential fish habitat because of their high productivity and regional significance for marine finfish, shellfish and wildlife. The Sailors Haven area serves as potential spawning and nursery grounds for many finfish species that are estuarine dependent during at least one life stage. Species include weakfish (*Cynoscion regalis*), winter flounder (*Pseudopleuronectes americanus*), summer flounder (*Paralichthys dentatus*), and blackfish (*Tautoga onitis*). The benthic community serves as an essential part of the food chain for local fish populations. The structure of the benthic community is determined in part by the frequency and intensity of physical disturbance (Thistle, 1981). Scheduling of dredging and construction activities has been limited to the late fall and winter to minimize impacts on wildlife. Ecological monitoring, including that for finfish, invertebrates, and water quality, will be conducted to evaluate the ecological effects of the project on benthic and pelagic species.

Methods for Evaluating Impacts in the Field

Short-term changes in physical conditions will be evaluated by identifying the controlling wind and wave processes and changes in topography and surface characteristics (sediments and wrack) in a 28-day (lunar cycle) time series in the winter storm season that will include effects of individual storms. Medium-term changes will be evaluated by measuring topography related to cumulative storm effects and movement of pulses of sediment alongshore. During the 28-day time series, wind speed and direction, wave heights, water levels, and current velocities will be monitored (1) on the foreshore and low tide terrace near the bulkhead; (2) near the western end of the fill to provide information on end effects; and (3) bayward of the bulkhead to determine the potential for sediment transport seaward of the structure. Measurement of the quantity of sediment in transport over swash cycles will be made using total load streamer traps. Dyed sand tracers will be injected into the swash zone to identify the relative proportion of sediment moved alongshore and offshore to the bars. A micro-topographic grid will be established near the middle of the fill segment to evaluate the elevation changes that occur over daily and tidal cycles and will be monitored before and after at least four relatively high energy events that occur during the 28 day deployment.

Topography will be mapped semi-annually at 1-m intervals at low tide along cross-shore transects. Sand samples will be taken to confirm that the fill is consistent with the native materials through time and that the movement of sediment from the fill does not change the grain size statistics in adjacent environments. These samples will be taken on the foreshore, transverse bars and low tide terrace environments prior to the fill operation, just after the fill is emplaced, and following the first winter storm season after the fill has been reworked.

Species composition and abundance (expressed in catch per unit effort) of nekton will be determined by analyses of seine samples collected monthly from March to November. Species composition and abundance for benthic infauna will be evaluated in the spring (June) and fall (October) by collecting, sieving, and processing infauna cores. Water-quality parameters, including dissolved oxygen, temperature and salinity, will be measured with an YSI-850 meter prior to the start of each seine haul. All ecological sampling will be conducted one year prior to initial project construction and a minimum of three years post-construction. Sampling in subsequent years will be determined using an adaptive management approach.

Benefits of Project

The results of this project will identify the rate of sediment transport out of the fill area, the kinds of events moving the sediment (episodic or chronic) and the way the beaches in the fill area and downdrift evolve. These characteristics will then be used to identify how much fill is needed and whether the volume and frequency of emplacement required are related to sediment volumes provided by maintenance dredging. The study will also identify how sediment bypasses low headlands to determine whether isolated fill areas placed next to bulkheads allow for sediment transfers alongshore or whether longer fills farther from structures are required. Identification of the pathways of sediment movement and locations where the sediment is deposited will determine whether the fill is moved to areas beneficial to the natural environment.

The need to restore natural functions while allowing for some stability using a strategy of controlled dynamism is becoming a new goal in managing shorelines altered by human use. This strategy is a way of incorporating traditional shore protection methods, such as beach fill, in a new context in locations where static structures were deployed (Nordstrom and others, 2007). This project will provide information about how the feeder beach concept can be implemented adjacent to bulkheads as a means of reducing the excessive local rate of erosion caused by the structures and should have application at other armored segments on the bay shore of Fire Island.

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Shoreline Armoring Impacts and Management Along the Shores of Massachusetts and Kauai, Hawaii

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Abstract. Shoreline armoring has both beneficial and adverse effects. On the beneficial side, shoreline armoring continues to save millions of dollars of valuable waterfront real estate, thus preserving valuable upland by reducing direct exposure to damaging coastal storm waves and flooding (fig. 1). Shoreline stabilization can also help waterfront property owners protect the sales value of individual properties. The financial benefits of maintaining the value of waterfront construction as a result of shoreline armoring, however, appear to remain only with the waterfront dwellings or dwellings within very close proximately of the shore. Property values only several rows inland lowers with the on-going effects of shoreline armoring, and even waterfront property values decline as more and more waterfront property owners rely on shoreline stabilization/armoring.

On the adverse side, shoreline armoring along eroding shores continues to be responsible for the reduction in the beneficial functions and sometimes complete loss of valuable coastal resources, such as beaches, dunes, and intertidal areas. This results in the loss or alteration of associated marine habitat. Lateral beach access can also be restricted or completely lost.

These impacts, particularly the loss of sandy beaches, have great relevance in states such as Hawaii, where the public has the right of use of all beaches statewide. Beaches also provide important social, cultural and ecological benefits to Hawaii’s residents and visitors. Hawaii’s beaches are the backbone of a $13 billion dollar visitor economy that provides approximately 171,900 jobs, the bulk of the state’s jobs and income. More than 60 percent of all jobs in Hawaii are related to tourism, which depends on the appeal of sandy beaches (Genz and others, 2007). Similarly, 16.9 million people work in the travel and tourism industry that contributes $1.2 trillion to the U.S. Gross Domestic Product and $223 billion in taxes (World Travel and Tourism Council, 2010). Beach tourism is by far the largest tourism industry in the U.S. (Houston, 1996).

Figure 1. Vertical concrete seawall with toe stones protecting waterfront buildings from the direct impact of storm waves along the South Shore of Massachusetts.

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Introduction

Worldwide sea level is continuing to rise and the rate of rise is predicted to accelerate (International Panel on Climate Change, 2007). In fact, a short-term acceleration in the rate of sea level rise has been recently documented (International Panel on Climate Change, 2007; Rahmstorf, 2007). Due to this continuing rise in sea level, accompanied by a growing coastal population, requests for coastal erosion control in the form of engineered shoreline armoring structures, such as seawalls, revetments and bulkheads could be anticipated to concomitantly increase. However, growing awareness of the actual, potential, and perceived impacts of coastal armoring has lead, in part, to shoreline armoring prohibitions or significant restrictions. States such as Oregon, North Carolina, Maine, Rhode Island, South Carolina, and Texas have banned shoreline armoring or imposed significant restrictions (Mohan and others, 2003). More than 30 years ago, Massachusetts banned shoreline armoring of landforms that are sediment sources to beaches, dunes and barrier beaches, and recently the County of Kauai, Hawaii, has prohibited ‘fixing the shoreline’, without a regulatory variance. Even non-structural erosion control alternatives, such as biodegradable coir (coconut husk) or fiber roll revetments are being scrutinized more closely due to site-specific potential impacts, such as the loss of or alterations to associated coastal habitats and the temporary loss of source sediment to fronting and adjacent beaches (compare figs. 2*A* and 2*B*).

Figure 2*A*. An eroding coastal bank/bluff acting as a sand source to fronting and adjacent beaches and dunes on Cape Cod, Massachusetts.

Figure 2*B*. The same coastal bank/bluff as shown in figure 2*A* showing a coir fiber roll revetment, that is, non-structural coastal armoring, that is preventing sand from eroding from the bank and feeding the fronting and adjacent beach and dunes.

Shoreline Armoring: A Two State Perspective—Hawaii and Massachusetts

The state of Massachusetts promulgated regulations that prohibit shoreline hardening or structural erosion control measures to protect buildings constructed after the promulgation date of the regulations, and the County of Kauai, Hawaii recently passed an ordinance that prohibits fixing the shoreline for any proposed construction or activity on shoreline lots within their jurisdiction.

Massachusetts

Massachusetts has approximately 1,500 mi of tidal shore, with approximately 70 percent of the state's population residing in coastal counties and 36,000 people living within 500 ft of the shore (Heinz Center for Science, Economics, and the Environment, 2000). Approximately 78 percent of the Massachusetts ocean-facing shore is exhibiting a long-term erosion trend, based on data generated by Thieler and others (U.S. Geological Survey, written commun., 2001; see O'Connell, 2002). Massachusetts coastal regulations, in part, prohibit armoring active coastal dunes, and prohibit armoring eroding coastal banks (coastal bluffs) when the proposed activity is intended to protect buildings constructed after the August 10, 1978, promulgation date of these regulations (State of Massachusetts, 2009). Coastal banks are defined in the Massachusetts regulations as, 'an elevated landform, other than a coastal dune, that lies at the landward edge of a beach, land subject to tidal action or other wetland'.

Massachusetts' regulatory prohibition on armoring eroding coastal banks is based on the recognition that these eroding coastal landforms are the main source of sediment to beaches, dunes and barrier beaches. Armoring coastal dunes is implicitly prohibited by a regulatory performance standard that states that structures and activities shall not interfere with the natural migration and constant changing of shape of coastal dunes in response to wind and waves. Furthermore, an activity cannot prevent a coastal dune from eroding and providing sand to other coastal resources, such as fronting and downdrift beaches.

Thus, being the primary source of sediment, these eroding coastal landforms allow for the continued existence of beaches, dunes and barrier beaches and their associated habitats in Massachusetts. Sediment eroded from coastal banks and subsequently transported along shore is also responsible for forming 681 mapped barrier beaches, which in turn create landward bays and estuaries and habitat for abundant marine organisms.

Approximately 26 mi (or ~30 percent) of the South Shore shoreline of Massachusetts is fronted by coastal engineering structures, not including regions that may be protected by shore-perpendicular structures (for example, groins and jetties). Prior to construction of these shore protection structures, sediment contained in the coastal banks was available to downdrift shorelines (State of Massachusetts, 2010). This armoring has resulted in extensive loss and narrowing of recreational beaches, reduction or loss of lateral beach access, and the elimination or alteration of marine habitat in many areas along the South Shore (compare figs. 3*A* and 3*B*).

Figure 3*A*. A post card from the early 1900s showing a sandy beach and a vegetated coastal bank/bluff along the South Shore of Massachusetts, prior to coastal armoring.

Figure 3*B*. The same coastal bank/bluff along the South Shore of Massachusetts (shown in fig. 3*A*) now structurally armored. As a result of 'passive erosion' and source sediment impoundment, the fronting beach has completely eroded away.

County of Kauai, Hawaii

The County/Island of Kauai, Hawaii, has approximately 110 mi of shore, with almost half of this length consisting of unconsolidated sandy beaches. Approximately 71 percent of the sandy beaches on the Island of Kauai are exhibiting a long-term erosion trend, eroding at an average rate of approximately -0.4 ft/yr (Fletcher and Coastal Geology Group, 2009). Due to the mountainous terrain, the majority of Island population resides in low-lying areas adjacent to the shore.

In January 2008, County government on the Island of Kauai promulgated the *Shoreline Setback and Coastal Protection Ordinance #863* (County of Kauai, 2008). The ordinance requires new buildings on small lots (<160 ft) to be setback a predetermined distance from the shoreline, based on the average lot depth, and for large lots (>160 ft) to utilize an erosion rate multiplied by 70, plus a buffer of 40 ft. The primary purpose of this setback ordinance is to preserve the beneficial functions of coastal resources, preserve lateral public beach access, improve public safety and property value protection, and to avoid shoreline armoring.

The ordinance also, in part, prohibits private and public facilities that may 'artificially fix the shoreline' and prohibits the alteration of primary coastal dunes (except for the addition of compatible sand). This prohibition on artificially fixing the shoreline can be overridden only as a result of the issuance of a 'variance'. A shoreline setback variance may be considered for a structure or activity otherwise prohibited by the ordinance if the County Planning Commission finds, in part, that the proposed 'private or public facility or improvement that artificially fixes the shoreline does not adversely affect beach processes and all alternative erosion control measures, including retreat, have been considered'.

The ordinance also states that any structure approved within the shoreline setback area by variance shall not be eligible for protection by shoreline hardening during the life of the structure. Furthermore, if a structure is permitted in the shoreline setback area by variance, the fact that the structure could be subject to coastal erosion and high wave action 'shall be written into a unilateral agreement that is recorded by the Bureau of Conveyances of Land Court'.

The implementation of shoreline setbacks and limitations on shoreline hardening is the result of the recognition of documented adverse impacts of shoreline armoring along the state of Hawaii's shores. For example, following an analysis of an aerial photographic time series of Oahu, Hawaii's shoreline Fletcher and others (1997) reveal that historical seawall and revetment construction (coastal armoring) to protect eroding lands has caused the narrowing of approximately 11 mi and loss of 6.4 mi of sandy beach over the period between 1928 or 1949 and 1995. This is approximately 24 percent of the 72 mi of original shoreline on Oahu.

The County of Maui (Hawaii) Planning Department mapped 15.6 of 56 mi surveyed as 'hardened', including seawalls, revetments, sandbags and groins (Surfrider Foundation, 2008). The Island's sandy shorelines are retreating inland an average rate of approximately 1.0 ft/yr. This has resulted in the loss of approximately 5 mi of dry beach since 1949 due to the effects of high water against hard engineering structures and natural rock outcrops on the Island of Maui, Hawaii (Fletcher and others, 2007).

The loss of dry sandy beach at high tide due to armoring on the Island of Kauai has occurred as well (fig. 4). Based on a preliminary unpublished analysis, slightly less than 4 mi of sandy beach has been lost due to shoreline armoring on the Island of Kauai (O'Connell, 2010).

Despite the efforts of Kauai County to preserve its valuable sandy beaches and minimize interference with beach processes by implementing progressive shoreline setback standards and prohibiting fixing of the shoreline, the state of Hawaii regulations and policies continue to permit shoreline armoring. The main issue in regulating shoreline armoring is jurisdictional: County vs. state jurisdiction in the coastal zone. Each Hawaiian island is a county, for example, the Island of Kauai is Kauai County.

The 'shoreline' delineates state vs. County jurisdiction. 'Shoreline' in Hawaii means, 'the upper reaches of the wash of the waves, other than storm or seismic waves, at high tide during the season of the year in which the highest wash of the waves occurs, usually evidenced by the edge of vegetation growth, or the upper limit of debris left by the wash of the waves' (HRS Ch. 205A-1). Therefore, the jurisdictional 'shoreline' is often well inland of a sandy beach or seaward eroding face of a coastal landform, for example, coastal dune. So, the jurisdiction for permitting coastal armoring of an eroding coastal landform that lies at the landward edge of a coastal beach is most often with the state, not the County. Before a proposed project can be permitted, the location of the shoreline on a lot must be certified by the state. All area seaward of a 'certified shoreline', which includes coastal beach and often some upland area adjacent to the beach, is designated for public use.

Hawaii Coastal Zone Management Program Policies for 'Beach Protection', Hawaii Revised Statutes, Chapter 205A-2(c)(9)(B) states, in part, 'prohibit construction of private erosion-protection structures seaward of the shoreline, except when they result in improved aesthetic and engineering solutions to erosion at sites and do not interfere with existing recreational and waterline activities; and (C) 'minimize the construction of public erosion-protection structures seaward of the shoreline'.

The Hawaii Department of Land and Natural Resources, Office of Conservation and Coastal Lands, is, in part, responsible for permit review and processing proposed activities within private and public State Land Use Conservation Districts which include lands seaward of the 'shoreline', that is, beaches and potential sediment sources to beaches and dunes. Hawaii Administrative Rules Chapter 13-5, Conservation Districts (CD), identifies land uses that may be permitted in Conservation District sub-zones. The 'Resource Sub-zone' includes lands and state marine waters seaward of the shoreline, that is, coastal beaches. In the Resource Sub-zone, seawalls, shoreline protection devices, and shoreline structures are listed as identified land uses. The objective of this sub-zone, however, is to develop, with proper management, areas within it to ensure sustained use of the natural resources of this area. So, while coastal armoring is a listed land use, alternatives to structural coastal armoring are preferred and no permanent coastal armoring has been permitted in at least in the past 7 years (D. Eversole, HI Sea Grant Program, oral commun. 2009). However, temporary, emergency coastal erosion control structures, for example, sand-filled geo-textile revetments and biodegradable sand bag revetments, continue to be permitted on a case by case basis.

Figure 4. Coastal armoring along the central coast of the Island of Kauai, Hawaii resulting in the loss of the fronting beach due to passive erosion and source sediment impoundment.

The Impacts of Shoreline Armoring: Benefits and Detriments

Shoreline Armoring Can Result in Benefits and Detriments

Benefits of shoreline armoring may include:

- stabilizes the upland;
- protects infrastructure; and,
- maintains property values (caveat: The first few waterfront property owners to stabilize their shoreline achieve significant benefits, but as more and more of their neighbors follow suit, property values drop to about where they started. In contrast, shoreline stabilization appears to lower property values a few rows in-land (Kriesel and Friedman, 2003).

Detriments of shoreline armoring may include:

- 'source sediment impoundment' resulting in increased erosion of the fronting and adjacent beach due to sediment budget reduction;
- 'passive erosion' resulting in the eventual loss of the dry beach and possibly the loss of the inter-tidal area along eroding shores;
- 'loss of lateral beach access';
- 'loss or changes to marine habitat';
- 'reduction of and possible loss of marine organisms and associated ecological functions';
- 'adjacent property impacts', such as end scour or flanking erosion; and,
- 'placement loss' resulting in the direct loss of beach and possibly habitat.

Source Sediment Impoundment

In Massachusetts, with few exceptions, the primary source of sediment to beaches, coastal dunes and near-shore areas is sediment eroded from coastal landforms, such as outwash plains, kames, drumlins and ground moraine (fig. 5). Thus, armoring these primary sediment sources reduces the sediment budget, resulting in the loss or reduction in the volume of source sand and gravel otherwise available to adjacent beaches and dunes. Accompanying the loss of beach and dune volume and form, the beneficial functions of storm and flood damage reduction to landward development and resources provided by these coastal landforms are diminished.

In Hawaii, the primary source of sediment that constitutes beaches is from the breakdown of coralline and calcareous algae, corals, mollusks, echinoderms, and to a minor extent the weathering and erosion of volcanic rock. Most sediment in reef systems is produced on the shallow nearshore platform, where carbonate productivity and erosion are the highest. Sediment exchange between near-shore reef-top sand bodies deposited in relic reef platform depressions and the beach face could be an important component of beach stability; however, their role in littoral processes needs to be better understood (Bochicchio and others, 2009). At present, the greatest accumulations of stored sands are found in formally accreting and now, for the most part, eroding coastal plains. Thus, long-term sediment budgets experiencing chronic deficits rely upon erosional release of sand from the adjacent coastal plain (Fletcher and others, 2007). In other words, the present-day primary source of sand for beaches is from the erosion and release of sand from the coastal plain.

Thus, along eroding shores with diminished sediment input due to source sediment impoundment as a result of coastal armoring, the loss of dry beach and eventually the loss of the inter-tidal area results as the beach and inter-tidal area continue to diminish in width as the high water line moves towards a shoreline armoring structure (fig. 6).

Passive Erosion—Loss of Dry Beach and Inter-tidal Habitat

Along a shoreline undergoing long-term erosion in response to a sediment deficit and/or relative sea-level rise, the high water line will continuously migrate landward. This process is termed 'passive erosion'. In response to relative sea-level rise, the shoreline will continue to migrate landward until it reaches a hardened surface, such as a revetment or seawall. The loss of dry beach results with high water forced against the structure.

This process of passive erosion is perhaps the most significant long-term effect of shoreline armoring, and cannot be mitigated, except through an on-going and permanent beach nourishment program which is only a temporary solution (Griggs, 2005). The process of passive erosion is accelerated if coupled with source sediment impoundment (as described above).

Figure 5. An eroding coastal bank/bluff along the south shore of Massachusetts providing source sand to the fronting and downdrift beaches.

Figure 6. The loss of beach and thus public lateral beach access due to shoreline armoring and chronic erosion along the east coast of the Island of Kauai, Hawaii. Note the sandy beach in the background where no coastal armoring exists.

Loss of Lateral Beach Access

As the beach width narrows and is eventually lost along eroding, armored shores, lateral access is diminished and ultimately lost (fig. 7), unless long-term beach nourishment is feasible. The site in figure 7 had a permit condition associated with the approval of the revetment to maintain lateral dry beach access fronting the revetment at all tides. However, after a short time following revetment construction it was recognized that lateral beach access was impossible to maintain and the permit condition was removed. The lateral beach access (fig. 7), which is now lost, led to a U.S. Fish and Wildlife coastal property.

Loss of Marine Habitat, Marine Organisms, and Alteration of Ecological Function

As in the loss of lateral beach access along an armored eroding shore, as the beach and intertidal area narrows and is ultimately lost, marine organisms and their habitat are affected. For example, marine organisms that rely on inter-tidal habitat can be lost and possibly replaced with an entirely different assemblage of marine organisms that thrive on a rocky marine environment, that is, rip-rap revetment. In a study of ecological effects of coastal armoring on sandy beaches in California, Dugan and others (2008) found the abundance, biomass and size of upper intertidal macro-invertebrates were significantly lower on armored vs. unarmored shoreline segments, as well as concomitant lower species richness and abundance of foraging shorebirds. Further investigation of ecological responses to coastal armoring is needed for the management and conservation of ecosystems (Dugan and others, 2008).

Adjacent Property Impacts: End Scour or Flanking Erosion

Local scour or flanking erosion at the ends of shoreline armoring structures, such as seawalls and revetments, can affect the existing structure and/or adjacent property (fig. 8). Unarmored, unconsolidated landforms on either side of a coastal armoring structure will continue to erode and the high water line will continue to migrate landward on either side of the armoring. Eventually, the frequency of interaction between waves and the armoring structure will increase and affect adjacent property, as well as the revetment or seawall itself, through a process known as end scour or flanking erosion. The intensity and frequency of the interaction between storm waves and a shoreline armoring structure can be related to placement of the structure along the beach profile, that is, landward vs. seaward, and this relates to the degree of impact or scour. In addition, local scour at the ends of coastal armoring structures is the result of the end configuration of the armoring structure, angle of wave approach, and wave height and period (Griggs, 2005).

Placement Loss: Type of Armoring

The type of armoring structure, for example, revetment vs. seawall, will affect the amount of total beach and inter-tidal area permanently lost by displacement (fig. 9), along with the loss of associated habitat and lateral beach access reduction or loss. Vertical structures displace less coastal resource area than do sloping revetments. However, the perception that sloping structures such as revetments have less of an impact on active beach processes due to its slope and permeability than vertical seawalls or bulkheads is the subject of on-going debate (Griggs, 2005).

Figure 7. The loss of public lateral beach access due to shoreline armoring along the shore of Chatham, Massachusetts. Prior to revetment construction, a dry sandy beach provided lateral public beach access to a U.S. Fish and Wildlife property.

Figure 8. End scour or flanking erosion at a seawall along the east coast of the Island of Kauai, Hawaii.

Figure 9. Depiction of the extent of placement loss of beach and marine habitat by comparing the extent of loss due to a revetment vs. a bulkhead.

Discussion

Importantly, placement location of coastal armoring, that is, at the shoreline, seaward vegetation line, or along the back beach, along with a host of other site-specific factors, play a large role in potential impacts to beach and near-shore processes, as well as potential impacts to marine organisms and their habitat.

Griggs and Tait (1988) and Griggs and others (1994) documented minimal long-term adverse impacts in an 8-year field study of the effects of shoreline armoring on fronting and adjacent beach processes along California's Monterey Bay shore. They documented that the berm is cut-back sooner in front of seawalls during the summer to winter erosional beach profile transition. In addition, during the winter to summer accretional transition phase, the berm builds seaward on the unarmored adjacent area until the seaward berm edge reaches the seawall, then the berm begins to build seaward in front of the seawall. Therefore, while short-term differences in seasonal and storm-recovery beach processes were measured where this seawall exists, minimal long-term (8 years) impacts were documented. This appears to be consistent with a comprehensive review of more than 100 technical papers on the effects of seawalls on the beach that concluded that beach change near seawalls, both in magnitude and variation, is similar to that of beaches without seawalls, *if a sediment supply and a wide surf zone exists* (*emphasis added*) (Kraus, 1988). In addition, the position of the seawall with respect to the surf zone is a critical parameter controlling the amount of local erosion and the beach recovery process (Kraus, 1988). The fact that an alongshore sediment source existed (225,000 m^3/yr) feeding the beach fronting the armoring that was studied along California's Monterey Bay shore (Griggs and Tait, 1988; Griggs and others 1994, described above), and placement of the armoring was landward along the back beach may have contributed to minimal measured impacts to long-term beach processes.

Importantly, retention of sediment behind the wall (impoundment) and flanking erosion or end scour are mechanisms that can be firmly identified by which seawalls may contribute to erosion of the coast (Kraus, 1988). Placement loss is also a major consideration in the loss of beach area and potential loss of marine habitat. Furthermore, if sea (or lake) level is rising at a site, erosion is more likely to occur at armored beaches as compared to unarmored beaches (Kraus, 1988), that is, passive erosion. An updated literature review including 40 additional papers on the effects of seawalls on the beach can be found in Kraus and McDougal (1994).

Conclusions

Coastal armoring can potentially affect physical, biological, and ecological characteristics of a shoreline, as well as property values and community considerations. The generalized impacts of coastal armoring, which can be both beneficial and adverse, are well documented. Impacts can be site- or littoral-cell specific and vary considerably based on a variety of factors, such as placement location, type of landform armored, structure type, seasonal changes in wave and beach form, and the density of armoring structures. With accelerating sea-level rise and continuing population migration towards the shore, coastal armoring will continue to be a subject of great debate. Much of the U.S. shore is already developed and most states allow consideration of protecting existing development that pre-date regulations governing waterfront development and armoring of the shore.

Managed retreat, in the form of shoreline setbacks, for example, is being widely considered - at least for 'new' or substantially re-constructed buildings. This may be the best method to mitigate damage and beach loss on a lightly populated coast, where the economic impact of erosion is relatively small and there is no threat to a resource of significant economic importance, for example, critical coastal road, or unique historical or ecological value (Mohan and others, 2003). Coastal armoring may be an economic choice along a heavily populated and developed coast. However, hard structures are often not considered desirable because of their possible impact on local or downdrift beaches (Mohan and others, 2003).

Identifying the potential impacts of coastal armoring on a site- or littoral-cell specific basis is critical in assisting coastal managers with decisions on whether to permit coastal armoring, to suggest alterations that may have less impact, or to assist in developing mitigation techniques for potential adverse impacts, if possible or feasible.

Shoreline and beach management plans identifying areas that should be preserved for their unique natural and beneficial functions, such as important sediment sources to adjacent beaches, dunes and barrier beaches, or beaches of economic importance, are vital to the preservation of coastal community character, and maintain a viable economic base.

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The Effects of Armoring Shorelines—The California Experience

Gary B. Griggs[1]

Introduction

Washington's Puget Sound shoreline varies significantly in its geologic make up and many areas of the shoreline are both developed and undergoing erosion. Increasing concern has recently been expressed regarding the impacts of armoring this coastline. This paper reviews what has been learned from the experience of armoring the more intensively developed coastline of California with the objective of providing insight to guide future decision making regarding armoring of the shorelines of Puget Sound.

While coastal zones globally have always been sites of human habitation, populations in these areas over the past 50 years have grown faster than in other regions (Crossett and others, 2004). In the United States in particular, coastal land has become increasingly more valuable as oceanfront communities and cities have expanded, recreational activities and tourism have grown, and people have chosen to build or purchase residences or vacation homes along the shoreline. At the same time, sea level has continued to rise, and hurricanes and El Niño Southern Oscillation (ENSO) events have taken their tolls as coastlines have continued to retreat.

The exposed outer coast of California is different in many ways from the protected shoreline of Puget Sound. In fact, about the only things the two areas may have in common are an adjacent body of salt water and a widespread desire of residents in both states to live as close to that water as their bank accounts will allow. California has an 1,100-mi long, roughly linear shoreline that experiences a maximum tidal range of about 6 ft to perhaps as much as 9 ft, and is directly exposed to the large swells of the Pacific Ocean. Puget Sound, on the other hand, has a 2,600-mi long, crenulated shoreline, a maximum tidal range of about 12 to 13 ft, and is sheltered from open ocean waves.

More than one-half (59 percent, or 650 mi) of the coastline of California consists of low relief cliffs and bluffs commonly eroded into marine terraces; 140 mi (13 percent) consists of high-relief cliffs and coastal mountains; and the remaining 310 mi (28 percent) is characterized by lowlands with beaches, dunes and lagoons or estuaries (Griggs and others, 2005). The coastline of Puget Sound is dominated by low to moderate height bluffs that have been eroded into mixed glacial deposits left behind by the glaciers that covered the Sound during the last Ice Age. The typical California beach is wide and sandy, whereas most Puget Sound beaches tend to be relatively narrow and commonly consist of gravel or a mix of sand and gravel.

In California, the state owns and has jurisdiction over all land below the mean high tide line. In the state of Washington, however, about half of the property owners have title to the land down to the mean lower low water line; in other words, they own or have control over the intertidal zone. California is crowded with a population of 38 million people; Washington is relatively uncrowded with 6.5 million people.

Coastal Erosion and Protection in California

Over the past 50 years, the typical response to coastal erosion in the United States has been the construction of a seawall, revetment, bulkhead or other "hard" structure, intended to protect wave-impacted development or infrastructure. In California, an astonishing 110 mi, or 10 percent, of the state's entire 1,100 mi of coast, has now been protected or armored. In southern California's four most urbanized counties (Ventura, Los Angeles, Orange, and San Diego), 33 percent of the entire 224 mi of shoreline has now been armored (Griggs, 2005). Most of California's shoreline development took place during the cool or less storm Pacific Decadal Oscillation (PDO) cycle that extended from 1945 to 1977. The warmer 1978–2000 PDO cycle was characterized by a number of strong ENSO winters, bringing shoreline-damaging events that led to large increases in requests for new armoring permits.

In contrast to the oceanfront homeowner's concern for the cost, lifespan, and effectiveness of a coastal protection structure, considerable public opposition has risen in recent years to proposals for new seawalls or revetments because of the potential impacts of these structures. Many of the concerns in California revolve around the issue of whether private property owners should be allowed to impact public beaches as they attempt to protect their own property, or in the case of government funded projects, how much taxpayers money should be spent in efforts to stabilize the position of an otherwise eroding coastline? With an increasing public awareness of global warming and a rising sea level, the issues of coastal erosion and protection are being viewed more critically than they were a decade or two ago.

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A number of potential impacts of coastal armoring have been identified and are the issues typically evaluated before any new seawall permit is approved. The following discussion focuses on each of the types of impacts or effects that are usually identified with the emplacement of coastal armor. These include: visual impacts, impoundment or placement losses, reduction of beach access, loss of sand supply from eroding bluffs/cliffs, and what have been termed passive erosion and active erosion. For a more complete discussion of these impacts, see Griggs (2005) as well as Krauss (1988) and Kraus and McDougal (1996).

Armoring

Visual Impacts

Any armoring structure built to protect either cliff, bluff, dune or back beach development will have some aesthetic impacts (fig. 1). Whether a seawall, bulkhead, revetment or some other form of stabilization or protection, there is a visual impact that can be much greater to the beach user or general public than to the owner of the property being protected, who may not even see the structure. In California, the visual impact of coastal armor is probably the issue that most concerns the public. This is something they can observe directly that does not require a scientific explanation or debate among experts. Prior to the requirements of Environmental Impact Statements or Reports, armoring projects were completed without any environmental review. Some of these very early projects consisted of dumping concrete rubble onto the beach or a variety of other non-engineered solutions. We are still living with some of these protection efforts. Because of these visual impacts, and general concern with covering over natural cliffs and bluffs with rocks or gunnite or seawalls, far more attention than ever before is being focused on reducing visual impacts.

One relatively recent approach in California has been the use of soil nail walls or sprayed concrete, which is colored and textured to match the native rock in the cliffs. Colored and textured gunnite or soil-nail walls have been used to stabilize highway road cuts, but only recently has this approach been applied to coastal protection projects as a way to mitigate the visual impacts. These structures involve anchoring soil nails or tie backs into the bluff materials, and then constructing a steel-reinforcing frame that mimics the shape of the existing bluff. This mesh is then covered with about a foot of gunnite, followed by a second 6- to 12-in. thick layer, which is textured and colored to match the adjacent rock as closely as possible (fig. 2). Weep or drain holes must be built into the structure in order to avoid the buildup of water behind it.

Figure 1. These cliffs in Capitola, California have been protected by a home-made seawall with visual impacts for beach users.

Figure 2. Bluff reconstruction and stabilization along the Pebble Beach area of the Monterey Peninsula, where the exact textures and colors of the existing granitic rock were duplicated to minimize visual impacts.

Concrete, if it is well mixed and prepared, and if the reinforcing rods are protected from exposure to seawater, can be very resistant to wave impact and erosion. While the color and texture of natural cliffs and bluffs can be duplicated, this is more problematic when beachfront or dune development is being armored or protected.

Placement Loss

When any protective structure is built at the base of a bluff, cliff, or dune, or well out on the beach profile, a predictable amount of beach will be covered by the structure. The effect is immediate beach loss, the extent of the loss being a function of how far seaward and alongshore the structure extends. Where a relatively thin vertical seawall or soil nail wall is built, there is usually very little beach loss because the structure has a very small cross-shore width, perhaps only several feet. Some very large concrete seawalls, however, such as the O'Shaughnessy seawall along San Francisco's Ocean Beach (fig. 3), or the Galveston seawall, do have an appreciable width and will cover over more beach area.

On the other hand, where riprap or a revetment is placed to protect a bluff, it may reach a height of 15 to 25 ft or more, and extend seaward at a 1.5:1 or 2:1 slope, covering 30 to 50 ft of beach (fig. 4). This placement loss can easily be calculated for any proposed revetment knowing the cross-sectional area and alongshore length, and this impact can then be quantified in relation to how much adjacent or surrounding beach area would still be available. In other words, if the existing beach is very narrow, say 30 ft on average, the riprap may cover the entire beach. Where the beach is wider, riprap may cover only one-third to one-half of the available beach area.

Figure 3. The massive and carefully engineered O'Shaughnessy Seawall in San Francisco was built in 1928 and has stood the test of time.

Figure 4. This revetment in the city of Santa Cruz has eliminated the entire beach through placement loss.

Reduction of Beach Access-Vertical or Lateral

In California, a major driving force for the passage of the original Coastal Act in 1976 was public access to the shoreline that was increasingly being threatened or restricted by oceanfront development. Depending upon the coastline being considered for armoring, and the nature of the protective structure being proposed, the potential exists to reduce or restrict access either to the beach (vertical access) or along the beach (horizontal lateral access). Depending upon the width of the beach and the typical tidal range, lateral access may be lost for differing amounts of time throughout the year (fig. 5). Loss of lateral access will be greater in the winter months, when the beach has been lowered and narrowed, than in the summer months, when a wide berm usually exists. A continuing rise in sea level, however, will increase the amount of time when lateral access becomes restricted.

While a seawall normally extends a lesser distance seaward than a revetment, both structures can restrict lateral access if the beach is narrow or present only seasonally. Knowing tidal ranges and wave run-up at a particular site, as well as typical beach widths or elevations during differing times of the year, a reasonable prediction of the amount of time that lateral access would be lost can be made. At some locations, stairways and elevated walkways have been built over these structures to help mitigate this impact.

Loss of vertical access is a somewhat different issue. Seawalls or bulkheads can restrict or eliminate access to the beach from the cliff or bluff top, but in steep cliffed areas, vertical access is limited to begin with. Access stairs can be built into most coastal armoring structure, however, so that this impact can be mitigated, although such stairs may also be damaged or destroyed by the wave action that led to the need for armoring to begin with.

Impoundment or Loss of Sand Supply from Eroding Bluffs/Cliffs

Coastal armoring has also become an issue as it affects sand supplied to beaches on a regional basis. In California, the great majority (70 to more than 95 percent) of the beach sand delivered to individual littoral cells comes from rivers and streams, with most of the rest coming from eroding cliffs or bluffs (Runyan and Griggs, 2003; Griggs and others, 2005). With a significant reduction in sand transport and delivery due to the construction of more than 500 dams on coastal streams in California (Willis and Griggs, 2003), there is increased concern about the cumulative impacts of additional sand supply reduction.

Figure 5. Under winter beach conditions, lateral access is significantly reduced due to the encroachment of these temporary protection structures onto the beach at Malibu.

Assessing the impact of any proposed coastline armoring on sand supply involves determining how much beach-compatible sand is supplied by the retreat of the particular coastline being armored. The alongshore length and height of the bluff, the percentage of sand or littoral-size material, and also the average annual erosion rate are the factors that need to be included in a sand reduction calculation. Determining the amount of littoral-sized material is straightforward in unconsolidated materials, but is more difficult for consolidated rock types. In addition, many cliffs or bluffs consist of several different types of materials with differing sand contents (bedrock and terrace deposits for example), or vary alongshore, which further complicates any calculations. The assumption is commonly made that particles of sand size or larger (>0.062 mm) will contribute to a beach, but because beach sediment size varies in response to local wave energy, this assumption is usually not a valid one (Limber and others, 2007). In some areas along California's coast, where because of the grain sizes of the cliff or bluff materials they contribute significantly to adjacent beaches, armoring will significantly reduce littoral sand supply, but in other areas this will not be an issue.

Passive Erosion

Whenever a hard structure is built along an eroding coastline, the shoreline will eventually migrate landward on either side of the structure (fig. 6). The effect will be gradual loss of the beach in front of the seawall or revetment as the water deepens and the shoreface profile migrates landward. This process is designated as *passive erosion* and has been well documented along many different shorelines (Griggs, 2005). Passive erosion takes place regardless of the type of protective structure emplaced. This process is perhaps the most significant long-term effect of shoreline armoring.

Active Erosion

The potential for a seawall or revetment to induce or accelerate beach erosion has been the source of considerable controversy over the past two decades. A common assertion is that seawalls cause beach erosion. Although differing opinions have been put forward on these issues, until fairly recently there had been a noticeable lack of sustained or repeated field observations and measurements with which to resolve the conflicting claims. Two major compilations of existing studies and references related to the issue of seawalls and their effects on beaches have now been completed (Kraus, 1988; Kraus and McDougal, 1996).

An 8-year field study was carried out along the central coast of California to resolve some of the seawall/beach impact questions (Griggs and others, 1994; Griggs and others, 1997). This is still the only long-term beach-seawall monitoring research that has been reported on in California. The project involved monthly cross-shore surveys of beaches fronting and both up and down coast from several different seawalls and revetments along the shoreline of northern Monterey Bay. The seawall that was monitored for the entire 8-year period was built 75 m seaward of the base of the coastal bluff and is exposed to wave impact every winter. Twelve cross-shore profiles at 60 m spacing were surveyed. These beaches undergo significant seasonal erosion and accretion, but are not experiencing long-term retreat. An additional factor in this area, which may be significant, is the average annual littoral drift rate of about 230,000 m^3/yr (Best and Griggs, 1991; Patsch and Griggs, 2006).

Figure 6. Passive erosion in southern Monterey Bay, California, has eliminated the beach in front of this riprap as the bluffs on either side continue to erode at more than 6 feet per year.

A number of consistent beach changes related to seawalls were recognized during this monitoring. During the transition from summer to winter, the berm was cut back slightly sooner in front of the seawalls relative to adjacent unarmored beaches. Once the berm retreated landward of the seawall, however, there were no significant alongshore difference in the beach profile. Repeated surveys and comparisons at a vertical concrete seawall and a rock revetment indicate little consistent difference in profile response due to differences in permeability or reflectivity. Either the apparent differences in permeability of the two types of structures are not significant to wave reflection, or the importance of reflected wave energy to beach scour needs reconsideration.

Local scour was often observed at the downdrift end of each structure as a result of wave reflection from the angled end section of a seawall. The extent of this scour (which was usually only a few to perhaps several tens of meters in downcoast length, appears to be controlled by end-section or wing wall configuration, the angle of wave approach, and wave height and period.

Surveys of the spring and summer accretionary phase indicate that the berm advances seaward on the adjacent control beach until it reaches the seawall. At that point, a berm begins to form in front of the seawall and subsequent accretion occurs uniformly along shore. Thus while the winter erosional phase is influenced to some degree by the presence of a seawall, this is not the case for the berm rebuilding phase. Comparison of data from 8 years of surveys reveals no distinguishable differences between the winter or the summer profiles for the seawall and the adjacent control beaches. Since the completion of this study, there have been no other long- or short-term studies in California of the impacts of shoreline armor on adjacent beaches.

Conclusions

Few issues in coastal areas are more complex and more divisive or controversial than shoreline armoring practices or projects. The extent of seawalls and revetments along the shoreline suggests that such projects are necessary to protect property, but the numerous issues associated with them suggest much disagreement or differences of opinion about this necessity. The fact that armoring now protects 110 mi, or 10 percent, of the entire coastline of California is indicative of the magnitude of development in hazardous areas prone to severe to damaging erosion.

In recent years, considerable opposition has often arisen when new seawalls or revetments have been proposed because of the potential effects of these structures. These potential effects include visual impacts, restrictions on beach access, placement losses, the reduction of sand supply from previously eroding coastal bluffs following armoring, and passive erosion, or loss of the beach fronting a seawall as sea level continues to rise. An additional issue, which has arisen with the proliferation of coastal armoring, has been that of the direct impacts of a seawall on the beach itself, or active erosion. Long-term field investigations of seawalls and adjacent beaches along the coastline of Monterey Bay, California, where littoral drift rates are high, indicate that seawall induced erosion is not a significant issue at this location.

Well-designed and constructed soil nail walls can effectively mitigate visual impacts, access restriction, and placement losses. Passive erosion will likely have the greatest impacts on California’s beaches as sea level continues to rise in the decades ahead.

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A Report from the National Research Council: Mitigating Shore Erosion Along Sheltered Coasts

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Abstract. The 2007 National Research Council report *Mitigating Shore Erosion along Sheltered Coasts* examined the impacts of shoreline management on sheltered coastal environments such as estuaries, bays, lagoons, mud flats, and deltaic coasts. Various approaches for stabilizing the shoreline were evaluated for their effectiveness in erosion control and for their impacts on nearshore habitat and adjacent or nearby coastal resources. The report discussed the potential for cumulative impacts from shore protection structures and recommended changes in the regulatory system to shift the trend from shoreline armoring towards less structural approaches that conserve more of the ecosystem services provided by the natural nearshore environment. This paper highlights a few of the findings and recommendations from the report that are of potential relevance to shoreline armoring in Puget Sound.

Introduction

The National Research Council's Ocean Studies Board undertook a study of coastal erosion on sheltered coasts under the sponsorship of the U.S. Environmental Protection Agency, the U.S. Army Corps of Engineers, and the Cooperative Institute for Coastal and Estuarine Environmental Technology. An ad hoc committee of nine experts in coastal processes, ecology, and management policy was convened to produce a report that would assess the impacts of armoring sheltered shorelines, identify alternatives to armoring, and recommend ways to aid decision makers. As part of the information-gathering process, the committee organized a workshop in October 2005 to bring together experts from around the United States to discuss the science and policy issues of shore protection on sheltered coastlines. The workshop examined the geomorphic settings on sheltered coasts and then explored various erosion control approaches. The membership of the committee and agenda for the workshop are available in the published report (National Research Council, 2007). This paper summarizes portions of the National Research Council (NRC) report's findings and recommendations. The reader is referred to the full report for more complete discussions of issues associated with shoreline armoring on sheltered coasts.

Sheltered Coasts on Puget Sound

Much of Puget Sound can be characterized as sheltered coast because the shorelines are partially or fully protected from the high-energy regime associated with the open ocean coast. Like other estuarine systems, Puget Sound has a convoluted shoreline that segments the coast into relatively small littoral cells, which as a consequence of limited fetch have lower energy. Such low-energy conditions facilitate the establishment of eelgrass, marsh, and mudflat habitats generally not found on ocean-facing coasts. These habitats, known for their high productivity, provide nursery and feeding grounds for many marine species, including valuable finfish and shellfish (fig. 1).

Erosion and landslides from high bluffs provide the major source of sediment for the coarse sand and gravel fringing beaches typically found in Puget Sound, with rivers and streams forming a secondary source of sediment (Thom and Shreffler, 1994). Major storm events, rather than continual wave action, cause most beach erosion, although some areas may experience appreciable erosion as a consequence of boat wakes.

In addition to the impacts of erosion, the effects of rising sea level will exacerbate the loss of waterfront property and increase vulnerability to inundation hazards. In Puget Sound, the local increase in sea level is anticipated to approximate the global trend in sea-level rise (Mote and others, 2008). By 2100, global sea level has been predicted to rise 0.5 m to 1.4 m above the 1990 sea level (Rahmstorf, 2007). The broad range of values reflects uncertainty in the changing rate of sea-level rise under various climate scenarios. Even at the lowest predicted rate for global sea-level rise (0.5 m in 2100), the corresponding landward shift in the shoreline on a coast with a 1:100 slope would be 500 m (approximately 547 yd).

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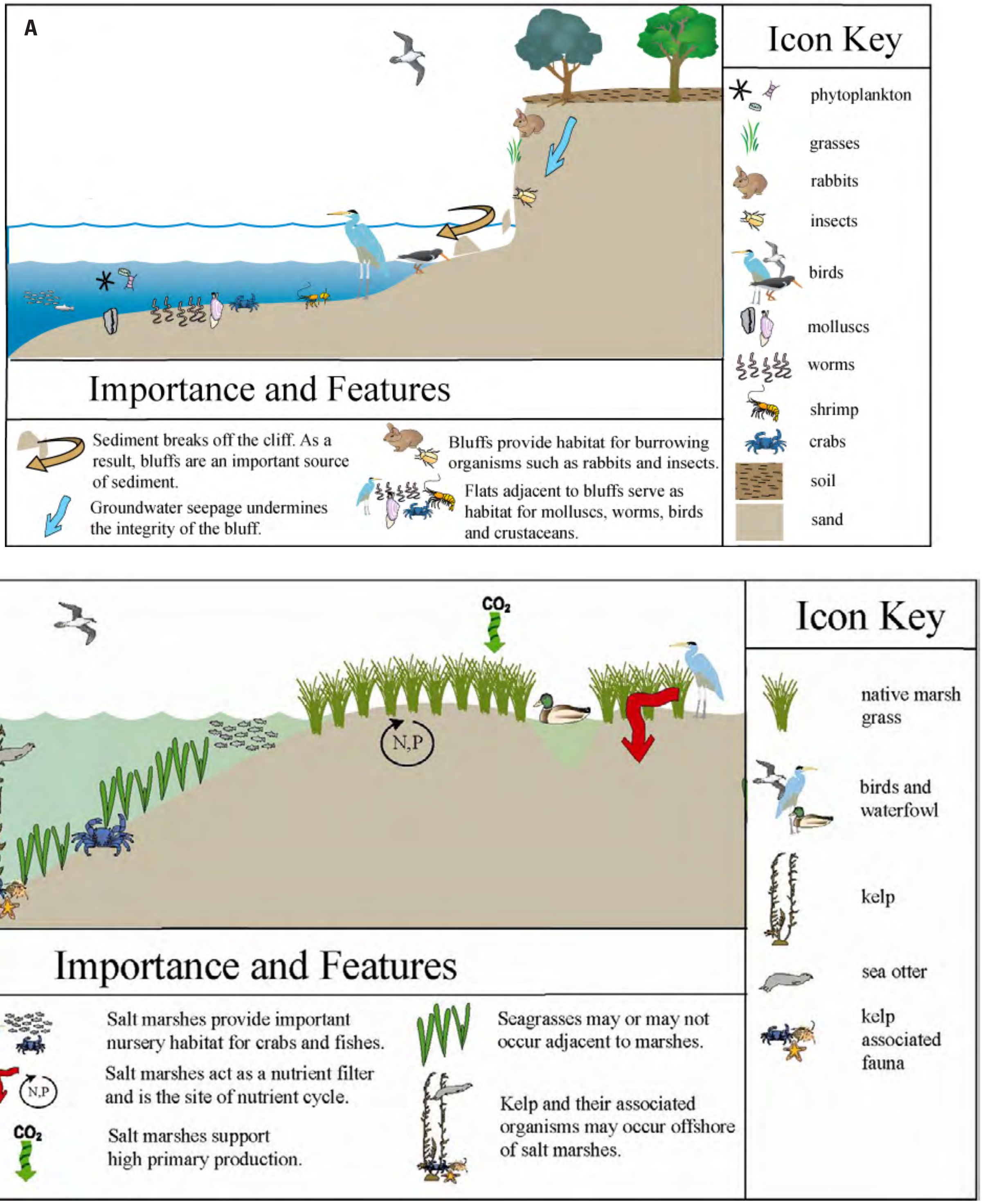

Figure 1. Conceptual diagrams of ecosystem services provided by a bluff (*A*) and a salt marsh (*B*) illustrating some typical components of the ecological communities and outlining the processes that characterize these coastal environments. Source: National Research Council (2007).

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Overview of Shoreline Armoring

The dynamic nature of shorelines commonly conflicts with the landowner's desire for a fixed, stable property line. In some cases, buildings constructed close to shore or near the edge of a bluff will be threatened by erosion, whether natural or accelerated by human modifications of the landscape or seascape. The common response to this problem has been to install hard, barrier structures such as bulkheads, seawalls, and revetments to prevent erosion. Global sea-level rise presents another incentive to armor the shoreline as protection against inundation, erosion, and land loss. Because sea-level rise is chronic and progressive, this "hold the line" strategy will likely result in a steady escalation in both the costs of structure maintenance and the consequences of failure. In addition, shoreline armoring often blocks sediment supply, starving the nearshore beaches, and preventing the landward progression of fringing beaches, marshes, and mudflats.

Indirect costs associated with erosion-control measures that armor the shoreline include loss of ecosystem services at the site and in surrounding waters and shorelines (fig. 1). Many of these costs are borne by the public rather than the individual landowner. For example, sea walls and bulkheads may lead to loss of the intertidal zone with subsequent changes in the plants and animals that inhabit these areas. When an installation causes degradation of a marsh, a highly diverse and productive plant and animal community will be lost along with vital ecosystem services such as nursery areas for important fish stocks, removal of excess nutrients from land runoff, feeding areas for migratory birds, and sediment stabilization. Some types of armoring may result in scouring at the edges of structures or disruption of the sediment supply for downstream beaches.

A shift away from shoreline armoring has been slow, in part because barrier-type structures are often installed as a reactive response to an erosion event rather than an integral part of shoreline management planning. Zoning and other proactive land-use planning approaches can be used to limit development where active erosion may undermine buildings or result in substantial land loss. Another factor that inadvertently promotes the use of hard barrier structures is the greater familiarity with armoring methods than with alternative approaches such as constructing a marsh fringe or using vegetation to stabilize a bluff. Contractors are more likely to recommend structures such as bulkheads because they have experience with the technology and know the design specifications and expected performance. Landowners frequently assume that only a hard, barrier-type structure will prevent loss of property and protect buildings. Even landowners who would prefer an alternative to hardening may resort to the standard bulkhead because in many regions the regulatory system unintentionally encourages shoreline armoring because it is simpler and faster to obtain the required permit(s).

In the 2007 report, the study committee recommended a regional management approach to assess the costs, benefits, and cumulative impacts of structural approaches and to encourage erosion-control alternatives that help retain the natural features of coastal shorelines. Creating a more proactive regional approach to shoreline management could address some of the unintended consequences of reactive permit decisions. The NRC report covered many topics related to erosion control on sheltered coasts. This paper highlights two aspects of national shoreline policies from the NRC report of potential relevance to the Puget Sound region.

Cumulative Consequences of Erosion Mitigation Approaches

Although loss of small parcels of shoreline habitat due to armoring may not have a large impact on the ecosystem, the cumulative impact of losing many small parcels will at some point alter the properties, composition, and values of the ecosystem. In addition, the economic, recreational, and aesthetic properties of the shoreline will be altered, with potential loss of public use, access, and scenic values. It is empirically difficult to determine when the cumulative impact of individual armoring projects alter ecosystem processes and substantially reduce the public trust values of the shoreline, hence it has been difficult for policy makers to balance the trade-offs between protection of property and potential loss of landscapes, public access, recreational opportunities, natural habitats, and reduced populations of fish and other living marine resources that depend on these habitats.

Cumulative impacts encompass the combined effects on legal, social, and physical systems as well as the ecological effects of shoreline armoring. From a legal or regulatory perspective, issuance of even one permit may establish a precedent, potentially facilitating the approval process for future requests for similarly situated structures. Another aspect of cumulative impact is the erosion-enhancing effect of structures such as bulkheads on adjoining properties. Flanking property owners are likely to respond by constructing their own bulkheads, with a domino-type effect up and down the shoreline.

The NRC report recommended inclusion of cumulative effects of shoreline hardening as part of shoreline management plans, accounting for both aesthetic and recreational values and the ecosystem services that stand to be lost. Incorporating potential cumulative effects in the planning process may require a multijurisdictional, regional approach, such as consideration of the level of armoring in Puget Sound, and anticipation of future requests for shore protection structures. If information is insufficient to support a comprehensive assessment of the cumulative impacts of shoreline armoring, a precautionary approach should be used to prevent the unintentional loss of shoreline features and potentially irreversible alteration of the coastal ecosystem.

Decision-Making and Regulatory Processes

The decision-making process for shoreline armoring begins with landowners who decide to alter the shoreline fronting their properties, typically to prevent erosion or inundation. The landowner must then seek the appropriate permits to proceed with construction. The process involves several layers of decision makers, including consultants and contractors such as civil engineers; government regulators, permitting and compliance officials; and policy-makers or lawmakers. The motivations, information sources and needs, and area of influence of the four levels of decision makers are summarized in table 1, which is reproduced from the NRC report.

Government officials at all levels—federal, state, county, and locality—have legal mandates and policies that regulate the shoreline and adjacent lands. Shoreline regulations have been implemented to both protect public trust areas (for example, beach access or wetland protection) and to recognize private property rights with regard to preventing land loss. The balance of these potentially conflicting objectives varies from jurisdiction to jurisdiction. Commonly, regulators limit encroachments below the mean high water line, where state jurisdiction begins in most coastal states, including Washington, although Washington allows for private ownership of some tidelands. It is generally easier for landowners to obtain permits for erosion control structures built directly upland of mean high water.

If a project is to be placed in waters of the United States, then a permit from the U.S. Army Corps of Engineers (USACE) is required. Two federal laws serve as the basis for the federal regulation of shoreline activities: the Rivers and Harbors Act of 1899 and the Federal Water Pollution Control Act (FWPCA; Clean Water Act) of 1972. Through its administration of both statutory programs, USACE plays the central federal role in the regulation of shoreline protection projects.

The U.S. Army Corps of Engineers (2009) issues two types of permits: General Permits (Nationwide and Regional) and Standard Permits (33 C.F.R. sec. 325.5). General Permits, in many cases, do not involve individual review of proposed activities and provide expedited authorizations for certain classes of activities that the USACE has determined are similar in nature and cause only minimal individual and cumulative environmental impacts (33 C.F.R. secs. 322.2(f) & 323.2(h)). For certain activities, General Permits require project proponents to notify the USACE and obtain confirmation that the proposed work is authorized by General Permit (33 CFR sec. 330.6(a)). Adoption of General Permits involves normal rulemaking procedures, such as public notice of the proposed rule and the opportunity for public comment.

Nationwide Permit 27 (NWP 27) for Stream and Wetland Restoration Activities (Federal Register, Vol. 72, No. 47, March 12, 2007, p. 11119) allows activities in waters of the United States associated with enhancement of degraded tidal and non-tidal wetland and riparian areas, as well as the creation of wetlands and riparian areas. In coastal areas, NWP 27 is used primarily for wetland restoration activities, creation of small nesting islands, and construction of oyster habitat. Under some circumstances, NWP 27 could also apply to shoreline protection such as the use of vegetation to stabilize a bank.

Another General Permit, NWP 13 for Bank Stabilization activities, authorizes the construction of structures and fills necessary for erosion prevention (Federal Register, Vol. 72, No. 47, March 12, 2007, p. 11108). Under NWP 13, the permittee must notify the USACE before beginning the work if the structure is longer than 500 linear feet or uses more than 1 cubic yard of fill material per running foot placed along the bank below the plane of Ordinary High Water or the High Tide Line. Thus, smaller bank stabilization activities can be constructed without notifying the USACE. The NWP 13 does not authorize stabilization projects in special aquatic sites.

A Standard Permit is required if the activity does not fall under the conditions of the Nationwide or Regional General Permits. For example, if a property owner wishes to protect an eroding marsh or install a stabilization alternative, such as a sill or breakwater to protect eroding upland, then neither of the nationwide permits mentioned previously could be utilized. The permit applicant would be required to go through the lengthier and more complex individual standard permit process.

The Nationwide General Permits do not have universal application because the States can impose conditions that are more restrictive than those of the USACE. These more restrictive state conditions often center on concerns regarding water quality and consistency with a State's approved coastal zone management plan (16 U.S.C. sec. 1456(c)). Many states have created or incorporated special area management plans and coastal setback zones to protect ecosystems, avoid property loss from erosion, and manage coastal development. In Virginia, for example, the Chesapeake Bay Preservation Act mandates that local governments amend their building codes, subdivision ordinances, and zoning codes to protect wetlands and other coastal habitats.

In general, nationwide permits ease the permitting process and shorten the approval time for activities like installing bulkheads or other vertical shore protection directly adjacent to eroding upland shorelines. As a consequence, property owners who select a shoreline protection alternative that does not encroach into the highly regulated "waters of the United States" can avoid significant transaction costs, lengthy permitting times, and numerous other aggravations.

Table 1. Characteristics of various groups of shoreline protection decision-makers.

Decision-maker	Objectives	Information needs	Information sources	Area of influence
Property owners	* Maximize the use of their property * Aesthetics * Maximize property value	* Effectiveness * Cost * Feasibility	* Handbook and/or online info * Expert / consultant * Government regulator * Neighbors * Flood zone maps	* Individual's property, as well as neighbors' properties
Experts and consultants (includes government scientists and engineers)	* Satisfy the client * Make a profit * Maintain credibility	* Knowledge of shoreline protection options (Structural and non-structural) * Feasibility (that is ease of permitting) * Physics, geomorphology, and ecology	* Professional networks * Experience * Field work * Trade publications * Government agencies * Vendors * Formal Education	* Geographical region in which they work
Government Regulators, Permitting and Compliance Officials	* Implement and enforce the regulations * Resource stewardship	* Knowledge of shoreline protection options (Structural and non-structural) * Physics, geomorphology, and ecology * Legal mandates * Public trust responsibility * Constraints imposed by other regulatory programs	* Reports or the NRC and other expert bodies * Professional networks * Experience * Consultants * Formal education * Legal counsel	* Jurisdiction in which they work
Policymakers and Law-makers	* Re-election * Maintaining the tax base * Resource stewardship * Serving their constituents * Environmental quality * Quality of life * Public health, safety and welfare	* Public trust responsibilities * Current law; its impacts and any unintended consequences * Perception and understanding of the problem to be solved	* Press * Constituents * Staff (trusted experts in the field) * Government agencies * NGOs	* Their jurisdiction, as well as their colleagues' jurisdictions

Note: Large public property owners can have broader geographical influence. SOURCE: NRC (2007).

In some circumstances, this creates an incentive for the permit applicant to avoid federal permit requirements by siting the erosion control project above the mean high water (MHW) line. State and local land-use planning and coastal construction permits may still apply in these cases, but the applicant has simplified the regulatory process by eliminating federal review. This strong incentive to avoid or minimize encroachment into waters of the U.S. has created a bias toward both requesting and allowing certain erosion mitigation options, such as bulkheads and similar vertical structures. Constructing a bulkhead above the MHW line may be quicker and easier than obtaining a permit for a vegetative solution developed in the nearshore waters because it potentially avoids the multiple layers of federal review. In this way, the regulatory framework affects choices and outcomes.

The NRC report concluded that the current regulatory framework for sheltered coasts contains disincentives to the development and implementation of erosion control measures that preserve more of the natural features of shorelines. The report recommended that state and federal agencies (EPA, USACE, and NOAA) convene a working group to evaluate the decision-making process used for issuing permits for erosion control structures to revise the criteria for sheltered coasts, including consideration of potential cumulative impacts. In addition, the regulatory preference for permitting bulkheads and similar structures should be modified to make it easier for landowners to adopt alternative approaches such as living shorelines that conserve more of the ecological features of the natural shoreline.

Conclusion

The NRC study found that reversing the trend in shoreline armoring will require a number of societal and institutional changes including:

- Better understanding of sheltered shoreline processes and ecological services,
- Improved awareness of the choices available for erosion control,
- Documentation of individual and cumulative consequences of erosion control approaches,
- Shoreline management planning that takes into consideration the unique ecological and physical processes of sheltered coasts, and
- A permitting system with incentives that support the goals of the shoreline management plan.

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Developing Alternative Shoreline Armoring Strategies: The Living Shoreline Approach in North Carolina

C.A. Currin[1], W.S. Chappell[2], and A. Deaton[2]

Abstract. This paper reviews the scientific data on the ecosystem services provided by shoreline habitats, the evidence for adverse impacts from bulkheading on those habitats and services, and describes alternative approaches to shoreline stabilization, which minimize adverse impacts to the shoreline ecosystem. Alternative shoreline stabilization structures that incorporate natural habitats, also known as living shorelines, have been popularized by environmental groups and state regulatory agencies in the mid-Atlantic. Recent data on living shoreline projects in North Carolina that include a stone sill demonstrate that the sills increase sedimentation rates, that after 3 years marshes behind the sills have slightly reduced biomass, and that the living shoreline projects exhibit similar rates of fishery utilization as nearby natural fringing marshes. Although the current emphasis on shoreline armoring in Puget Sound is on steeper, higher-energy shorelines, armoring of lower-energy shorelines may become an issue in the future with expansion of residential development and projected rates of sea level rise. The implementation of regulatory policy on estuarine shoreline stabilization in North Carolina and elsewhere is presented. The regulatory and public education issues experienced in North Carolina, which have made changes in estuarine shoreline stabilization policy difficult, may inform efforts to adopt a sustainable shoreline armoring strategy in Puget Sound. A necessary foundation for regulatory change in shoreline armoring policy, and public support for that change, is rigorous scientific assessment of the variety of services that natural shoreline habitats provide both to the ecosystem and to coastal communities, and evidence demonstrating that shoreline armoring can adversely impact the provision of those services.

Introduction

North Carolina has an estimated 9,000 mi of estuarine shoreline, and most of that shoreline has relatively low-relief, with adjacent uplands less than 3 m in elevation (fig. 1). Estuarine erosion rates have been determined primarily for the shoreline north of Cape Lookout, with estimates ranging between -0.25 and -8.8 m y^{-1} (Riggs and Ames, 2003; Cowart, 2009). In response, property owners attempt to stabilize their shoreline using a variety of methods. The most frequently employed practice in North Carolina is to build a bulkhead, a vertical structure that may be constructed of wood, concrete, metal, or vinyl. In addition, shoreline stabilization approaches incorporating natural vegetation (salt marsh) have been developed (Broome and others, 1992), and in 2004 the state issued a General Permit to promote the implementation of shoreline stabilization projects that incorporated rock (riprap) sills in combination with coastal wetlands. This alternative approach, which has also been promoted by environmental groups, is often termed a ‘living shoreline’. To date, however, there has not been an appreciable reduction in the demand for bulkheads by property owners in North Carolina, and only limited changes to the permit process allowing bulkhead installation.

Ecosystem Services Provided by Natural Shoreline Habitats

A variety of habitats comprise the intertidal and shallow subtidal areas of the estuarine shoreline along the relatively low-relief coast of the southeastern United States. These include salt marshes, oyster reefs, tidal flats, seagrasses, and shallow unvegetated bottom. Each of these habitats provides a suite of ecosystem services, including primary production, provision of fish and shellfish habitat and nursery areas, biogeochemical cycling of nutrients, carbon (C) sequestration, sediment trapping, and wave attenuation. In North Carolina and other east coast states, *Spartina alterniflora* is particularly emphasized in living shoreline designs because of its wave attenuation and sediment-trapping functions, which help to stabilize the estuarine shoreline. In the Pacific Northwest, however, *Spartina spp* are invasive and the target of control efforts (Hacker and others, 2001; Civille and others, 2005).

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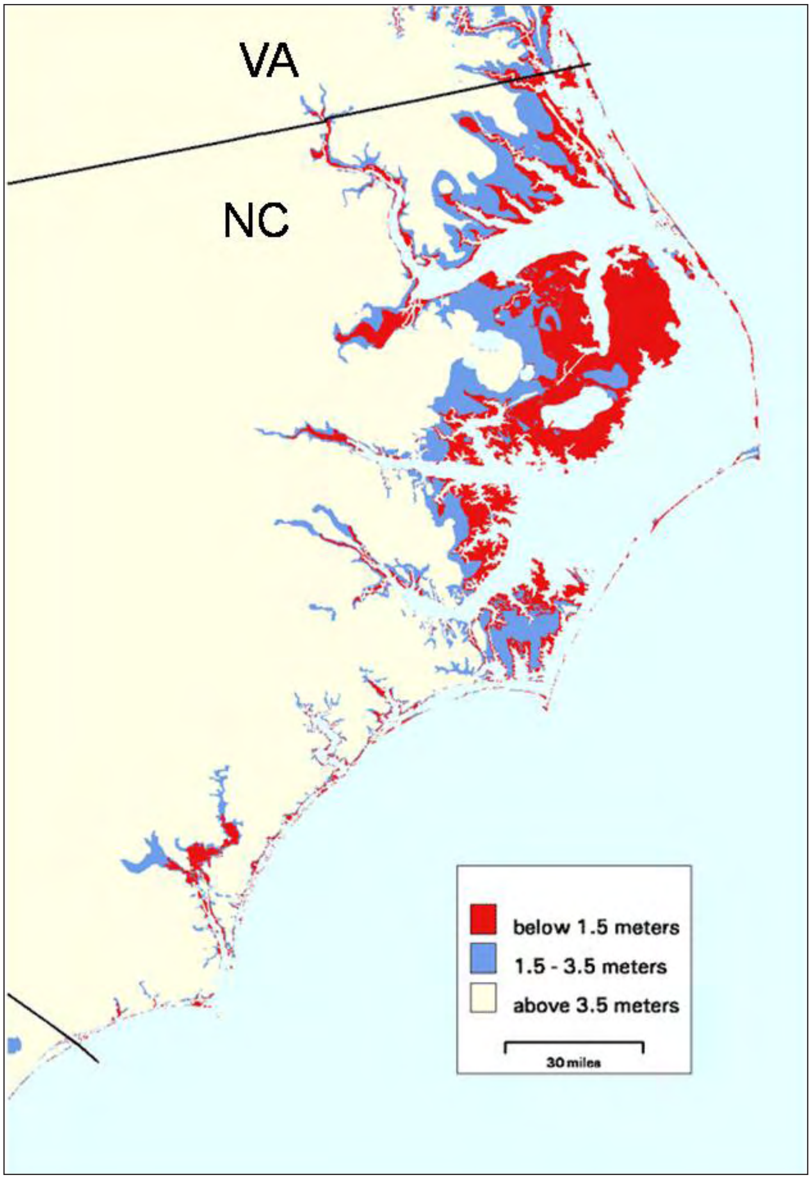

Figure 1. Map of eastern North Carolina showing elevation of coastal lands. Source: U.S. Environmental Protection Agency Climate Change Web site.

In the microtidal setting of North Carolina, salt marshes dominated by *S. alterniflora* can reduce wave height by 90 percent within 20 m of the marsh edge (Knutson and others, 1982). The effectiveness of marsh vegetation in attenuating wave energy is limited by stem height, water depth, and tidal amplitude (Moller, 2006). Along the macro-tidal shorelines of northwest Europe, salt marshes dominated by *S. anglica* are estimated to reduce wave heights by more than 50 percent in the first 20 m of marsh (Moller, 2006). Salt marshes have a well-documented ability to trap sediments, which is related to their ability to baffle currents and wave energy (Leonard and Croft, 2006). For intertidal marshes, the amount of sediment accretion varies with sediment supply, tidal range, marsh elevation, and plant biomass (Morris and others, 2002). Salt marshes may also increase their surface elevation through the production of below-ground biomass, which is incorporated into the sediment (Cahoon and others, 2004).

Salt marshes also exhibit some of the highest primary production rates found in coastal ecosystems (Mitsch and Gosselink, 1993). This plant production, including vascular marsh grasses, epiphytic and benthic algae, is an important component of the food web supporting estuarine secondary production (Currin and others, 1995; Deegan and others, 2000). The high rates of above ground and below ground biomass production by estuarine marsh plants contribute to high estimates of their role in C sequestration, an increasingly valuable ecosystem service in light of projected global climate change (Choi and Wang, 2004). Marshes provide important nursery habitat for many species of estuarine-dependent fish, whose larvae are transported into the estuary and spend their juvenile stages in shallow estuarine waters (Ross, 2003). Juvenile fish, as well as small resident species, find refuge from predators in the dense marsh canopy, and may be found in high numbers (>1,000 per 10 m marsh edge) in salt marsh habitats (Hettler, 1989).

Seagrass beds, tidal flats, and oyster reefs, which are shoreline habitats found throughout Puget Sound, also may be incorporated into living shoreline designs. These habitats provide many of the same ecosystem services as do salt marshes. Seagrasses, which are rooted vascular plants, exhibit relatively high rates of primary production (McRoy and McMillan, 1997), which is augmented by the epiphytes, benthic diatoms and macroalgae that are associated with seagrass beds (Moncreiff and others, 1992; Kaldy and others, 2002). Seagrass bed primary production in turn supports secondary production of fish and invertebrates (Moncreiff and Sullivan, 2001). Seagrass beds also offer refugia to fishery organisms, and the habitat value of seagrass beds is well-documented, as both greater diversity and higher abundance of fishes are found in seagrass beds compared to unvegetated habitats (Heck and others, 2003). Finally, the seagrass canopy can reduce wave energy (Fonseca and Callahan, 1992), and the reduction of current velocity within the canopy results in sediment trapping (Fonseca, 1996).

Shallow-water unvegetated habitats, which lack macrophytes and include tidal flats and sub-tidal bottom, have been described as a ‘secret garden’ because of the productive benthic microalgal community that occurs there (MacIntyre and others, 1996; Miller and others, 1996). The primary production of the microscopic diatoms and cyanobacteria in estuarine sediments has been estimated to provide between 25 and 50 percent of total ecosystem primary production (Pinckney and Zingmark, 1993). Benthic microalgae are more palatable than vascular plants, and are an important component of estuarine foodwebs (Sullivan and Currin, 2000). Apart from food resources, unvegetated shallow water habitat also provides valuable refuge for juvenile fish and crustaceans (Ruiz and others, 1993). Because of these ecosystem services, the loss of shallow-water unvegetated habitats via erosion or deepening should be minimized, and these unvegetated habitats can be incorporated into living shoreline designs.

Oyster reefs, which were historically present in Puget Sound, are another unvegetated habitat that provides primary production, via algae, and even higher rates of secondary production (Grabowski and Peterson, 2007). The structure and food resources associated with oyster reefs in the southeastern U.S. result in higher abundance, biomass, and species richness of finfish species than found on unstructured estuarine habitats (Coen and others, 1999). Oyster reefs also have the ability to trap sediments, build reefs, and stabilize estuarine shorelines (Meyer and others, 1997; Allen and others, 2003). These functions, in addition to the potential of the filter-feeding activity of the oysters to improve water quality and alter nitrogen cycling, have resulted in oyster restoration efforts throughout the southeast and mid-Atlantic (Coen and others, 2007; Grabowski and Peterson, 2007). Currently, scientists in North Carolina are evaluating the utilization of oyster reefs as part of natural shoreline stabilization designs.

Eutrophication, or an excess of nutrients, has altered primary and secondary production rates in estuaries throughout the United States. Excess nitrogen in the water column increases the growth of phytoplankton, which can lead to declines in overall water quality and submerged aquatic vegetation (seagrasses), and increases in hypoxia and harmful algal blooms. Another important function of shallow-water habitats is the removal of dissolved inorganic nutrients, particularly nitrogen (N), from the estuarine water column. Shallow-water habitats occupied by vascular plants and benthic algae remove nitrogen both through direct plant uptake of N, and via denitrification, a microbial process that transforms dissolved inorganic N to dinitrogen gas, which is lost to the atmosphere (Joye and Anderson, 2008). Shoreline stabilization structures that lead to an increase in nearshore water depth effectively reduce the amount of benthic habitat that receives sunlight, which in turn reduces the distribution and productivity of benthic plants that utilize dissolved nitrogen (Fear and others, 2004).

Living shoreline projects typically involve the conservation or restoration of a fairly narrow (<30 m) band of marsh habitat, and the question of whether a narrow band of intertidal habitat provides a full suite of ecosystem services is a topic of concern to resource managers. Studies of marsh nekton usage have demonstrated preferential utilization of the marsh edge (Minello and others, 1994; Peterson and Turner, 1994). In addition, adult blue crabs utilize marsh edge habitat in preference to open-water habitats, perhaps taking advantage of the abundant prey as well as avoiding predation themselves (Micheli and Peterson, 1999). Currin and others (2008) found that fish utilized fringing marshes in North Carolina in similar numbers as have been reported for more extensive marshes. Similarly, the marsh edge provides the highest rates of wave attenuation and sediment trapping (Leonard and Croft, 2006; Morgan and others, 2009). Fringing marshes have also been demonstrated to effectively remove groundwater nitrate inputs (Tobias and others, 2001). Together, these studies suggest that even relatively narrow fringing marshes, such as those incorporated into living shoreline designs, can provide a tremendous return in ecosystem services.

Adverse Impacts of Shoreline Hardening on Ecosystem Services

Bulkheads can have adverse impacts on coastal habitats, including accelerated erosion, loss of shallow intertidal bottom, loss of fringing marshes, and increased scouring and turbidity in nearshore waters (Pilkey and Wright, 1989; Pilkey and others, 1998; Rogers and Skrabal, 2001; Bozek and Burdick, 2005; National Research Council, 2007). During construction, use of heavy equipment and backfilling above the high water line, where bulkhead construction is allowed, may destroy wetlands and transitional vegetation. Rather than allowing native vegetation to recolonize landward of a bulkhead, property owners often replant with landscape shrubs and lawn grasses. These plants are not as effective at reducing and treating stormwater laden with nutrients and toxins as is natural vegetation, and are less apt at deterring erosion (Watts, 1987; National Research Council, 2007). Once bulkhead construction is complete, changes in hydrography and geomorphology often follow, with resultant negative effects on shallow nursery habitats. Scouring at the toe of bulkheads erodes the shoreline, undercuts the living root mass of marsh grasses, and deepens the adjacent water, thereby reducing or eliminating vegetated and unvegetated intertidal and/or shallow subtidal habitat (Riggs, 2001; Bozek and Burdick, 2005). Hardened structures along the North Carolina oceanfront were banned for similar indirect effects and resulting loss of intertidal beach. Garbisch and others (1973) showed that marsh vegetation seaward of bulkheads suffered 63 percent mortality post-construction due to stress from increased turbulence and scour. The change in hydrography and deepened water at the base of bulkheads prevent wetland vegetation from reestablishing itself once it is lost (Knutson, 1977; Berman and others, 2007). As sea level rises, bulkheads also obstruct shoreward migration of fringing wetlands, resulting in the eventual drowning and loss of wetland vegetation, particularly in the upper transition zone (Titus, 1998; Bozek and Burdick, 2005; National Research Council, 2007). Construction of bulkheads also reduces shallow water habitat by preventing transport of sediment to adjacent shorelines, diminishing the extent of nearby intertidal and shallow subtidal zones (Riggs, 2001; National Research Council, 2007).

Deepening of waters adjacent to the bulkhead structure allows large piscivorous fish access to previously shallow nursery areas, enhancing their feeding efficiency on small and/or juvenile fishes looking for shallow water (Rozas, 1987). Bulkheads also degrade spawning and nursery habitat for many species, including river herring and striped bass, which utilize the vegetated marsh edge (O'Rear, 1983). Vertical structures effectively remove narrow marsh fringes, thereby making areas adjacent to bulkheads less suitable as nurseries, even where seagrass beds or oysters are present offshore.

Numerous studies have documented lower relative abundance and diversity of fishes and invertebrates adjacent to bulkheaded shorelines compared to that in unaltered marsh, beach, or forested wetland habitats. In the James River, Virginia, fish community integrity was reduced along bulkheaded shorelines with both low and high density upland development as compared to natural and riprap shorelines with low density upland development. Species diversity was also lower along bulkheaded shorelines, with many tidal marsh species absent from this habitat (Bilkovic and Roggero, 2008). In the Pascagoula River estuary, Mississippi, Partyka and Peterson (2008) found that epifaunal-nekton and infaunal species richness and density were always greater at natural shore types than at hardened ones. Bilkovic and others (2006) showed that in the Chesapeake Bay, two indices of macrobenthic biological integrity were reduced significantly when the amount of developed shoreline exceeded 10 percent. In the lower Chesapeake Bay, bivalve abundance and diversity were higher in subtidal habitats adjacent to natural marsh than those in habitats adjacent to bulkheaded shorelines. Fish and blue crab density and diversity also tended to be higher adjacent to natural marsh shorelines than in bulkhead habitats (Seitz and others, 2006). On the Gulf coast, the most abundant fauna along unaltered marsh and beach shorelines, including penaeid shrimp, blue crab and bay anchovy, were least abundant along bulkhead or rubble shorelines. In addition, diversity was lowest adjacent to bulkheads (Peterson and others, 2000).

Although the effect of a single bulkhead on the adjacent habitat complex may be comparatively small, the cumulative impact of multiple bulkheads can result in significant habitat degradation with associated ecosystem effects (National Research Council, 2007). McDougal and others (1987) found that nearshore wave impact increases in relation to the horizontal length of the bulkhead structure. This higher wave energy renders the waterward and surrounding areas unsuitable for wetland vegetation. Therefore, multiple, contiguous bulkheads have a greater impact on the adjacent natural shoreline than that of spatially distinct structures. The cumulative impact of shoreline hardening on a broader ecosystem level is a subject that requires further study.

The ‘Living Shoreline’ Alternative to Shoreline Stabilization

In an effort to minimize the adverse impacts of hardened shorelines, alternative approaches to estuarine shoreline stabilization have been developed (Broome and others, 1992; Rogers and Skrabal, 2001; National Research Council, 2007). The term ‘living shoreline’ has been popularized by a number of environmental groups and regulatory agencies along the mid-Atlantic coastline to describe these alternatives (Burke and others 2005; Duhring and others, 2006). The living shoreline approach is an effort to incorporate natural habitats into a shoreline stabilization design, maintain the connectivity between aquatic, intertidal and terrestrial habitats, and minimize the adverse impacts of shoreline stabilization on the estuarine ecosystem. These efforts range from maintaining or transplanting natural shoreline vegetation, particularly *Spartina alterniflora*, without additional structural components, to incorporating shoreline vegetation with hardened features, such as rock sills or wooden breakwaters, in settings with higher wave energy (fig. 2). The combination of hardened structures and natural vegetation is also termed a ‘hybrid’ approach to shoreline stabilization. Several states, including North Carolina, Maryland, and Delaware, have implemented a regulatory process designed to encourage, or even require, the use of a living shoreline approach instead of a bulkhead (table 1).

Site specific conditions of wave energy, tidal currents and amplitude, elevation and underlying geomorphology dictate the specific design of a living shoreline installation. The nature of the shoreline adjacent to the project is an additional consideration. A generic design that meets the specifications of the North Carolina General Permit (GP) is illustrated in figure 3. The regulatory guidance offered by states usually includes information on the physical setting in which various living shoreline designs are appropriate, with fetch, proximity to navigation channels, and total channel width the primary considerations (table 1; Durhing and others, 2006). Fetch and navigation channel proximity are proxies for the wind wave and boat wake energy, respectively, which may be experienced at a living shoreline site. Because winds are not evenly distributed around the compass, fetch may not be an accurate representation of the relative wind energy experienced at a site. Calculation of relative wave energy (RWE), utilizing wind direction and intensity, in addition to fetch and bathymetry (Malhotra and Fonseca, 2007) provides a more accurate measure of site-specific wave energy. This may aid efforts to determine appropriate living shoreline design, in particular whether natural vegetation will provide adequate erosion protection, or the appropriate heights for structural components.

In North Carolina, there are no significant regulatory concerns in regard to a living shoreline project that includes only the preservation or transplanting of vegetation, and this is recommended as the most desirable approach to estuarine shoreline stabilization by all the states listed in table 1. However, property owners and contractors often prefer a hardened structure to further attenuate wave energy, and there are several regulatory concerns about the inclusion of rock sills into living shoreline projects. These concerns include the replacement of shallow-water habitat with rock and consequently an alteration in ecosystem services of the site, filling of intertidal lands with potential for loss of public trust resources (particularly in states where MHW represents the private/state boundary), loss of connectivity between aquatic and intertidal and terrestrial habitats, introduction of a foreign substrate that may harbor invasive species, increased erosion to adjacent property owners, scouring at the base of the sill, and possible hazards to navigation. Therefore, there are restrictions on the amount of fill, the height and water-ward placement of the sill, and requirements for providing sill openings (drop-downs) to promote access by nekton.

A reduction in the adverse ecosystem impacts of estuarine shoreline stabilization structures is consistent with North Carolina’s Coastal Habitat Protection Plan (Street and others, 2005), and the N.C. Coastal Resources Commission and the Division of Coastal Management (DCM) have worked to develop policy, regulatory changes and educational tools to accomplish that goal. To develop shoreline stabilization rules that take into account the dynamic nature of the estuarine system and consider the benefits and impacts of various shoreline stabilization methods on biological communities and physical processes, DCM formed a science-based panel, the Estuarine Biological and Physical Processes Work Group, in 2002 (North Carolina Division of Coastal Management, 2006). The Work Group evaluated erosion control methods, including land planning, vegetation control, beach fill, sills, groins, breakwaters, sloped structures (that is riprap revetments or cast concrete), and seawalls/bulkheads, to determine which would be appropriate for various shorelines, considering the ecological functions and values of each North Carolina shoreline type. Among its recommendations, the Work Group determined that bulkheads should be the last resort to stabilize estuarine shorelines where marsh, seagrasses and oyster reefs are present. In 2005, a GP for marsh sills was implemented in an effort to simplify the application process for a property owner. In addition, an environmental group, the North Carolina Coastal Federation, has obtained grants to construct several living shoreline projects and worked to promote this approach (North Carolina Coastal Federation, 2009).

Figure 2. Photographs of shoreline stabilization projects in North Carolina that illustrate the living shoreline approach (*A*) Project to replace failing seawall includes fill, marsh transplanting, and rock sill; 2 years post-construction. (*B*) Project to protect marsh edge, which included rock sill, no fill, and minimal transplants; 4 years post-construction. A drop-down in the sill provides marsh access to nekton. Oysters can be seen colonizing the lower rock surfaces. (*C*) Project to protect eroding sandy beach includes only natural habitats, achieved with salt marsh transplants and oyster reef restoration; 4 years post-installation.

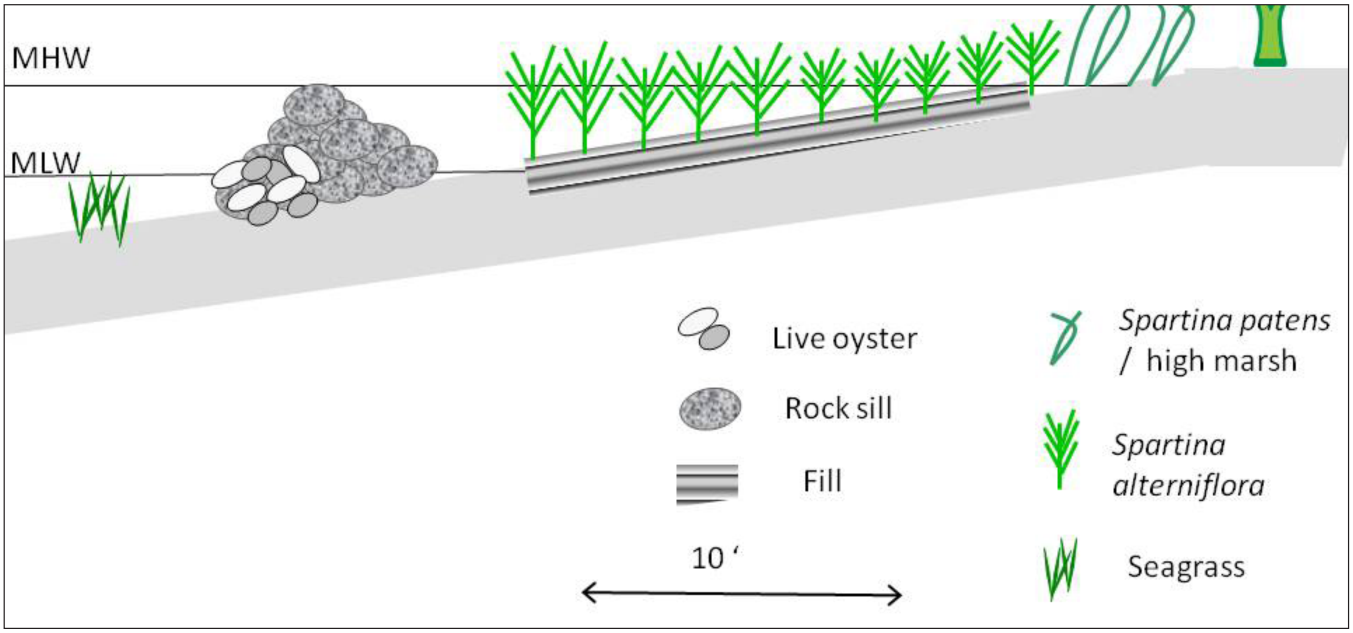

Figure 3. Schematic of a generic living shoreline design appropriate to permit requirements in North Carolina (MHW, mean high water; MLW, mean low water).

Table 1. Description and availability of regulatory and guidance documents available from state agencies in regard to living shorelines.

[Boundary locations include mean high water (MHW) and mean lower low water (MLLW). Information provided for North Carolina (NC), Virginia (VA), Maryland (MD) and Delaware (DE)]

State	Regulatory permit / guidance document title	Private / state boundary	Link to guidance material
NC	General Permit for the construction of riprap sills for wetland enhancement in estuarine and public waters	MHW	http://dcm2.enr.state.nc.us/rules/Text/t15a-07h.2700.pdf
VA	Local wetlands boards make determination; no state permit	MLLW	http://ccrm.vims.edu/livingshorelines/index.html
MD	Living Shoreline Protection Act	MHW	http://mlis.state.md.us/2008rs/chapters_noln/Ch_304_hb0973E.pdf
DE	Regulations governing the use of sub-aqueous lands	MLLW	http://regulations.delaware.gov/AdminCode/title7/7000/7500/7504 shtml#TopOfPage

Despite these actions, since 2000, only 19 living shoreline projects have been constructed with a Major Permit and 9 projects have been completed under the 2005 GP, for a total of approximately 1.5 mi of shoreline (North Carolina Division of Coastal Management, 2009). During this same period, an estimated 167 mi of bulkheads were permitted (North Carolina Division of Coastal Management, 2009). One of the difficulties in encouraging property owners in North Carolina to employ a living shoreline approach rather than constructing a bulkhead, is that the current bulkhead General Permit (table 1) has few site-specific considerations, does not require review by other agencies, and can usually be obtained within 2 days, whereas a marsh sill permit has numerous site-specific conditions and requires an outside review by state agencies, a process that often takes more than 30 days to complete. To further encourage the utilization of the living shoreline approach in N.C., in July 2009 the N.C. Soil and Water Conservation Community Assistance Program approved marsh sills as a Best Management Practice for reducing stormwater impacts, a designation that allows partial reimbursement for construction costs. However, it is likely that there will not be significant change in the utilization of living shoreline approaches by N.C. property owners until the permits for bulkheads and living shoreline projects have similar costs, review requirements and time constraints. In Maryland and Delaware, states that have had considerable success in reducing the number of bulkheads installed on estuarine shorelines, the permit process for installing a bulkhead along low-energy shorelines is at least as time-consuming and costly as is the permit process for installation of a living shoreline (table 1).

Evaluation of Living Shoreline Projects

At present (2010), there are few peer-reviewed, quantitative evaluations of living shoreline projects, although several researchers and state agencies are currently designing or have recently implemented evaluation projects (Berman and others, 2007). Several aspects of three living shoreline projects in North Carolina, including marsh vegetation cover, sediment characteristics, sediment elevation change, and nekton utilization, were compared to values from adjacent natural reference marshes (Currin and others, 2008). In that study, there was no significant difference in the nekton utilization of natural fringing marshes and marshes behind stone sills. The sills examined in that study either had drop-downs every 20 m, and/or were open at the ends. Sediments in both marsh types were sandy, with low organic matter content. Marsh stem density and percent cover was higher at two of the natural reference sites than at adjacent living shoreline sites. Sediment accretion rates in the marshes behind the stone sills were approximately 1.5 to 2-fold greater than those recorded in the adjacent natural marshes, and Currin and others (2008) noted that this elevation increase could result in the conversion of low marsh to high marsh, and reduce the fishery habitat value of the marsh. The observed accumulation of sediment behind the sill is similar to that reported in the evaluation by Airoldi and others (2005) of offshore breakwaters in a high energy setting off the coast of England. Subsequent to that study, Currin and colleagues continued their evaluation of sediment accretion rates and surface elevation changes in marshes associated with stone sills (hereafter sill marshes) using the Surface Elevation Table (SET) methodology (Cahoon and others, 2004). SETS were established at the lower and upper extent of *Spartina alterniflora* in four paired sill marshes and adjacent natural fringing marshes. Measures of marsh surface elevation were made every fall and spring between March 2005 and March 2008. As demonstrated in table 2, sediment elevation increased significantly more in sill marshes than in natural fringing marshes. This study also demonstrated that natural fringing marshes were losing elevation at the lower edge, while the upper edge was closer to maintaining elevation relative to the local sea level rise. The rate of sediment elevation increase in the sill marshes was nearly twice the rate of relative sea level rise, and the lower marsh vegetation moved seaward into the rock sill (fig. 2*B*), while the upper marsh in some cases became high enough to exhibit a vegetation change (table 2, Currin, unpub. data).

An evaluation of 36 living shoreline projects in Virginia, based on field evaluation and observation, was presented in Duhring and others (2006). Most of the projects were judged to provide effective erosion control, and about half (55 percent) were also judged to be effective as living shoreline treatments, based on marsh condition. Unlike the North Carolina results based on SET measures, authors of the Virginia report concluded that little sediment had accreted behind the sill and noted that an unvegetated border persisted between the rock sill and marsh at several sites (Duhring and others, 2006).

A review of the permits approved for marsh sill, or living shoreline, projects in North Carolina since 2000 was

Table 2. Results from Surface Elevation Tables placed at the lower and upper edges of *Spartina alterniflora* in marshes behind stone sills (Sill) and nearby natural fringing marshes (Natural).

[Elevation data were collected approximately every 6 months between October 2005 and March 2008. Letters indicate statistically significant effect of marsh type on accretion rates ($p<0.001$) by location within the marsh (Lower, Upper), n equals number of marshes sampled, with one SET per location per marsh]

Marsh type	Marsh edge location	Net sediment accretion (mm y^{-1})	n
Natural	Lower	-6.92 A	4
Sill	Lower	5.36 B	4
Natural	Upper	1.18 A	4
Sill	Upper	4.73 B	4

completed by NC Division of Coastal Management (DCM) staff in July 2009 (North Carolina Division of Coastal Management, 2009). As noted previously, 19 projects were established with a Major Permit and 9 projects were established under the new General Permit. The Major Permit projects were an average length of 370 ft, while the General Permit projects averaged 114 ft, and the average height of all projects was 0.5 ft above MHW. Overall, the amount of shallow bottom converted to marsh habitat was approximately equal to the amount of shallow bottom covered by rock sill. The state will be conducting an on-site evaluation of marsh sill projects in summer 2010 to further evaluate their effectiveness and impacts on adjacent habitats and property.

These limited studies of alternative estuarine shoreline stabilization projects support the need for careful permit review policies, as well as the need for site-specific design recommendations. Variables such as sediment supply, wave exposure (wind waves and boat wakes), and sediment type must be accounted for to insure that a living shoreline project creates or preserves sustainable natural habitat. Resource managers will need to weigh the costs and benefits of the habitat trade-offs inherent in converting one habitat and bottom type to another. A problem noted in both North Carolina and Virginia is the use of shoreline stabilization measures in situations where no shoreline erosion is occurring (Duhring and others, 2006; Currin, personal observation, 2009). To many homeowners, a straight bulkhead edge is aesthetically more pleasing than the curves and variability of a natural shoreline. Public education on the economic and ecological benefits of natural shoreline habitats, and on the adverse impacts of bulkheads and other shoreline armoring structures, is the key to successfully implementing a sustainable shoreline stabilization policy.

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Human Dimensions of Nearshore Restoration and Shoreline Armoring, with Application to Puget Sound

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Abstract. Human relationships with the environment are exceedingly complex. Human dimensions research, with origins both within the academic community and among resource management agencies, is aimed at shedding light on those relationships. Because ecosystem restoration is an activity underlain by human values, findings from human dimensions research should be important underpinnings to its conduct. The role of the environment in quality-of-life is one important touchstone in human dimensions research. Human dimensions studies directly applicable to coastal and estuarine environmental programs in the Puget Sound region have been relatively few, especially with regard to human relationships with the specific environmental attributes that can be altered by nearshore ecosystem restoration. Seawalls and other engineered features of occupied shorelines embody the many contradictory aspects of human relationships with nature. Because they protect property from erosion or wave attack, seawalls are generally regarded as making positive contributions to human well being. However, they may also diminish sediment delivery to the nearshore, negatively affecting its associated bundle of ecosystem goods and services. Improved scientific understanding reveals numerous tradeoffs across ecosystem functions, goods, and services associated with the extensive armoring that now exists along Puget Sound's shores, but understanding of how people in the region value these tradeoffs remains incomplete. Dialogue with public stakeholders can enlarge understanding of the roles that removal of shoreline armoring can play in a restored Puget Sound ecosystem in which humans are viewed as integral elements. However, stakeholder engagement is not a substitute for the kind of understanding that emerges from directed and sustained research. Integrated human-dimensions and natural scientific research is an attractive but as yet little utilized avenue for enlarging scientific understanding relevant to nearshore ecosystem restoration.

The 'What' and 'Why' of Human Dimensions Research Applied to Nearshore Restoration

Ecosystem restoration is an activity, which, although dependent on numerous scientific disciplines in its planning and execution, is rooted in human values and preferences. This idea is captured well by environmental philosopher Eric Higgs, who argues that, "To restore something means to consider *what that thing is and what it means*" (Higgs, 2003, p. 41, emphasis in original). As in other areas of human endeavor, meanings can be multiple, disputed, exist on multiple levels, or change over time. For example, a long dominant idea in the thinking of restoration scientists is that to restore an environmental system is to in some sense put it back the way it once was, motivated by the desire to recover lost (and valued) aspects that the system formerly possessed. Bradshaw (2002) characterizes ecosystem restoration as the return of environmental systems to their former ecological condition or to former levels of ecological functioning. In that sense, some, including Higgs (2003), have likened environmental restoration to restoring works of art. From another perspective, ecosystem restoration is an opportunity to test ecological theories (Young and others, 2005), while another emerging strain of thinking regarding the purpose of ecosystem restoration is that rather than looking backwards to past conditions, restoration should aim to build resilience into ecosystems so that they will be sustainable under conditions they have never before experienced, namely those created by climate change (Harris and others, 2006).

As defined by the Society for Ecological Restoration (SER), restoration is "the process of assisting the recovery of an ecosystem that has been degraded, damaged, or destroyed" (Society for Ecological Restoration, 2004). Restoration may seek to recover directly structural aspects of ecosystems or be process-based, in which case impaired ecological processes are the restoration targets (Palmer and Filoso, 2009). The broader goal may be to recover lost or impaired ecosystem services (National Research Council, 2004; Tallis, and Polasky, 2009), making the removal of process impairment a means to that end. In consonance with these ideas, the Puget Sound Nearshore Ecosystem Partnership (PSNERP) emphasizes process-based restoration and sees reduction in human-caused impairment to these processes as the means to restore lost ecological functions, goods and services. In the end, recovered or maintained ecosystem services are important restoration targets because of their roles in human well-being (ICSU-UNESCO-UNU, 2008). To restore the environment is to desire that it be in a state different from its current condition, which is fundamentally an expression of values.

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Elaborations on the meaning and content of ecological restoration often couch discussion in terms like *ecosystem health*, *ecological integrity*, or *environmental sustainability*. Society for Ecological Restoration (2004) notes, "The terms ecosystem integrity and ecosystem health are commonly used to describe the desired state of a restored ecosystem." Considerable scientific input is required to give such concepts the concreteness required for their effective use in restoration planning. Nevertheless, to manage ecological systems for health or integrity is to make values-based judgments (Lackey, 2001). Not surprisingly, expert constructions of ecosystem health or integrity often differ substantially from those of laypersons. How laypersons go about constructing their environmental valuations is poorly understood (Cox and others, 2006; Stinchfield and others, 2008), and thus a central question for human dimensions (HD) research (Endter-Wada and others, 1998). Analytical challenges abound. Values may prove malleable and not easily "measured" in the sense that natural scientists employ the term. They may be influenced by the ways they are measured and also by participation in decision making, which ideally leads to social learning (Sabatier and Jenkins-Smith, 1993). In this sense, public participation and outreach represent opportunities for regional environmental management programs like that of PSNERP.

Divergence of views of the lay public from those of experts seems especially likely if laypersons see their personal interests at stake in the restoration actions being considered (Buckley and Haddad, 2006). Under such circumstances, scientific analysis may fail to influence public sentiments (Sabatier and Jenkins-Smith, 1993; Carr, 1995; Endter-Wada and others, 1998). People may generally be in favor of ecological restoration, but see it specifically as (a) an overriding ecological imperative; (b) generally desirable, but conditional upon non-ecological considerations; or (c) in some other still different way (Woolley and McGinnis, 2000).

These considerations can lead to the view that human dimensions research should focus primarily on political issues, such as how to educate the public so that people become more understanding and accepting of the goals experts set for ecosystems (Endter-Wada and others, 1998). While such concerns may be legitimate aspirations for HD research, they are far from the full agenda. At its core, human dimensions research is the attempt to understand human—environment interactions—as Endter-Wada and colleagues put it (1998, p. 892), to generate "substantive social data about humans in ecosystems." Both public involvement and education efforts and social analysis contribute to the social learning that is necessary for ecosystem-based management. A key underlying premise of the fully formed HD research agenda is that humans are integral parts of ecosystems and not entities standing outside them and causing "impacts" (fig. 1).

The origins of "human dimensions" studies or perspectives can be traced both to the academic community—particularly to researchers in the social and natural sciences concerned with the increasing pace and scale of anthropogenically driven global environmental change (National Research Council, 1992)—and to federal resource agencies like the U.S. Forest Service (Carr, 1995) and NOAA. The motivation for the federal agencies was the recognition that people and communities needed to be explicitly included

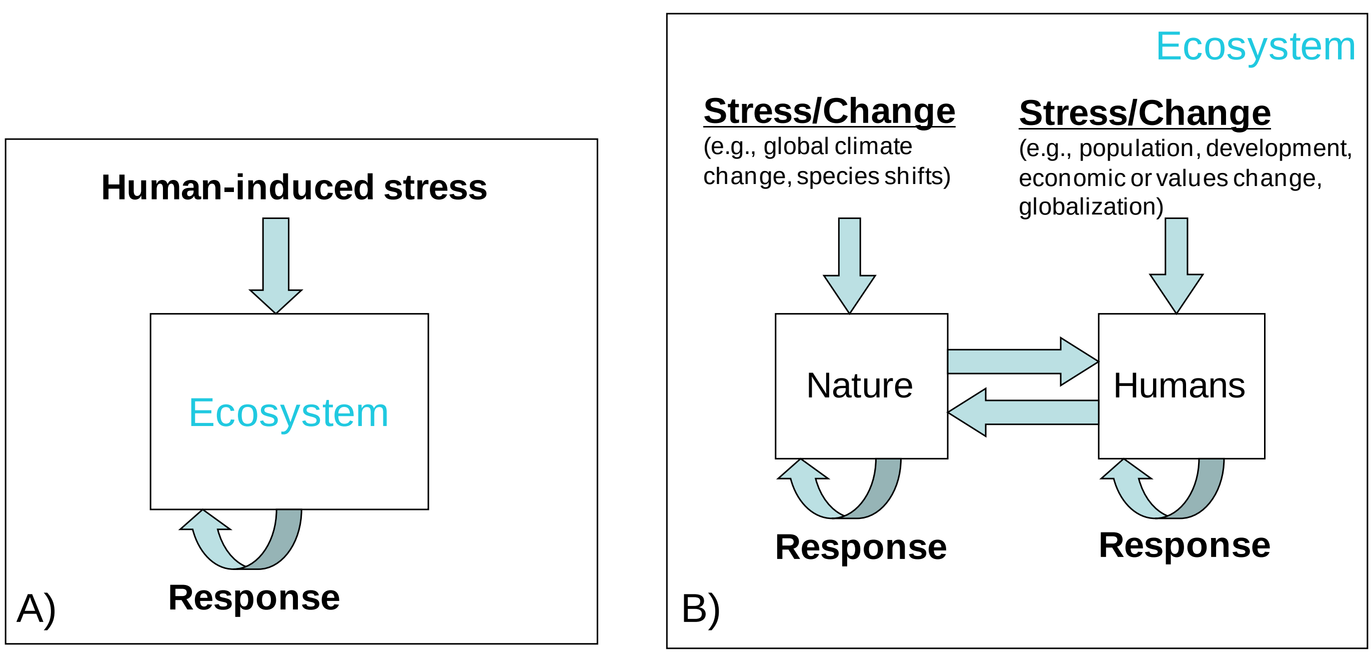

Figure 1. Two views of ecosystems.

in resource management decisions that affected them. An underlying driver is the desire that those decisions result in improved environmental outcomes, an elusive goal when agencies and affected interests are at loggerheads (Carr, 1995). As elaborated by NOAA's National Centers for Coastal Ocean Science (NCCOS), the goals of HD research are to better understand human – environment interactions, and to put that understanding to work in support of decisions affecting environmental processes and related societal outcomes. The belief is that by so doing, the use of science in decision making can be improved (http://ww.nccos.noaa.gov/human/welcome.html).

Puget Sound Nearshore Restoration in 'Human Dimensions' Terms

That the human dimensions perspective is essential to gauging the likely effects of the program of nearshore ecosystem restoration envisioned by PSNERP—particularly the removal or modification of existing shoreline armoring—becomes evident when one considers the nature of the envisioned program of restoration in light of current human uses of the Puget Sound shoreline. Much of the Puget Sound shoreline, particularly in the central reaches of the sound, is in private ownership (Lombard, 2006) and much of the shoreline in private hands is armored. Often this armoring is to protect private homes along the shore or local road access. Where lands are publicly owned, such as state and local parks, the perceived needs that motivated armoring are often similar, protection of infrastructure and access.

Another major and heavily armored feature of the Puget Sound shore is the Burlington Northern–Santa Fe (BNSF) railroad corridor that runs along the sound's eastern shore between Seattle and Everett. The rail corridor presents a major restoration opportunity given the inevitability of transportation upgrades in the next few decades. But this will involve those with interests in the rail corridor's future including the region's major seaports (Seattle, Tacoma, and Vancouver, B.C.), the regional mass transit agency (Sound Transit), and BNSF itself, one of the U.S.'s "Big Four" railroads.

Common local natural features that may or may not still be present in the nearshore system compared to their pre-European settlement distribution are barrier beaches, coastal lagoons and other embayments (that were typically protected by barrier beaches and sometimes backed by bluffs of loosely consolidated post-glacial sediments) (Shipman, 2008). Over time, development in the nearshore has "simplified" the shoreline, leaving it less heterogeneous as to shore type compared to how it was in the middle and late 1800s. One important premise of the proposed PSNERP ecosystem restoration program is that the systematic armoring of so-called "feeder bluffs" has reduced and reconfigured the supply of sediments to shorelines, inducing in turn losses in numerous ecosystem functions, goods, and services. There is evidence that people like the idea of restoring nearshore features that have been lost over time to development and also value the ecosystem services that have been lost (Lipsky, 2010). But there is also countervailing evidence that people along the shore value what they have now and are resistant to local change, a classic NIMBY (not in my backyard) response not inconsistent with the first view (Safford and others, 2009).

Likewise, a formerly extensive system of deltas and estuaries and associated saltwater wetlands has been dramatically reduced in acreage via filling and levee construction. In major river systems, a primary rationale was the development of ports and harbors and the coastal cities that supported them. In other cases, these modifications were done for agriculture or to facilitate the logging industry, purposes that may or may not remain economic in their original locations today.

The human legacies of these many transformations of Puget Sound's shores are many. Considerable enjoyments are associated with waterside living and recreating, while private ownership of shorelines (commonly extending in Washington State to mean low water) has also meant relatively restricted and regulated access. Agricultural lands, even if no longer productive, may still provide "free" open space to surrounding populations. Abandoned or lightly used reclaimed agricultural lands, often with dikes and drainage that is still maintained, may provide hunting, fishing, and wildlife viewing opportunities.

On the other hand, fish spawning and rearing habitat has shrunk, notably for salmon, fewer beaches provide clamming opportunities, and the habitat and food support for a variety of nearshore-dependent wildlife is not what it once was. Chinook salmon and Killer Whales have iconic value in the region, and both are now listed as "threatened" under the Endangered Species Act. Populations of other species that are highly dependent on the nearshore, including some shorebirds and seabirds that utilize the nearshore for feeding or nesting habitat, are in decline.

From a human dimensions perspective, ecosystem restoration is replete with tradeoffs that do not have simple bivariate value states associated with them. Different interests in society will view prospective environmental change in different ways and the same people may value change that occurs nearby and similar changes in more distant locations differently (Buckley and Haddad, 2006). Shoreline armoring in particular, because of its propensity to promote one set of human values at the expense of others, and in some cases to benefit some groups to the possible detriment of others, embodies these contradictions. In short, how people value the changes in landscape and amenities that come with restoration requires human dimensions research, the collection of "substantive social data", as Endeter-Wada and others (1998) put it.

Quality-of-Life Impacts and "Wicked" Environmental Problems

Human values are exceedingly complex and intimately bound up with notions of quality of life, also referred to as human well being (Schneidler and Plummer, 2009). In support of an effort to undertake the monitoring of quality-of-life worldwide, the World Health Organization (WHO) has given the term explicit definition (1999; quoted in Cox and others, 2006):

> "An individual's perception of their position in life in the context of the culture and value systems in which they live and in relation to their goals expectations, standards and concerns. It is a broad concept affected in a complex way by a person's health, psychological state, personal beliefs, social relationships *and their relationship to salient features of their environment*" [emphasis added].

Environment, while important, is not the sole determinant of quality-of-life. Determining with more precision the role that perceived environmental condition plays in the quality-of life-judgments people make has proved elusive. It has not been well studied by HD researchers from the perspective of how interactions with specific types of environmental features influence quality of life (Cox and others, 2006).

Much of the work done to date with reference to shoreline armoring has been motivated by a desire to identify socio-economic benefits and costs associated with the *protection* such features afford from flooding and other storm-related damage. The approach is typically cost-benefit analysis (for example, Bouma and others, 2009). Recreation of all types has been extensively studied, with some of that work directed at beach recreation. Work that takes into account qualitative aspects of beach character or other more readily quantifiable characteristics of beaches has often been done by resource economists whose aim is "non-market valuation," given locational factors or the presence or absence of amenities (see for example, Bell and others, 1990; Parsons and others, 1999). With appropriately chosen research sites, "hedonic price modeling" (Bartik, 1988) could be used to explore the interaction between the amenity value of living on or near a "wild" shoreline on the one hand and the value of averted risks associated with the presence of shoreline armoring on the other. Such a study could provide insights into how the dual presence of amenities and risks (or avoided risks) is reflected in average housing prices.

As the WHO definition of quality-of-life makes clear, however, what people value about a place (sometimes referred to as their *sense of place*) may be bound up in deeply held personal feelings and beliefs or in social relationships, with the physical place itself serving more as context. Thus people may have great attraction to highly modified shorelines of little ecological value or aesthetic appeal to most (for example, beach goers who recreate in highly modified and crowded beachscapes). Or they may have strong affinities for sites of high ecological value, but for reasons that have little or nothing to do with that value ("I come here because it's a place where I can think.")

For such reasons, perhaps, people may react strongly if they feel that what really matters to them is threatened. Under such circumstances, environmental problems can begin to take on a character that has been called "wicked" by social scientists, whereby they cease to have right or wrong answers, but rather solutions that are more or less useful from holistic, often political, perspectives (Carr, 1995). Science, being reductionist in nature, becomes less useful as an arena for resolving complexity and uncertainty in such circumstances, as competing understandings are brought by different research groups into the decision-making arena (Sarewitz, 2004). This can pose problems for both the social and the natural sciences (consider the controversy in which climate science is presently embroiled). The fear of getting trapped in "wickedness" may serve to turn government agencies away from social analysis in particular and instead toward reliance on "selling" programs through stakeholder involvement and public education strategies. Reliance on feedback from polling and other approaches to gauge the public mood then takes the place of real social understanding.

Applying Human Dimensions Considerations in Nearshore Restoration and Shoreline Armoring Removal: Some Practical Considerations

Human Dimensions Thinking Applied to Indicators of Human Well Being

The Washington State Legislature, in creating the Puget Sound Partnership (PSP) for the purpose of restoring Puget Sound by the year 2020, directed that the Puget Sound recovery program be guided by a quality-of-life goal (in addition to other goals for a healthy Puget Sound). In the PSP's 2008 *Action Agenda*, that goal is stated as "A quality of human life that is sustained by a functioning Puget Sound ecosystem" (Puget Sound Partnership, 2008). As with its other goal statements, the PSP describes several "desired outcomes" that point in turn toward potential indicators to help assess progress toward the goal (Puget Sound Partnership, 2008, table 1-1). They include aesthetic values and recreational opportunities, tribal treaty rights and values, ecosystem support for natural resource and marine industry uses, and economic prosperity that is compatible with the protection and restoration of Puget Sound.

Schneidler and Plummer (2009) supported the above PSP goal through development of a conceptual approach for choosing indicators of human well being. Although similar to the so-called “DPSIR” framework (drivers-pressure-state-impact-response; see Cairns and others, 1993), Schneidler and Plummer departed from DPSIR by incorporating feedback flows into the underlying conceptual model. The intent is to incorporate institutional responses to the environmental externalities that are otherwise the end target of the typical DPSIR approach. In effect, these researchers argued that, when humans are agents of actions with both deleterious effects and benefits, it is the net of the benefits and losses associated with the actions themselves, and the net outcomes of efforts to deal with them, which ultimately define the level of human well being (HWB).

With this approach, short-term and long-term HWB impacts may be different; initially HWB benefits from activities affecting the environment may be quite high, but unsustainable if they come at the cost of declining environmental health (for example, overfishing). Policy interventions may initially reduce HWB as it pertains to unsustainable activity, but at the benefit of initiating ecosystem recovery, ultimately to the benefit of HWB as well. In effect, thinking about “impacts” has shifted away from a unidirectional model by which impacts are delivered mostly from humans to ecosystems (as in fig. 1*A*), and instead to a coupled-systems perspective that more easily highlights both near- and longer-term impacts on HWB (fig. 1*B*). Stress or change affecting either humans or the environment has repercussions for both systems, because of the ways in which they are linked. The “stress” of sea-level rise may precipitate shoreline property owners to reinforce existing shoreline armoring, while also inducing policy makers to impose setbacks on new construction that result in greater protection for nearshore processes (and increased restoration opportunities) at broader spatial and longer temporal scales.

Accounting for feedbacks and dynamic responses in both human and natural systems over relevant spatial and temporal scales adds complexity but also realism. Understanding of the characteristics that “good” indicators should possess is enlarged, thereby enriching discussion regarding how to think about human values in relation to environmental change (Bowen and Riley, 2003). As these authors point out, each of the individual elements of the DPSIR framework can be populated with socio-economic attributes and indicators as well as indicators amenable to natural scientific measurement, thereby creating broad latitude for consideration of social, cultural and economic dimensions—along with traditional environmental impacts—in environmental decisions.

Ecosystem Services as Vehicles for Integration Across Natural and Social Sciences

Ecosystem services are essentially benefits to humans from nature (Daily, 1997; Leschine and Peterson, 2007). The desire to make the protection and restoration of ecosystem services central to environmental decision-making is currently very high (Daily and others, 2009). But the ability to do so has been considerably constrained by a lack of scientific understanding (Ellison, 2009). The limitations extend to both the natural and social sciences. From the natural science side, the problem is to understand better the “production functions” by which ecosystems generate services (National Research Council, 2004; Palmer and Filoso, 2009; Ruckelshaus and Guerry, 2009; Tallis and Polasky, 2009). Process-based restoration, PSNERP’s primary focus, has the greatest chance of producing positive gains for ecosystems, in the view of Palmer and Filoso (2009). However, the lack of scientific understanding hampers prediction of environmental outcomes and their associated benefits. From the social science side, the limitations are primarily a need for a better understanding of the key human–environment relationships as they are affected by the production, realization, and consumption of ecosystem services.

Because ecosystem services flow from biophysical processes, yet represent benefits to HWB, incorporating the goal of protecting and restoring ecosystem services into management offers opportunities for the integration of natural and social science in decision making. By implication, these are opportunities for integrated natural science and human-dimensions research, as ecosystem services are key linkages that bind social and ecological systems (McLeod and Leslie, 2009). Nature produces ecosystem services, while humans modify nature in ways that affect its capacity to produce them. Humans also develop and apply technologies whose purpose is to facilitate realization of the variety of benefits derivable from natural systems.

Issues of scale also enter into the equation, adding additional complexity. As McLeod and Leslie (2009, p. 4) put it: “Human well-being is intimately connected to ecosystems through the delivery of ecosystem services across a range of scales. Cultures, economies, and institutions form and evolve in response to their local or regional ecosystem contexts.” Humans also continually modify ecosystems, at local, regional, and increasingly, at global scales. A multitude of cross-scale couplings exist, both within the individual domains represented by human and nature systems as well as across those domains. These provide challenges and opportunities for integrated natural and social scientific research and the application of integrated understanding in the name of better environmental decisions.

The benefits of better understanding both sides of the natural science – social science equation are illustrated by consideration of shoreline armoring from an ecosystem services perspective. By considering shoreline armoring from an ecosystem services perspective, one is not necessarily led to unambiguous conclusions about what to do—that is, remove it or keep it in place. Viewing the matter from a human dimensions perspective reveals two potential complications. First, the actual *production* of many ecosystem services as "end products" of nature depends as well on non-nature products and services (Boyd and Banzhof, 2006; Leschine and Peterson, 2007). As an example, full realization of the provisioning service of fish production (that is, food for humans) requires that someone go fishing, implying that a fishing rod or net and maybe a boat have been employed. Second, there are inherent tradeoffs in the production of some ecosystem goods and services when viewed as outcomes of potential decisions that managers can make. Thus, consideration of the ecosystem services associated with various decision outcomes can argue for leaving armoring in place as well as for removing it, and in some instances, for building it where it does not presently exist (table 1).

Table 1. Contributions and detriments of shoreline armoring to human well being, via provision of ecosystem and non-nature services.

Type of service	Specific services or goods affected by Shoreline Armoring	Roles of armoring *vis-à-vis* service provision	How argues for (+) or against (-) leaving armor in place
Supporting	Nearshore sediment supply and distribution	Armoring generally understood to impede supply and influence patterns of distribution	**-:** Healthy sediment supply likely contributes recreational and aesthetic value (for example, well nourished beaches) and material support for such HWB constituents as biodiversity and marine foods; argues for removal.
Provisioning	Food: As produced from terrestrial, estuarine or marine systems, and via wild capture or via culture	May protect low-lying agriculture lands and access to food supply; may however have eliminated marsh and estuarine contributions to food provision in its original placement	**±:** Food security a central element of HWB; + likely outweighs – in many instances, esp. where levees support agriculture in lowland rivers and deltas prone to flooding.
Regulating	Flood regulation	The *raison d'être* for armoring in many instances; may in some cases exacerbate flooding "downstream"	±: Presence of housing and built infrastructure argues strongly for leaving in place, as shelter and access to goods and services are basic HWB constituents
Cultural	Aesthetics and recreation	"A thing is right when it tends to preserve the integrity, stability and beauty of the biotic community." (Leopold,1949)	**±:** Recreational choice much studied but hard to reduce to predictive rules; otherwise, "beauty is in the eye of the beholder." –unk.

It is clear from table 1 that tradeoffs are inherent in thinking about seawalls, even when the objectives set for decision making is confined to the realm of service provision. Moreover, the existence of significant uncertainties (in both natural and social scientific understanding) heightens prospects that shoreline armoring decision making will take a “wicked” turn as tradeoffs are considered or otherwise become apparent. Better understanding of both biophysical and social and cultural relationships is necessary, and an integrated approach that brings a common set of assumptions to both the natural and social science inquiry would be useful (Liu and others, 2007; 2008). As Liu and others (2007) note, a scenario-based approach to organizing the research might be most useful.

Key sources of uncertainty include the effects of climate change (including, but not limited to sea-level rise) in relation to the trajectories of the “with project” vs. “without project” scenarios. The aim is to estimate the aggregate impacts on ecosystem services of each scenario, as projected into the future, so that the two can be compared. Similarly, social scientists would like to understand better how citizens and other affected interests value the potential impacts and tradeoffs given the same scenarios of change. The need to understand those values should be reflected in the scientific (natural and social) research agenda, in essence, coupled HD and natural-science research pursued within a framework that is “analytic-deliberative” (National Research Council, 1996): Science *informs* citizens’ deliberation of alternatives and feedback from that deliberation helps *frame* the research that is done. The second proposition that stakeholder process should help frame scientific inquiry is particularly challenging for ecological science. While it is rarely done (albeit fairly common in public health science), the importance of doing so is increasingly being highlighted, as it was in the 1996 report of the Ecological Society of America’s (ESA) Committee on the Scientific Basis for Ecosystem Management (Christensen and others, 1996).

As the shoreline armoring example in table 1 illustrates, humans experience ecosystem goods and services in bundles. If asked what factors are most important to the value they derive from interactions with nature, people will often include attributes that nature played little role in producing, or identify goods and services that cannot all be produced simultaneously (Leschine and Peterson, 2007). As was discussed above, ecosystem goods and services, while inarguably essential to human well being, are not everything as far as human decision making and behavior go. People act to maintain or enhance their quality of life, and non-nature goods and services are also required for fulfillment. To understand how the ecosystem goods and services produced by successful nearshore restoration are valued is to engage what Endeter-Wada and colleagues (1998) refer to as the “public involvement” portion of the HD research agenda. In addition to better understand what humans value in the context of living in the nearshore is to engage in the broader “social analysis” aspect. Tools like InVEST, under development by the Marine Initiative of the Natural Capital Project at Stanford University (Ruckelshaus and Guerry, 2009; Tallis and Polasky, 2009) can help. InVEST aims to assess changes in flows of ecosystem services under different scenarios of marine and coastal use (Tallis and Polasky, 2009).

The Future HD Research Agenda, with Implications for Puget Sound Nearshore Restoration

With some 7 million residents spread over a catchment basin of some 41,500 km^2, Puget Sound is a *human-dominated ecosystem* (Vitousek and others, 1997; Alberti and others, 2003). The implication is that social, cultural, economic, and institutional factors are likely to influence strongly how restoration takes place within the region. The findings of a recently completed comprehensive review of the social and economic research that has been done relative to Puget Sound restoration speak to this point (Stinchfield and others, 2009):

- Restoration occurs in particular socio-economic and institutional contexts, and these influences can act either to impede or to facilitate its conduct.
- To people in the Puget Sound region, both urgency and knowledge with respect to the need for restoration are low.
- People need compelling reasons to support and participate in restoration (for example, salmon recovery and leaving future generations a healthy environment).

To paraphrase Stinchfield and others (2009) most basic finding, however, although a fair amount of social and economic research has been done on questions pertaining to Puget Sound protection and restoration, relatively little systematic understanding has emerged. The reasons for this are many, but of particular importance is that funding has been limited and thus has resulted in episodic work that occurs as isolated, one-time and small-scale studies where generalization is problematic. Too many studies, especially the many public opinion polls and surveys whose primary purpose is to gauge the public mood on matters environmental, have been *atheoretical* in their design, compounding the problem of applicability of results. The situation is not unlike that in the field of ecology that led NSF to launch programs like Long-Term Ecological Research (LTER), whose overarching goal was to create larger, better formulated, and longer-term ecological studies that could meaningfully address fundamental questions in the field.

In order to overcome the general lack of robust findings that can more fully inform the region's restoration initiatives from a human dimensions perspective, a more systematic attack on the most important research questions is needed. An important first step is the formulation of a detailed and broadly acceptable human dimensions research agenda for the region, a discussion initiated by the USGS with publication of its CHIPS (Coastal Habitats in Puget Sound) research plan (Gelfenbaum and others, 2006). CHIPS Research Goal 4 is to—

> Understand the effects of social, cultural, and economic values on restoration and protection of nearshore ecosystems.

As elaborated in the report (Gelfenbaum and others, 2006, p. 18 ff.):

> "The purpose of Goal 4 is to provide the scientific basis for better understanding the effects of social, cultural, and economic values on restoration and protection of the Puget Sound nearshore."

They further identify eight specific objectives associated with this goal.

Pursuing a long-term HD research agenda for Puget Sound framed around objectives such as those identified by Gelfenbaum and others (2006) would significantly improve our general understanding of how HWB influences and is influenced by the condition of Puget Sound's nearshore ecosystems and their ability to provide ecosystem services. With respect to shoreline armoring per se, even broadly framed studies aimed at general understanding can help gauge and build support for removal of armor that impedes the flow of ecosystem services (which are social and cultural as well as ecological). By the same token, each area of inquiry lends itself to research relevant to generating more specific understanding of the barriers and opportunities that exist with respect to the removal or modification of existing shoreline armoring.

As examples, consider several of the objectives defined in Gelfenbaum and others (2006) but rephrased to be specific to shoreline armoring: Objective 1—understanding the regulatory and institutional environment that supports the construction and maintenance of armoring in the present era; Objective 2—understanding land use and land cover in areas immediately adjacent to shoreline armoring whose removal may be desired; and Objective 3—understanding human uses of armored shorelines, and the attitudes and beliefs of users in relation to the armoring they encounter as they engage in shoreline use. As Swart and others (2001) point out, the scale of relevant social scientific inquiry in relation to restoration shifts naturally with the locus within the planning process itself—from helping to frame the general principles that guide a particular ecosystem restoration program on the one hand to the design specifics of the particular projects defined within it on the other. Objectives 1-3 reflect roughly, in their order of presentation that shift in framing. For example, studies framed under Objective 3 might reveal that shoreline armoring is important to people locally because of the access it provides to some activity like fishing or to the shore itself, leading planners to incorporate access features into project designs, thereby addressing public concerns and increasing local public acceptance.

Integrating Natural and Social Scientific Research

Opportunities should be sought to integrate wherever feasible human dimensions research elements into research endeavors whose goals are otherwise directed at natural scientific understanding of biophysical processes that govern restoration processes and outcomes. To do so would be to further goals for integrated research on coupled human and natural systems espoused by numerous proponents of greater integration of human and natural systems research (Liu and others, 2007). These same goals are now championed by the National Science Foundation under an initiative labeled Dynamics of Coupled Nature and Human Systems (CNH).

The opportunities for achieving such integrated research are many as the goals and approaches in the natural sciences and social sciences are frequently the same. For example, both natural sciences and studies of human use and social attitudes use a pre- post-intervention monitoring design. A common strategy in the field of Social Impact Assessment (SIA) is to approach situations with potential social impacts with designs intended to capture those shifts, as opportunity presents itself (Branch and others, 1984).

Work of relevance can be done at the level of a single site in both natural and social sciences. Prospects for broader understanding of course increase as one is able to generalize from individual sites. In the social sciences, this is done by treating sites as cases and building multiple case study designs into broader studies aimed at achieving more robust results. To cite one example, PSNERP-supported investigators currently have a small, single-site study of shoreline armoring at a Puget Sound site (Seahurst Park, located in Burien, Washington). At present, it involves natural science-based inquiry only. Companion social studies could focus on how human behavior at the site is influenced by the presence or absence of shoreline armoring, pre- and post-removal. Such work would address the role that environmental attributes (in this case, presence or absence of shoreline armoring) play in quality-of-life at a particular place, along lines of the work of Cox and others (2006) described above.

Summary

In summary, there is growing recognition of the importance of attending to long-neglected human dimensions aspects of ecosystem research. For environmental restoration, especially in the densely populated central regions of Puget Sound, greater attention is a necessity. The current push toward ecosystem-based management is in part a response to a record of less than satisfactory outcomes for resource management decisions that have been largely driven by natural scientific understanding and have poorly incorporated human dimensions.

A strong argument can be made that, given the considerable natural scientific underpinnings that already exist, it makes sense to pursue research on social scientific aspects of nearshore restoration in concert with natural science. In such a "coupled human and natural systems" framework, the questions posed for study should come from an integrated assessment of current understanding and research needs, both social and natural. The idea that the provision of ecosystem goods and services, essentially benefits to humans produced by nature, should be the sought-after endpoints of restoration especially offers opportunities to pursue integrated natural science and human-dimensions research. Opportunities to establish social monitoring baselines in concert with efforts to develop baselines for biophysical parameters should not be neglected.

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Coastal Geologic and Oceanographic Processes

Eroding bluff and gravel beach on the west side of Whidbey Island. Photograph taken by Hugh Shipman, Washington Department of Ecology.

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“Design with Nature” Strategies for Shore Protection: The Construction of a Cobble Berm and Artificial Dune in an Oregon State Park

Paul D. Komar[1] and Jonathan C. Allan[2]

Introduction

Figure 1. Natural cobble beach on the shore of Oceanside, Oregon, which has protected the sea cliff from erosion, evident in its extensive cover of vegetation.

The book “Design with Nature” was written by the Scotsman Ian McHarg, a town planner and landscape architect. With the advances in the science of ecology during the 1960s, the focus of his book (published in 1969) concerned what constitutes a natural, sustainable environment, with one chapter having been devoted to the preservation of barrier islands. On the basis of our investigations of the designs of environmentally compatible shore-protection structures as substitutes for conventional armor-stone revetments or seawalls, we have expanded on McHarg’s concept to include the idea that we can learn from nature in the search for improved ways to protect our shores from the extremes of waves and tides (Komar, 2007). Our goal is to design structures that are more natural in appearance, while at the same time providing an acceptable degree of protection to coastal properties.

Our interest in this philosophy was initiated by the erosion experienced in a state park on the Oregon coast, where a high protective dune ridge had been eroded away, followed by a major storm in 1999 that washed through the campground destroying much of its infrastructure (Allan and Komar, 2002; 2004). It was apparent that some form of shore protection was needed, but it was decided that a conventional riprap revetment or seawall would be incompatible with this natural park setting. Instead, the decision was to construct a cobble berm that is effectively the same in appearance and in its dynamics to a natural cobble beach, backed by an artificial dune that is reinforced by a core of sand-filled geotextile bags. This decision to construct a cobble berm to protect the park was based on observations along the Oregon coast that the presence of a natural cobble beach can provide a significant degree of protection to ocean-front properties. Figure 1 shows an example of such a beach on the shore of the community of Oceanside, where the absence of erosion is evident in the heavy vegetation that covers the sea cliff, with photos dating back to the early 20th century being essentially identical.

The choice of a cobble berm backed by an artificial dune for shore-protection in the eroding state park proved to be cost effective, the expense being a small fraction of what it would have cost to construct a revetment or seawall. Important for the park visitors, the completed cobble berm and artificial dune are nearly indistinguishable from their natural counterparts on the Oregon coast, such that the visitors have little or no notion that these are in fact shore protection structures.

Here we report on the successes and limitations of these “Design with Nature” structures, their installation in this state park having been something of a “test case” on a prototype scale in applying environmentally compatible structures for shore protection. This paper ends with a broad discussion of this philosophy with suggested variations on its potential approaches directed toward protecting coastal properties.

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Cobble Berms and Artificial Dunes

The idea for constructing a cobble berm for shore protection can be traced back to the early 1970s, when an artificial gravel beach was constructed along the bank of the entrance to Rotterdam Harbor in the Netherlands, primarily to dissipate the energy of ship wakes. This approach came to be referred to by engineers as a "dynamic revetment," in the sense of it being composed of gravel and cobbles that can be readily moved by waves, in contrast to being static, as in a conventional riprap revetment built of large quarry stones (Ahrens, 1990). An alternate name used by coastal scientists is "cobble berm," a term that may be more acceptable in management applications, where the use of engineered revetments or seawalls are discouraged, or outright forbidden by law.

There are a number of advantages in using a cobble berm for shore protection rather than a rock revetment or seawall. Stone sizes are significantly smaller than required for armor in a riprap revetment, and construction is simpler than that of a conventional revetment, in which each massive stone must be individually placed in order for the structure to be stable. Although more material generally is needed for a cobble berm, the gravel and cobble-sized material is less expensive and more readily available than armor stone, either being "pit run" material from a quarry, or gravel and cobbles derived from natural sources (for example, rivers or other beaches).

Another advantage is that because a primary goal in constructing a cobble berm is that it has the general appearance and morphologic details of a natural cobble beach, to a degree this makes its design and construction relatively straightforward. The design first involves an assessment of the volume of gravel and cobbles that will be required to produce a berm having a sufficient width and elevations so that it will provide a buffer for shore-front properties from the expected combinations of extreme tides and storm waves. Placement of the cobbles in the berm during construction mainly involves the creation of a beach that has the expected equilibrium slope for its grain sizes and the wave climate of the site. This choice of a slope in the design need only be a first approximation in that it can be expected the cobbles will be transported and sorted by the waves into what constitutes the correct "design" for that site.

It is fortunate that conceptually the design of a cobble berm/dynamic revetment is relatively simple in that only limited research has been undertaken by coastal engineers directed toward their design, with their studies having mainly involved experiments in laboratory wave channels. More relevant have been the field investigations over the years of gravel and cobble beaches undertaken by geologists, which have documented their slopes, morphologic responses to storms (their morphodynamics), and the rates of transport and size sorting of the cobbles. When faced with the design of a cobble berm, those past studies provide guidance, but it is also important to investigate the natural cobble beaches along the coast where the artificial berm is to be constructed. This was the objective of the study by Everts and others (2002) of the cobble beaches on the coast of southern California, in preparation for the construction of a test-section cobble berm in Ventura. Similarly, in preparation for the design and construction of the cobble berm to protect the eroding state park on the Oregon coast, as illustrated in figure 2, we initiated an extensive study of the natural cobble beaches, including those within the park itself (Allan and Komar, 2004).

Figure 2. Natural cobble beach on the Oregon coast, being surveyed and with the cobble sizes measured to serve in the design of the artificial cobble berm for shore protection in Cape Lookout State Park.

Conceptually, the construction of a cobble berm is not much different from the implementation of a beach nourishment project, both being “soft” approaches to beach restoration and shore protection. Although both involve the importation of sediments, beach nourishment most commonly is directed toward the restoration of an existing beach composed of sand, although there have been cases of the nourishment of gravel beaches. The primary objective in constructing a cobble berm is not beach restoration and could equally be undertaken on a shore where there had not been a pre-existing cobble beach. As has been the case for the state park on the Oregon coast, the choice of constructing a cobble berm primarily could represent an alternative to a “hard” structure, a riprap revetment. Furthermore, there are aspects in the design and construction of a cobble berm that differ from those in beach nourishment. In the end, however, the distinction is subtle and not particularly important as both involve “soft” solutions, and both are variations on the “Design with Nature” philosophy.

Nourishment of sand beaches along the United States East and Gulf coasts generally has the objective of restoring recreational beaches, although it is recognized that in having created a wider beach it also serves to protect the shore-front properties by dissipating the energy of the waves. However, it is fairly standard practice to include the restoration or construction of foredunes at the back of the nourished beach; this mainly having the objective to protect the properties from the combined surge and waves of storms. At some sites, the restored foredunes have been reinforced with a core of sand-filled geotextile bags or a long geotextile tube. For example, this approach was used to protect homes on Galveston Island, Texas, a low-lying barrier island that has experienced decades of shoreline recession and impacts from storms, with minimal development of a natural foredune that offered protection to the homes (Heilman and McLellan, 2003). Although the waves of even modest tropical storms were able to wash away the sand of the small constructed dunes, the geotextile tubes generally remained in place, offering for number of years a degree of protection to the homes. However, that protection proved to be insufficient during Hurricane Ida in 2008, when its surge and waves washed over the entire barrier island destroying nearly all of the homes.

The Erosion of Cape Lookout State Park

Although the construction of a cobble berm for the protection of coastal properties had not been previously demonstrated on a prototype scale to be a satisfactory management strategy, the substantial evidence offered by the natural cobble beaches along the Oregon coast recommended this approach when erosion significantly damaged the facilities at Cape Lookout State Park on the northern Oregon coast (Allan and Komar, 2002 and 2004; Komar, 2007). The added protection offered by the restoration of the foredunes suggested their inclusion in the impacted area.

Cape Lookout State Park lies at the south end of Netarts Spit, north of the Cape Lookout headland (fig. 3). Prior to its erosion, a wide sandy beach had existed along this shore, backed by a ridge of high dunes covered with thick vegetation, including large trees. The presence of those dunes sheltered an extensive campground, one of the most popular on the Oregon coast. The inception of the erosion occurred during the major El Niño of 1982–83, which produced erosion at a number of sites along the coast (Komar, 1986). A significant factor was that during a major El Niño the measured tides throughout the winter are on the order of 0.5 m above the predicted astronomical values, resulting from the combined effects of the ocean water along the coast being warmer than usual, the higher temperatures producing a thermal expansion of the water, and with the geostrophic effects of intensified northward flowing ocean currents acting to pile water up along the shore. The result of the elevated water levels is that during a major El Niño many of Oregon’s low-sloping beaches are “flooded out” at all stages of the tides, so that the storm-generated waves are able to reach and impact the sea cliffs and foredunes, resulting in significant erosion of shore-front properties.

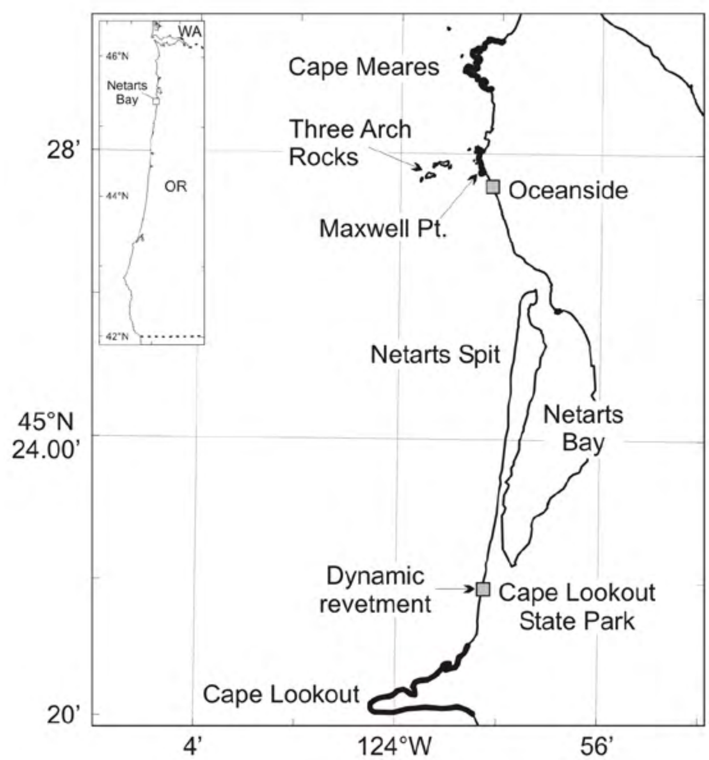

Figure 3. Netarts Littoral Cell on the northern Oregon coast, the location of Cape Lookout State Park where a cobble berm and artificial sand dune were constructed for shore protection.

The elevated monthly-mean water levels and tides were an important factor in the erosion of Cape Lookout State Park, but most significant was that the park is positioned in what we call a zone of “hot-spot” erosion, where the greatest impacts have occurred during major El Niños. During the winter of an El Niño, the storms crossing the Pacific Ocean tend to follow more southerly tracks than during normal winters, so they cross the coast of central California rather than the shores of Oregon and Washington. As a result, the sand on Oregon’s beaches is transported alongshore to the north by the waves that arrive from the south-southwest, creating hot-spot zones of erosion immediately north of headlands, where the greatest losses of beach sand are experienced, leading to the complete loss of the protective beach at some sites. The unprecedented erosion at Cape Lookout State Park during the 1982-83 El Niño therefore largely was a result of a classic example of concentrated hot-spot erosion caused by its position just north of Cape Lookout (fig. 3).

Figure 4. Erosion of Cape Lookout State Park, photographed during the 1997–98 El Niño. The remnants of the high dune ridge and a failed log seawall are seen in the background. Riprap temporarily protected the bathrooms, but they were removed after having been damaged the following winter when the March 1999 storm breached this area and washed through the campground (Allan and Komar, 2004).

To a large extent, the Park’s beach recovered following the 1982–83 El Niño, as the sand returned from where it had been temporarily displaced to the north. There was little additional loss of Park grounds until the next major El Niño in 1997–98, when there was a near repeat of the processes and impacts, leading to the loss of more of the high protective dunes (fig. 4). In a “one, two punch,” the following winter of 1998–99 was eventful in that there were a series of exceptional storms, with the strongest in early March 1999, which generated 14-m wave heights that combined with high tides to flood across the Park’s campground, which was no longer protected by a ridge of dunes (Allan and Komar, 2004).

After the Park experienced significant losses to erosion and flooding, the choices seemed to be either to abandon the campground or to construct a conventional rock revetment that would consist of sufficiently massive quarry stones to withstand the high wave energies of the Oregon coast. Such a structure would have required that it be designed by an experienced coastal engineer, and its construction would have had to be undertaken by a private contractor using heavy-duty equipment to individually place the stones. The estimate of the cost for constructing a riprap revetment having the required vertical scale and length of 300 m was placed at $500,000; in reality the cost likely would have been much higher because stone would have to be trucked in from the Columbia Gorge because of the lack of suitable stone size in the quarries along the coast.

In addition to the concerns regarding the cost involved in its construction, there was an inherent aversion on the part of State Park’s officials to having a “hard” structure in the Park, a high mound of rocks between the campground and the recreational beach. Such concerns ultimately led to the decision to construct the cobble berm backed by a line of restored sand dunes, which was viewed as being an environmentally compatible approach in this park setting. A cobble beach was already present along much of the length of Netarts Spit, backing the otherwise dominant sand beach. However, in the area of the developed park, the deposit of cobbles was too low in elevations and width to provide adequate protection; we had not even been aware of its existence prior to its being uncovered by the erosion of the sand beach and loss of the high dunes. Although inadequate, this narrow cobble beach along the eroding shore supported the decision to import additional gravel and cobbles to construct a cobble berm. A decision also was made to include the construction of a restored foredune that would back the cobble berm, a line of low dunes that would replace the high dune ridge that had been lost. In recognition of the reduced scale of the artificial dunes, it was decided to reinforce them with a core of sand-filled geotextile bags.

Design, Construction, and Monitoring

The design for the cobble berm and restored foredune is shown in figure 5, consisting of two “Design with Nature” components, having become a “hybrid” structure (Komar, 2007). The coupling of these two components was such that each could be downsized compared with its scale required if constructed alone. If only the cobble berm had been constructed, for the berm to adequately protect the park it would have had to be much larger and reached a higher elevation at its crest, to prevent overtopping during storms. That would have represented a problem given the limited availability of gravel and cobbles for construction. The decision to include the restored foredunes made it possible to reduce the size of the cobble berm, since the presence of the dunes would block the extreme water levels of tides and waves during storms that would overtop the berm and potentially carry cobbles as projectiles into the campground. At the same time, although downsized, the cobble berm would dissipate much of the wave energy so the dunes would not have to be as massive and as high in elevation to prevent overtopping. The elevations of the components of the structures given in figure 5 (relative to the NAVD 88 datum) were based on calculations of the total water levels expected during extreme tides and storm-generated waves, confirmed by surveys of the elevations of the natural cobble beaches and their landward vegetations lines, and evidence for the total water level reached during the extreme March 1999 storm that had flooded the Park’s campground.

The artificial foredune was constructed first, its core consisting of 2,750 geotextile bags, each filled with approximately 0.7 m^3 of sand. The sand for the reconstructed dunes came from an area several kilometers to the south of the park, where there had been problems with sand blowing onto the roadway. The mound of bags was buried beneath 15 to 30 cm of sand, covered with a biodegradable jute-coconut fiber mat (fig. 6), that in turn was covered by another layer of loose sand planted with dune grass that is native to the Oregon coast (*Elymus mollis*). The construction of the cobble berm was undertaken following the completion of the dune. The cobbles were obtained from natural accumulations on the beaches within the Park, primarily toward the north end of Netarts Spit, where the net northward transport of the gravel and cobbles tends to accumulate, and where erosion of the dunes has been minimal and infrastructure is not present. The cobbles were transported to the construction site on a front loader (fig. 6) and placed evenly across the pre-existing profile of the natural cobble beach. The top of the added cobble berm overlaid the scour blanket that had been placed beneath the artificial dune, and lapped up onto the front of the constructed dunes to offer protection from the waves. No attempt was made to provide toe protection for the placed cobbles as would normally be done in the construction of a conventional static revetment. The deposit of cobbles instead extended below the beach sand in the offshore, providing the primary toe support for the constructed cobble berm.

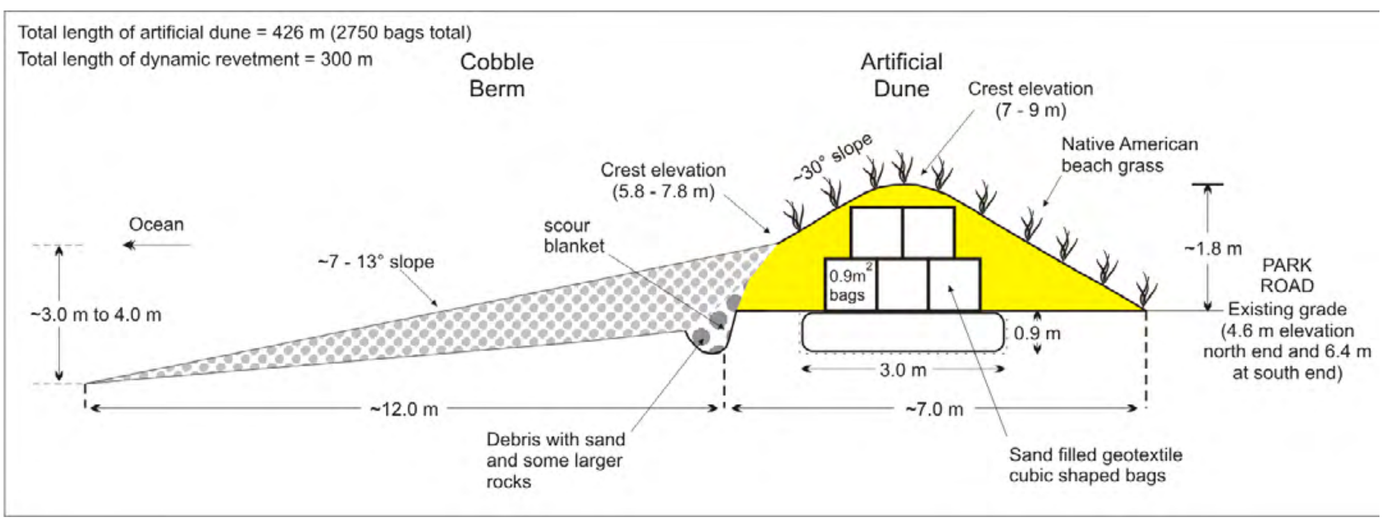

Figure 5. Design for the cobble berm and reinforced foredune to protect Cape Lookout State Park from erosion and flooding. The elevations are referenced to the NAVD 88 datum.

Figure 6. Construction of the cobble berm and artificial foredune in Cape Lookout State Park during the fall of 2000. A continuation of the old dune ridge is seen in the background, which had previously extended past this area of erosion.

Construction of the 300-m long cobble berm and artificial foredune was completed by December 2000, prior to subsequent major storm events. Growth of the planted vegetation quickly covered the dune so that, as seen in figure 7, the completed project had the desired appearance of a natural cobble beach and foredune as seen along the Oregon coast. Their construction was undertaken by Oregon State Parks and Recreation Department, with the employment of work-released labor from the State penitentiary. This kept the total cost of the project to approximately $125,000, significantly less than the $500,000 estimated cost for a conventional static riprap revetment having the same 300-m length.

The construction of these environmentally compatible structures for shore protection provided the opportunity to monitor them, to determine their degrees of success, and possibly to improve their designs for future applications (Allan and Komar, 2004). Monitoring included a program of periodic surveys and analyses of the tides and wave runup that occurred during the winter storms for comparison with the structure elevations and surveys of the morphologic responses to extreme storms. The surveys immediately demonstrated that the constructed cobble berm and foredune did not meet the design specifications in terms of their elevations required to limit overtopping by the expected wave runup elevations of major storms. The top of the dune along the northern one-third of the structure was found to be 1 to 2 m below the 8 to 9 m NAVD 88 recommended elevation, although the southern one-half meet the specifications. As seen the photograph in figure 7, taken soon after a winter storm, the cobble berm experienced frequent attack by even modest storm waves, although the line of restored foredunes provided a variable level of defense, overtopping occurred along its northerly stretch of lowest elevation. On at least one occasion during our monitoring program, extreme waves were documented to have overtopped the entire length of the structure.

This significant construction “flaw,” however, resulted in a more meaningful “experimental test” of the structure’s capacity to withstand the forces of extreme waves and tides. Although wave overtopping has occurred a number of times since construction was completed in 2000, occasionally carrying a few cobbles and drift logs into the campground, both the cobble berm and foredunes largely have remained intact. The combination of the cobble berm backed by a line of foredunes has proven to be an effective strategy in protecting Cape Lookout State Park from storms that otherwise would have rendered the campground unusable (Allan and Komar, 2004).

Being a “soft structure” with the waves able to entrain and transport the cobbles on the constructed berm, it was expected that some replenishment eventually would be required. Our monitoring surveys extended alongshore beyond the length of the constructed cobble berm, demonstrating the occurrence of continued erosion along the adjacent

Figure 7. Completed cobble berm and foredune, having been overtopped by a winter storm along the stretch that had not been constructed to the designed elevations. The riprap that previously had protected the bathrooms (fig. 4) can be seen in the background.

unprotected stretches of the park. That erosion has been particularly severe to the immediate south of the structures, and began to impact the volumes of cobbles within the constructed berm. As part of our monitoring program we traced the movement of a large number of cobbles with PIT (passive integrated transponder) tags, to document their mobility and net transport within the cobble berm (Allan and others, 2006). It was found that the cobbles are transported alongshore toward the north, carried in that direction by the waves of winter storms that arrive from the southwest. With the eroding beach to the south being deficient in gravel and cobbles, it has been unable to supply beach material to replace that being lost from the cobble berm. The result was that by 2008 the cobble berm had lost 5,000 m^3 of gravel and it was evident that maintenance was required. During that summer, State Parks added about 3,500 m^3 of gravel and cobbles to the berm, most of it recovered from where the lost material had accumulated near the north end of Netarts Spit. The maintenance during the summer of 2008 still left the cobble berm deficient in cobbles, about 1,500 m^3 less than when it was constructed, so its capacity to protect the park from winter storms remains compromised.

With the almost annual wave overtopping of the foredunes where they had not been constructed to the design elevations, it has become evident that in places the vegetation and sand cover has been lost, exposing the geotextile bags. A decade after their construction, maintenance is definitely needed, and it also has been recommended that in the process their elevations be raised to bring them closer to those specified in the original design. Along the southerly stretch of constructed foredunes, which had achieved the design elevation, there has been minimal degradation of the dune as a result of the absence of frequent overtopping; this stretch of constructed foredune demonstrated its capacity to protect shore-front properties if properly designed and constructed.

In spite of not having been constructed to their designed elevations along their entire length and not having been adequately maintained, the cobble berm and foredune in Cape Lookout State Park have survived the intensity of wave attack on the high-energy Oregon coast, and have provided an acceptable level of protection to the campground. Furthermore, it is evident that had they been constructed to the elevations needed to prevent overwash, and with a longer length or having included a feeder beach of cobbles to the south, their stability would have been significantly greater. But from this experience it was reaffirmed that being “natural,” such structures are dynamic and require some level of periodic maintenance. However, even including the expenses for maintenance they can be expected to cost far less than a conventional rock revetment or a seawall (bulkhead), and most importantly, they provide a natural form of shore protection from erosion and flooding, one that is compatible with their coastal setting.

“Design with Nature”—Variations on a Theme

There potentially are variations on this “Design with Nature” approach for shore protection, involving other components and designs than were employed in Cape Lookout State Park. For example, rather than constructing an artificial dune as backup for the cobble berm, a scaled down boulder revetment could be used. The incorporation of a seemingly static revetment might seem contrary to this philosophy, but large-stone “revetments” can be found in nature wherever coarse material is available along the shore. For example, such accumulations are found along the rocky coast north of San Francisco, providing toe protection to the large active landslides that are common along that coast. Our recognition of this natural development of self-protection by landslides proved to be of interest when the California State Highway Department decided to dispose of rocks and sediment derived from the reconstruction of a stretch of highway by dumping the excavated material from the mountainside down the steep cliff face, in effect creating a massive artificial landslide. This provided another “experiment” that permitted the documentation of the early stages of landslide erosion, mainly involving the processes of waves cutting away the toe of the slide (Komar, 1997 and 1998). The material being disposed of in that slide came from the Franciscan Formation, which contains a full range of sediment sizes from clay to large boulders. It was observed that a beach immediately began to form along the toe of the eroding slide, consisting of the coarsest materials, gravel, cobbles and boulders. With its accumulation, the rate of toe erosion progressively slowed, the material having sorted itself into a protective gravel and cobble beach, backed in riprap-like fashion by a line of armor-sized boulders.

The natural landslides and the evolution of that artificial slide on the California coast illustrated the potential for another “Design with Nature” strategy for shore protection. They also demonstrated the basic difference between the regularity of a riprap revetment designed by an engineer, compared with nature’s design where there is far less organization in the piling of the boulders, and their presence tends to blend to a greater degree with the fronting cobble beach. The design of such a hybrid cobble berm plus a boulder revetment is illustrated in figure 8, having been proposed to protect an eroding mudstone bluff on the coast of New Zealand, where a cobble beach was already present but was insufficient to protect the bluff and homes. Previously, unnatural gabions had been used to protect the bluff from the attack by waves, each gabion consisting of a wire-mesh cube filled with cobbles; however, within a few years the wire mesh rusted, and most of the gabions were broken apart by the waves. It is apparent in figure 8 that the replacement of the gabions with boulders and the addition of cobbles to the beach represented a far more aesthetic and effective

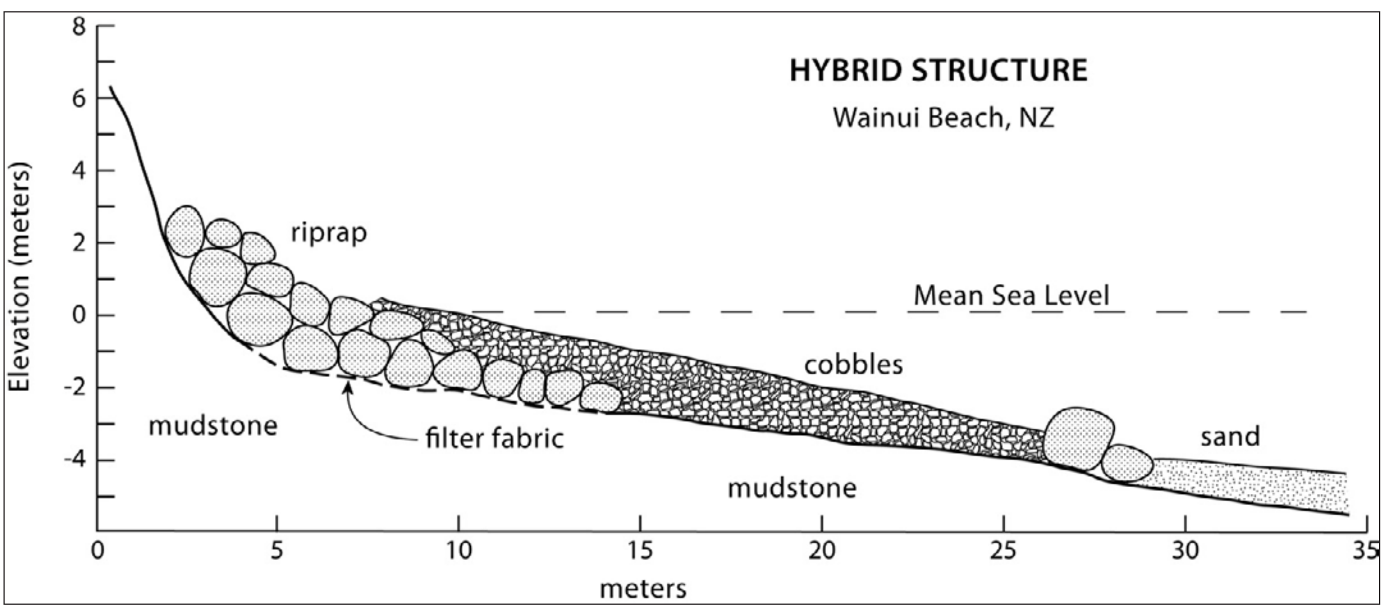

Figure 8. Hybrid “Design with Nature” approach for protecting a bluff from erosion, consisting of a cobble berm backed by a natural form of boulder revetment.

structure. Similar to the combination of the cobble berm and artificial foredune constructed on the Oregon coast, this combination permitted the use of a scaled down line of boulders since the cobble beach would first act to dissipate the energy of the waves. Alongshore from that site, which lies at the end of a pocket beach within a bay, the cliff is fronted by a sand beach rather than cobbles, and wind-blown sand tends to accumulate during the summer to form a foredune, which, however, is frequently eroded during winter storms, leading to erosion of the bluff. It was proposed to use a constructed foredune reinforced with geotextile bags, virtually like that in Cape Lookout State Park. Although it is expected that much of the sand in the dune would be lost during winter storms, the presence of the geotextile bags can be expected to continue to protect the bluff and homes from wave attack, until the dune is naturally reformed by the wind the following summer, or is artificially restored by "beach scraping" (bulldozing a portion of the summer beach onto the dune).

Figure 9. Logs at the back of a gravel beach on the shore of Puget Sound, placed to protect the property from high tides and waves.

A variation on that seen in figure 8, but on a smaller scale, was constructed along the shore of Yaquina Bay on the Oregon coast, where erosion was impacting a pathway leading from the Mark Hatfield Marine Science Center of Oregon State University, used by visitors to view this natural estuarine environment. It again was deemed undesirable to construct an imposing "hard structure", and based on our recent experience at Cape Lookout State Park, it was decided again to construct a gravel-cobble berm. But in this application the design included a line of large rocks in the water along the toe of the fill, upgraded from those illustrated in figure 8 to have a sufficient size such that they would not be displaced by wind-generated waves on the bay or by ship wakes. This simple approach has been successful in protecting the shore and path from further erosion, while being entirely natural and compatible with in this estuarine setting.

Another potential design component is the use of drift logs, which are common on most shores in the Pacific Northwest. On the Oregon coast, logs accumulate locally in large numbers at the back of the beaches, their crisscrossing arrangement providing a degree of self stability even when impacted by high tides and waves, being important to the entrapment of wind-blown sand and the growth of foredunes. Similar to the use of the boulder revetment in figure 8, a "Design with Nature" protection consisting of a line of logs could be employed as backup for a constructed cobble berm or natural gravel beach, but this would need to be designed to be stable and protective of the shore, while at the same time maintaining as natural an appearance as possible, not making it look too much like a designed wall.

An example of the use of logs for shore protection in Puget Sound, Washington, illustrated in figure 9, consists of a largely random arrangement of logs, held by anchored chains, that have been placed at the back and out across the beach. This example demonstrates the potential use of drift logs on low-fetch shores where drift wood is plentiful and the wave energy is relatively low. Interest in this approach likely also stems from it being a low-coast approach to protecting one's property. However, the designs are questionable and there has been little or no monitoring to document their stability and effectiveness. Because most beaches in Puget Sound being composed of gravel and cobbles (fig. 9), a common strategy for shore protection involves beach nourishment or the construction of a cobble berm (Shipman, 2001), that expands the potential for employing a variety of "Design with Nature" approaches for shore protection in Puget Sound, with a reasonable expectation that the property will be defended for a number of years. The applications in Puget Sound, and along other coasts, only require a greater level of imagination and creativity rather than constructing still another massive rock revetment or seawall.

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Gravel Transport and Morphological Response on a Supply-Limited Beach, Point White, Bainbridge Island, Washington

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Abstract. Direct measurements and observations of coarse sediment (gravel) transport, beach morphological change, scour and accretion patterns, beach sediment characteristics, and forcing mechanisms have been obtained over a number of time intervals from 2000 to present from a mixed sand and gravel (MSG) beach on Bainbridge Island, Puget Sound, Washington. The beach is backed by bulkheads and seawall structures along the full length of the study site (approximately 1 kilometer) and has been exposed to wind waves, vessel-generated waves from both passenger-only fast ferries (POFF) and conventional vessels, and tidal currents. Studies that have included integrated process modeling and direct measurements of gravel transport have been undertaken to quantify the relative role of the different forcing mechanisms and determine the corresponding time scales of sediment transport, morphological response, and scour. This paper provides a synthesis of observations of gravel transport over 14 months and beach morphological response over 8 years on Point White, Bainbridge Island in Rich Passage. The observations indicate distinct differences in transport regime and morphological response between storm and non-storm conditions and between POFF and non-POFF vessel operations. The long-term observations of beach morphology change, transport patterns, and sediment size and volume variations that include a downdrift fining and thinning, are consistent with the observation that the MSG beach at Point White is supply limited and undergoing long-term passive erosion most likely as a result of construction of bulkheads along the length of the study area and severe erosional episodes during previous POFF operations and storms.

Introduction

Accurate predictions of sediment transport and beach response are essential for making well-informed decisions regarding the design, permitting, and placement of both engineered structures and beach nourishment projects in the coastal environment. Improper design of structures may lead to long term erosion of the adjacent or down-drift beaches and subsequent impacts to sensitive beach habitat.

Understanding the seasonal and longer-term dynamics of mixed sand and gravel (MSG) beaches is limited, compared to that for sandy beaches, by the lack of long term data on beach response and forcing mechanisms, and the limited predictive capability of numerical models. In particular, there is a lack of information documenting the impacts (long term and short term) of seawalls and bulkheads on MSG beaches.

The operation of ferries in the fetch restricted coastal system of Rich Passage in Puget Sound, Washington, USA, has provided the unique opportunity to study the dynamics of a MSG beach with bulkhead structures that is exposed to a wide range of wakes, wind waves, and tidal currents. In one sense, the site specific nature of the study described here is somewhat unique owing to the influence of the fast-ferry wakes and the relatively low exposure to wind waves in Rich Passage itself. However, most beaches in Puget Sound are influenced to an extent by a combination of shipwakes, wind waves, and tidal currents, and most beaches exhibit mixed sediments with a morphology broadly similar to that in the Rich Passage area, bulkheads and structures are widespread, and the exposure typically varies widely from place to place. The study results may, therefore, provide a preliminary basis for characterization of mixed beach behavior in Puget Sound. The extension of this work through a system of integrated numerical models (for example, Osborne and MacDonald, 2007) will further extend the applicability of results. During previous passenger-only fast-ferry (POFF) operations from 1999 to 2002, the upper foreshore of beaches in Rich Passage were eroded and the slopes were reduced. It is hypothesized that the longer period POFF wakes caused the flattening and erosion of the upper foreshore, whereas wakes from car ferries have resulted in beach steepening and accretion of the foreshore. The presence of bulkheads or seawalls also is hypothesized to have had a long-term (decadal) impact on sediment supply and thereby contributed to passive erosion in the study area (Osborne and others, 2007).

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The goals of the present study were to resolve seasonal patterns of sediment transport and morphology change on a MSG beach that is backed by bulkheads, quantify the relative role of the different forcing mechanisms (wakes, waves, and tidal currents), and apply the measurements to validation of a system of integrated numerical models that can be used for wake impact assessment in the study area. In this paper, we provide an overview of the results of direct measurements and observations of coarse sediment (gravel) transport and beach morphological change obtained over a number of time intervals from 2000 to present from a MSG beach on Bainbridge Island, Puget Sound, Washington. From these data, we comment on the relationships between sediments and supply, morphology, processes, and forcing on a typical Puget Sound beach that has been armored by bulkheads and subject to variable wake and wave climate for several decades. The study is part of a large multi-disciplinary study investigating the feasibility of re-introducing POFF operations to the Seattle-Bremerton ferry route, which includes extensive physical and biological data collection, integrated impact assessment modeling, and vessel design, optimization, and in-situ testing. The interested reader is referred to papers by Curtiss and others (2009), Osborne and others (2007), and Osborne and MacDonald (2007) for more detailed discussion of the measurements and modeling. Additional technical information on the study may be found on the project web site (Pacific International Engineering, 2009) at www.pugetsoundfastferry.com.

Study Area and Sediment Characterization

The study site (fig. 1) is an approximately 500-m length of MSG beach in Puget Sound on the east shore of Point White, at the southern end of Bainbridge Island. Point White lies at the western end of Rich Passage, a narrow channel that provides the most direct vessel route between downtown Seattle and the city of Bremerton, Washington. The beaches are backed by bulkheads and revetments of varying type and condition along the length of the study area. Data including wind, wave, current measurements, sediment samples, and gravel tracer measurements were collected at two separate sites which are denoted here as PWA and PWB (see Curtiss and others, 2009, for details).

The sites were selected for study because of their location in proximity to the vessel sailing line on the Seattle-Bremerton ferry route, and because they both occur in relatively close proximity to one another within the same drift cell but exhibit notable differences in sediment properties and response. Beach and inter-tidal deposits at Point White are a thin layer of unconsolidated sediment eroded into a beach platform composed of consolidated Holocene age Vashon till (Haugerud, 2005). The mobile sediment layer is the result of reworking of coastal exposures of till, outwash sediments, and glaciomarine and glaciolacustrine deposits (Finlayson, 2006). The beach foreshore along Point White generally is steep (slopes from 1:5 to 1:7), with a 20- to 30-m wide strip of beach gravel (pebble and cobble) overlying mixed sand and gravel or consolidated till. The beach unconsolidated layer varies in thickness from a few centimeters up to 2 m in places on the upper foreshore and at the toe of bulkheads. The unconsolidated layer generally is thicker at PWB than at PWA; the beach to the south of PWA is a single grain thickness of gravel over till. The gravel layer varies from 0.5 m to as thin as a single grain thickness of armor on the lower foreshore. The cross-shore sorting is related to the relationship between swash energy, tide, and gravity/slope effects (for example, Osborne and Simpson, 2005). The sediments were characterized by pebble counts of the surface layer and sieving samples from the upper 30 cm. The median grain size based on the pebble count is 22.5 mm at PWA and 17.0 mm at PWB. The median grain size for the entire sediment mixture based on the results of sieving is 16.0 mm at PWA and 11.0 mm at PWB. A unique feature of the beach is the median size of the gravel, which increases with decreasing elevation on the beach, which was also observed by Nordstrom and Jackson (1993) on a low energy estuarine beach.

Gravel Tracer Measurements

Direct measurements of pebble and cobble (gravel) transport were obtained at Point White using Radio Frequency Identification (RFID) Passive Integrated Transponder (PIT) particle tracking methods (Allan and others, 2006). Tracer particles were made from samples of beach surface sediment chosen to match the size and shape of the native distributions as closely as possible but constrained by the minimum size of the PIT tags (12 mm). Sets of 48 tracers were deployed in random grids with 30-m spacing about the mean tide level at PWA and PWB from 1 August 2006 through 5 October 2007. A tracer survey consisted of finding the tracers with the RF control module and recording their positions with the RTK-GPS, leaving the tracers undisturbed. The RFID tracking methodology provided high recovery rates of the tracers. In general, the recovery was greater than 80 percent (minimum of 73 percent) throughout the study. Lowest recovery occurred during winter months, when storms resulted in higher burial rates, offshore transport, and higher tidal elevations during surveys which generally coincided with daylight hours. Tracers surveys were conducted approximately twice per month during the deployment interval (Curtiss and others, 2009).

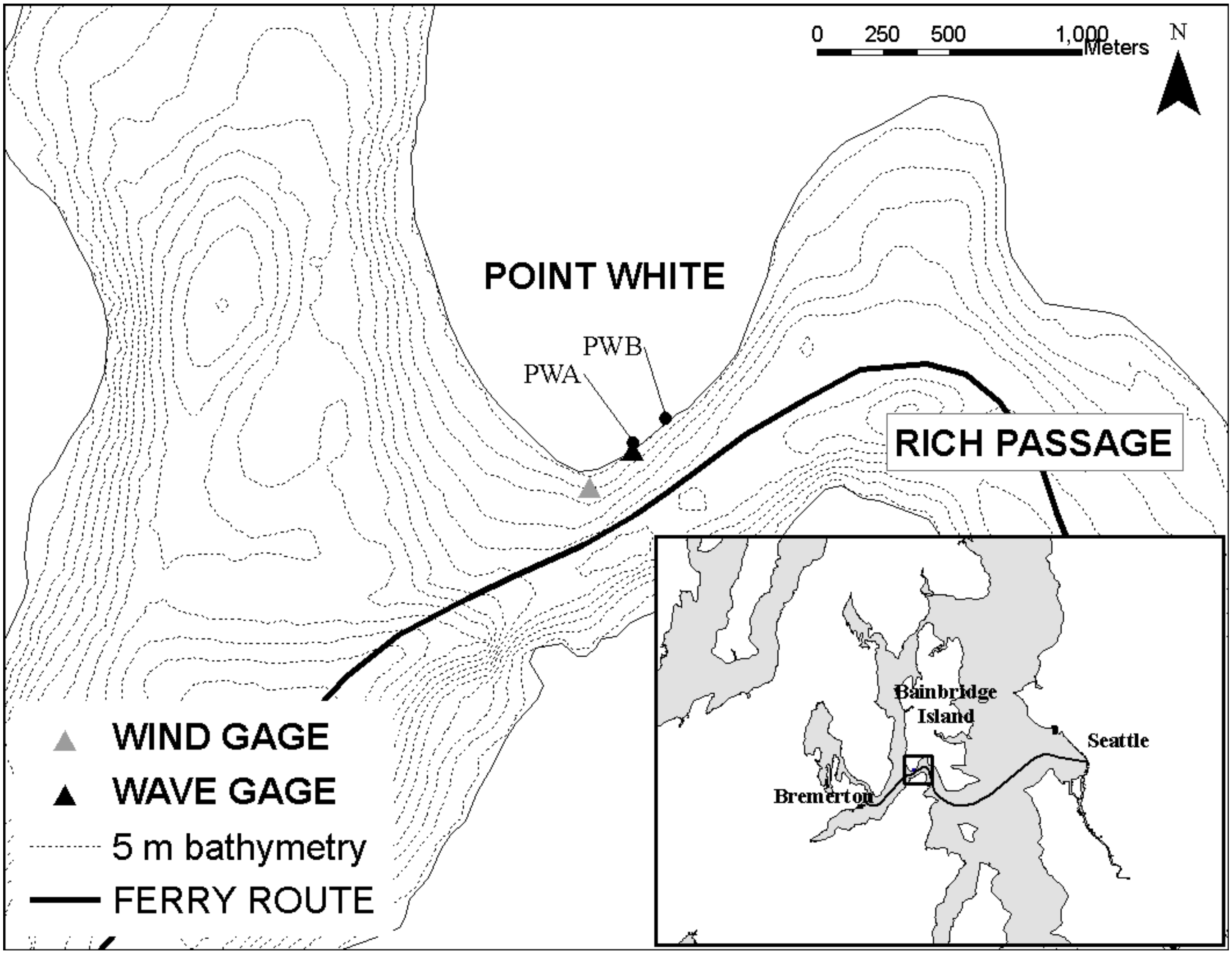

Figure 1. Study area and the location of tracer deployments, and wind and wave measurements.

The particle tracking data were analyzed to determine the magnitude of alongshore and cross-shore transport between survey periods as well as any dominant patterns based on particle size or location on the beach. Figure 2 is a map of the tracer distributions on August 1, 2006, and October 5, 2007, and of the centroid of the tracers through time. Tracers moved predominately alongshore to the northeast at both sites, with greater transport magnitude occurring at PWA than at PWB. Following an initial episode of southwesterly alongshore transport at PWB, the tracers moved to the northeast. Figure 3 is a time series of the alongshore transport distance for the tracer centroids at PWA and PWB. The most noticeable feature is the amplified alongshore movement of the tracers to the northeast at both sites between November 2006 and the end of December 2006. Tracers at PWA move alongshore at a rate of approximately 0.065 m/d between April and November, whereas at PWB, the rate of movement alongshore is 0.005 m/d in the same interval. The daily transport rate at PWA increases by a factor of 6 in the period between November and January. At PWB, the alongshore transport rate increases by a factor of 90 during December. The transport during December largely is a result of the 10-year storm that occurred on December 13–14, 2006. The magnitude of alongshore movement in December is similar at both sites. However, the magnitude of alongshore movement during the non-storm intervals is higher at PWA and is possibly explained by site specific differences in exposure to wind waves and vessel wakes. The patterns of dispersal in relation to forcing are discussed in more detail in Curtiss and others (2009).

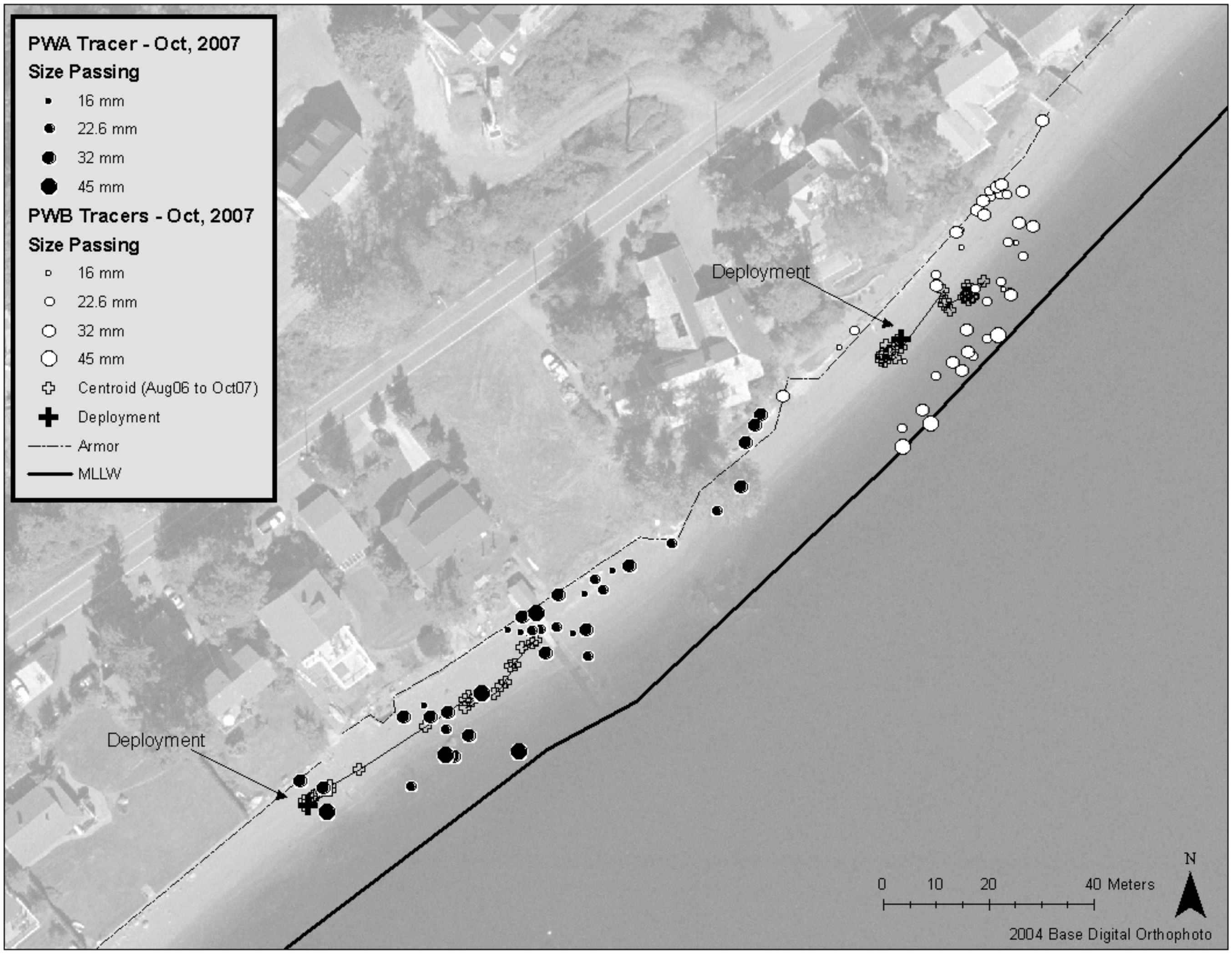

Figure 2. Spatial map of tracer distributions at the final survey in October 2007 and the position of tracer centroids through time between August 2006 and October 2007 at Point White (PWA and PWB are data-collection sites at Point White).

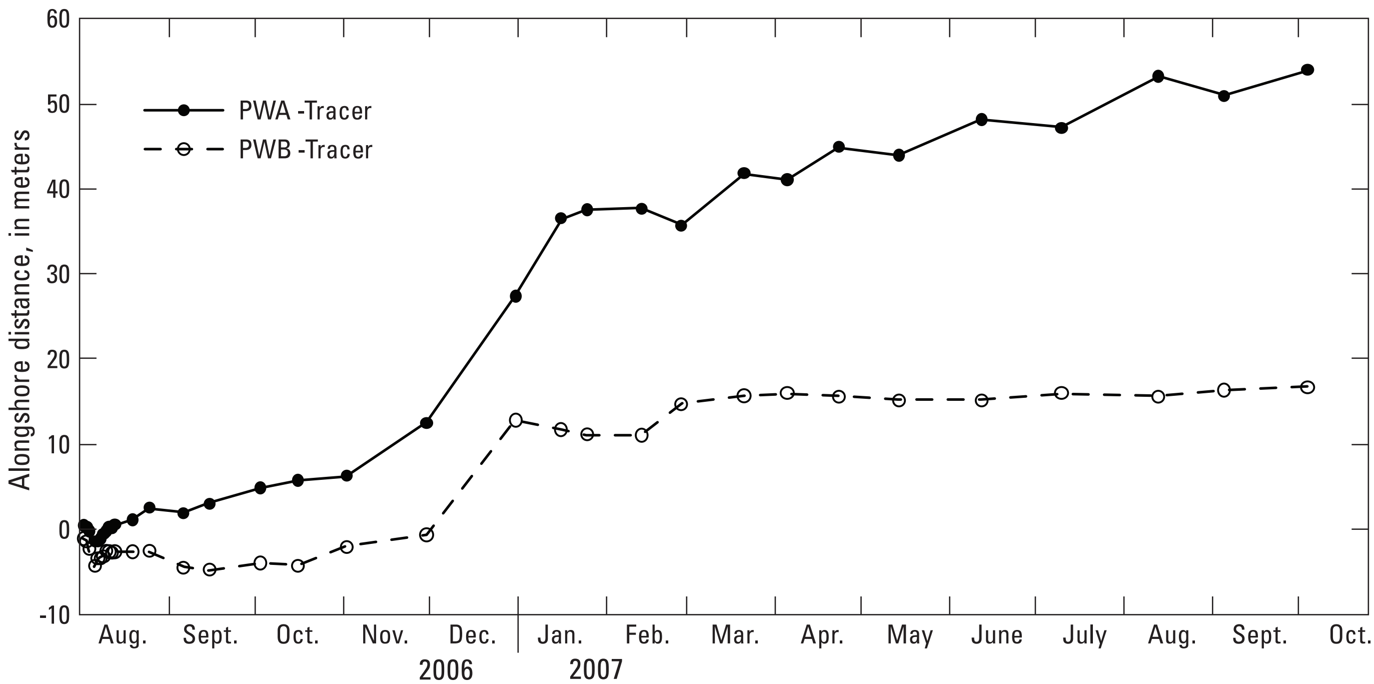

Figure 3. Alongshore transport distances of the tracer centroids between August 2006 and October 2007.

Beach Morphology Change

A number of different POFF vessels have been operated periodically through Rich Passage from the late 1980s until October 2002. All operations thus far have met with opposition from waterfront property owners because of reported damages to property and erosion of beaches (see Osborne and MacDonald, 2005, for a review). Figure 4 shows the most recent intervals since 1998 of passenger fast ferry operations in Rich Passage and the volumetric change to the upper and lower profile (above and below mean tide level) from the last 8 years at both PWA and PWB relative to May 2000, when a beach profile monitoring program was initiated. The resumption of high-speed ferry operations in 2000 initially resulted in erosion from the upper foreshore and accretion on the lower foreshore. The lower foreshore eventually eroded as well at both sites. The profile at PWA indicates a gradual erosion trend since 2004; erosion during the winter of 2008 was particularly severe. Between 2004 and the time of the gravel tracer study, the entire beach at PWB was slowly accreting sediment such that the beach recovered to the volumes present in May 2000. Erosion of the entire profile occurred during the winter of 2008 (fig. 4). It is evident that this winter erosion, which is caused by wind waves, is equivalent in magnitude to the erosion caused by the fast ferries. The winter storm erosion appears to remove sediment from both the upper and lower profile (profile retreat) rather than to re-distribute the sediment across shore (profile flattening or steepening).

Discussion

The gravel tracer measurement from the MSG beach on Point White indicate the system is dominated by alongshore sediment transport from southwest to northeast under existing conditions. The transport largely is driven by wind waves during winter storms. Storms also enhance offshore transport of gravel and cobble and result in flattening of the beach profile and exposure of sand. The combination of car ferry wakes and tidal currents contribute to a weak net alongshore transport to the southwest during non-storm conditions at PWB but not at PWA, where the net tidal flux is weaker. Car ferry wakes also contribute to net shoreward transport during non-storm conditions (Curtiss and others, 2009). In contrast, passenger-only fast-ferry operations may result in a significant cross-shore shift of sediment volume and flattening of the beach profile, which can dominate storm-induced and seasonal variations depending on site-specific conditions (Osborne and others, 2007).

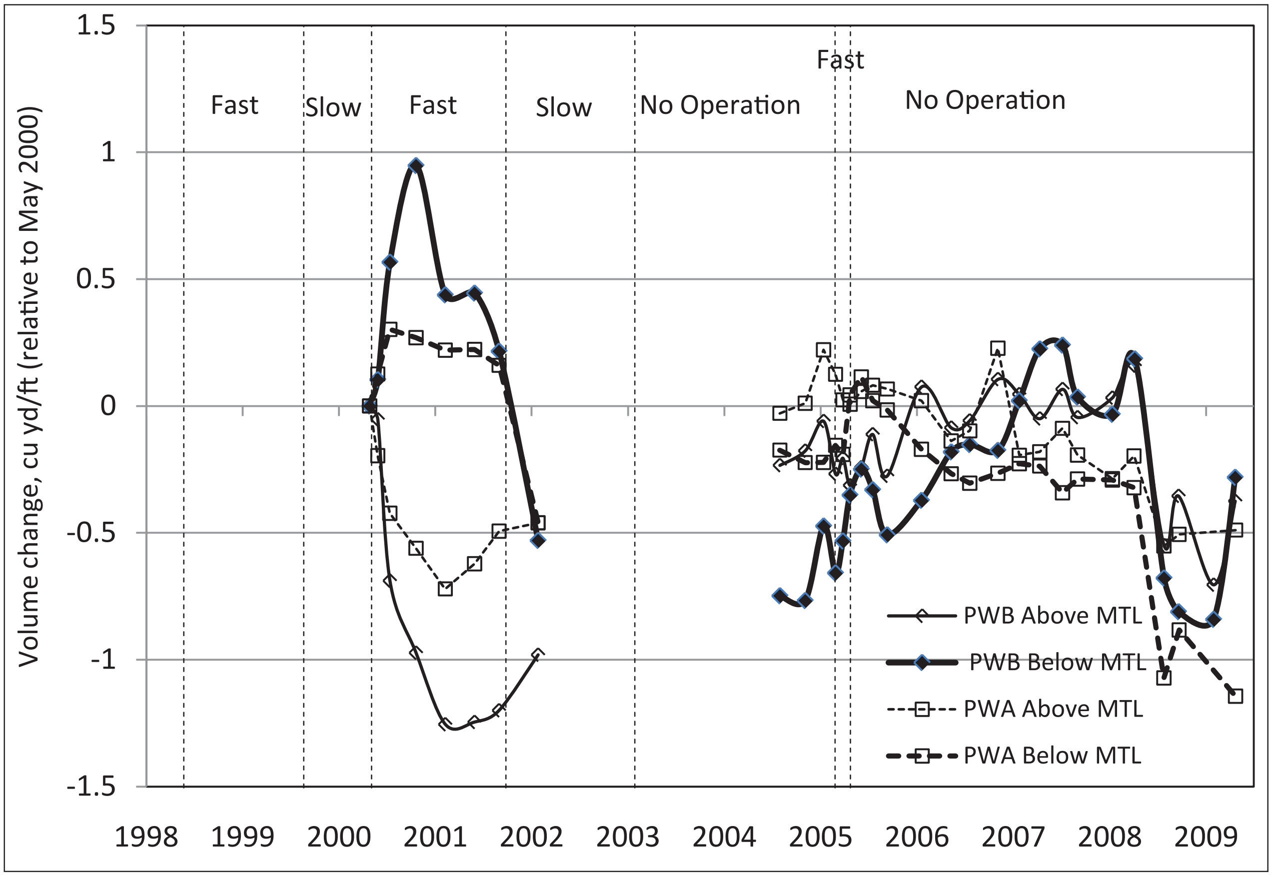

Figure 4. Volume change at PWA and PWB over an 8-year period relative to May 2000 above and below mean tide level. The intervals of fast, slow, and no operation of passenger-only fast ferries are shown with vertical dashed lines. The long-term data indicate the beach is gradually losing sediment at PWA but not at PWB.

The following observations indicate that the beach is supply limited and undergoing long-term, passive erosion, most likely as a result of construction of bulkheads along the length of the study area:

- The layer of unconsolidated sediment overlying consolidated Vashon till increases in thickness from no more than a single grain of cobble just south of PWA to more than 1 m of MSG at PWB. The median grain size also decreases in the downdrift direction between PWA and PWB consistent with a reduction in supply of finer sediments to the beach and the development of a gravel/cobble lag at the proximal end of the drift cell.

- The differences in the trends in volume change at the two sites are consistent with the above interpretation and may be attributed to their respective location in the alongshore drift cell on Point White and the relative sediment supply. PWA is near the proximal end of the drift cell where sediment supply is limited, whereas PWB is more distal and the sediment supply to the latter is being maintained thus far by erosion of the updrift beach.

Conclusions

The observations indicate differences in the sediment transport regime and morphology response between storm and non-storm conditions and between POFF and non-POFF vessel operations.

Storm intervals (typically from November through April) are characterized by an alongshore sediment transport rate of 6 to 90 times the rate during non-storm intervals as a result of offshore transport of coarse sediment (removal of surface armor) and the exposure of sand on a flat upper beach slope induced by wind waves.

Non-storm intervals (typically from May through October) are characterized by minimal alongshore transport (resulting from contributions by vessel wakes and tidal currents), and weak onshore transport, which leads to gravel berm formation on the upper beach and steepening.

Despite small differences in wave height, POFF wakes can be significantly more energetic because their periods are longer than wakes from slower and smaller vessels. The longer POFF waves result in greater swash and backwash excursion, which often interact with structures. Beach profile response to

POFF operation is rapid, occurring over an interval of several weeks. Large POFF wakes mobilize and remove sand and coarse-grained sediments from the upper foreshore and deposit it on the middle and lower foreshore and shallow sub-tidal areas. Smaller and shorter period wakes from smaller and slower vessels (such as car ferries) result in net accretion of sand and gravel on the upper beach over periods of months to years.

Downdrift portions of the beach have recovered from previous POFF operations nearly a decade ago as a result of continued longshore sediment transport and dominating onshore transport under the prevailing wake regime. However, bulkhead construction along the length of the study area has reduced sediment supply to the beach and the long term morphological observations over the past 8 years indicate a passive erosion trend beginning near the proximal end of the drift cell on Point White.

Acknowledgments

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Assessing Littoral Sediment Supply (Feeder Bluffs) and Beach Condition in King and Southern Snohomish Counties, Puget Sound, Washington

Jim Johannessen[1]

Abstract. The term feeder bluff, as defined by Wolf Bauer in the mid-1970s, refers to eroding bluffs that provide the majority of sediment to Puget Sound beaches and littoral cells. Shore modifications such as shoreline armoring/bulkheads have substantially changed Puget Sound nearshore conditions and impacted nearshore habitats. Feeder bluff mapping was completed to allow for "process-based" restoration, the strategy adopted in Puget Sound to restore and protect self-sustaining processes that create and sustain valued nearshore habitats. The geomorphic mapping methods developed by Coastal Geologic Services entail assessment of individual shore reaches using data from present and historic times separately, using a geomorphic systems approach. Methods were developed to efficiently identify feeder bluff segments for protection (conservation) and restoration (armor removal) at both the site-specific and drift cell levels. The study discussed here evaluated bluff and beach segments within 121 miles of shore in King and southern Snohomish Counties in Central Puget Sound. Highlights of current and historic geomorphic (feeder bluff) mapping and sediment supply-based conservation and restoration prioritizations are presented to demonstrate the uses and value of this dataset. Shore modifications were present along 59 percent of the total study area length in current conditions. When comparing current to historic sediment sources, there was a 63.4 percent loss for the entire study area. On a broader scale, current conditions mapping has been completed along more than 800 miles and historic conditions along 385 miles out of approximately 2,000 miles of greater Puget Sound shore to date. Of 99 littoral cells with current and historic feeder bluff mapping data (250 miles) from this study area and others, 14 drift cells no longer had any intact nearshore sediment sources, 29 drift cells had lost 50 percent or more of the (linear extent) of historic sediment sources, 23 drift cells had lost 1–50 percent of the of historic sediment sources, and 33 drift cells had not incurred a loss of sediment sources. These data illustrate the magnitude of sediment impoundment in the Puget Sound region and the necessity of restoring (removing armoring) and conserving (protecting) bluff sediment sources in order to maintain the processes that create and maintain nearshore habitats. Completing the dataset Sound-wide would enable systematic restoration and conservation planning based on coastal processes.

Introduction

Bluffs are present along the majority of Puget Sound shores (Shipman, 2004 and 2008), and the input of sediment from these bluffs is thought to account for the large majority of the total sediment input to Puget Sound beaches (Keuler, 1988; Shipman, 2004). Beaches, or accumulations of loose sand and gravel, are present along almost all of Central Puget Sound (fig. 1). Beaches here typically consist of mixed gravel and sand deposits at the toe of bluffs or along low elevation backshores. Beaches and bluffs are components of littoral cells, a concept that has been employed in coastal studies to represent a coastal sediment transport sector from a source area to depositional area at the cell terminus (Inman and Chamberlain, 1960), and which emphasizes a systems approach to understanding coastal evolution. An idealized littoral cell in Puget Sound is defined as consisting of three components: a site (usually along erosional bluffs) that serves as the sediment source and origin of a drift cell; a zone of transport, where sediment may be deposited temporarily and waves transport sediment alongshore; and an area of deposition (and transport), which is the terminus of a drift cell (Jacobson and Schwartz, 1981). Littoral cells are often called net shore-drift cells in Puget Sound (Jacobsen and Schwartz, 1981) or just drift cells. Littoral cells have been mapped throughout the greater Puget Sound area using geomorphic indicators of long-term, littoral sediment supply and transport (Schwartz and others, 1991, Johannessen 1992).

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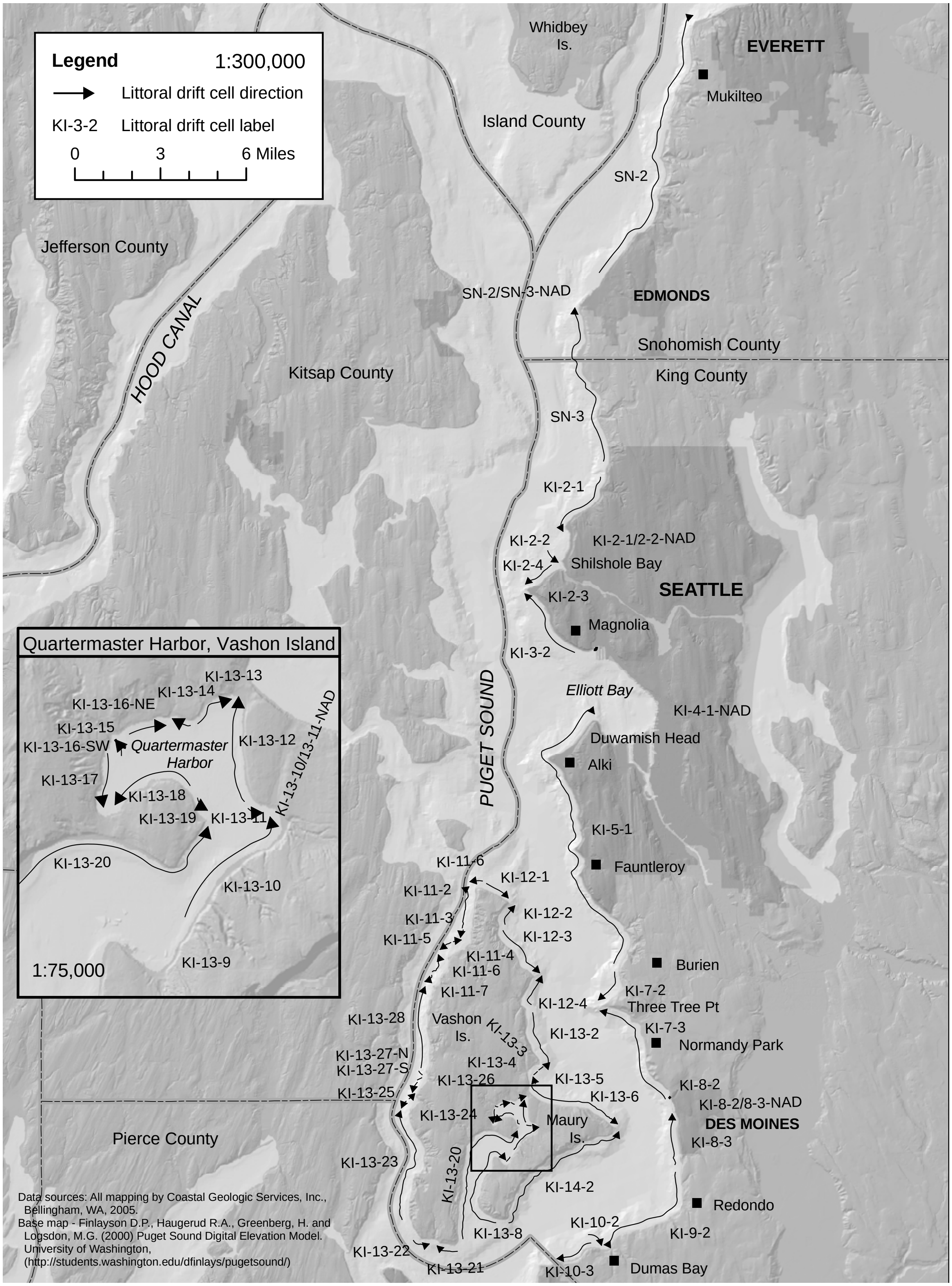

Figure 1. King County and southern Snohomish County study area, showing littoral cells and places described this paper.

Geomorphic based mapping of littoral cells has been widely accepted and used in Puget Sound studies, and littoral cells comprised the basic unit for the recently completed shore typology "change analysis" completed for the Puget Sound Nearshore Ecosystem Restoration Project (PSNERP) and US Army Corps of Engineers (Simenstad and others, 2010). However, feeder bluff mapping differs from this recent typology mapping in that feeder bluffs define a landform specifically linked with a physical process—the delivery of new sediment to the littoral system. Feeder bluff mapping follows some of the same general geomorphic principles of littoral/net shore-drift mapping completed in Washington State. Examples of geomorphic indicators used in both net shore-drift mapping and feeder bluff mapping include the direction of spit progradation (Hunter and others, 1979), progressive change in bluff morphology and vegetation cover (McGreal, 1979), and alongshore sediment size gradation (Self, 1977). Less rigorous methods for feeder bluff mapping were developed by Bauer (1976) in Whatcom County in the 1970s. These data have been superseded by recent mapping by Coastal Geologic Services (Johannessen and Chase, 2005b).

The declining health of Pacific salmon and other species has been linked to habitat loss resulting from the proliferation of shore modification structures such as bulkheads. Bluff sediment input to littoral cells is critical to the integrity of nearshore habitats associated with beaches (MacDonald and others, 1994), such as tidal wetlands. However, detailed studies of bluff erosion rates, feeder bluff mapping, and littoral sediment budget work have been very limited in the complex Puget Sound region (Johannessen and MacLennan, 2007). Recent feeder bluff mapping was carried out to partially fill the data gap of accurate locations of feeder bluffs and related geomorphic shoretypes that has hindered restoration and conservation planning efforts to maintain physical processes. Additionally, most local shoreline management programs prohibit or substantially limit armoring of feeder bluffs, yet these areas were not even mapped for current conditions (Johannessen and Chase, 2005a). Detailed historic pre-development feeder bluff mapping also was lacking. The most detailed historic data source is the topographic (T-sheet) maps produced in the late 1800s by government surveyors (University of Washington, 2009, at http://riverhistory.ess.washington.edu/). However, when examined in detail, this map set highlighted only those areas that were the most obviously erosional. Also, bluff mapping was inconsistent from one T-sheet to the next, which further limited their use to map historic bluffs. Efforts to recreate historic conditions by relying heavily on T-sheets such as Simenstad and others (2010) did not result in an accurate representation of feeder bluffs. Hence, the studies discussed herein continue to be initiated county by county to allow for management and planning for protecting and restoring natural sediment processes. These local feeder bluff mapping results have been utilized by a wide variety of groups working in the Puget Sound nearshore, including counties, Native American Tribes, Marine Resource Committees (MRCs), Watershed Resources Inventory Areas (WRIAs), regional salmon enhancement groups and others.

We evaluated our method of mapping feeder bluffs to methods used in previous work by comparing results for a 44-mi section of shoreline on Whidbey Island (Johannessen and Chase, 2005a). The comparison revealed that mapped "eroding bluff" and "feeding" areas in the Coastal Zone Atlas of Washington (Washington Department of Ecology, 1979) agreed very poorly with those determined by other methods (as also pointed out by Keuler, 1988). Mapping at the coarse scale of 1:100,000 by Keuler (1988) did not capture many shorter feeder bluff segments and the study results did not fully agree with the new data (Johannessen and Chase, 2005a). A different unpublished comparative analysis examined how the occurrence of littoral cell "divergence zones" (areas contributing sediment to two adjacent littoral cells; Schwartz and others, 1991) matched mapped feeder bluffs in the same Whidbey Island area. That analysis revealed that divergence zones generally were within mapped feeder bluffs, but accounted for only 24 percent of mapped feeder bluffs.

Feeder Bluff Mapping in King and Southern Snohomish Counties

Feeder bluff mapping within Water Resources Inventory Areas (WRIA) 8 and 9 was funded by the King County Department of Natural Resources and Parks in order to provide process-based data and analysis for the Puget Sound shore (Johannessen and others, 2005). The study entailed field mapping to document the current geomorphic conditions within the study area (fig. 1), followed by research into the historic condition of all currently modified shores within this mostly urban marine environment. Detailed mapping of feeder bluff and accretion shoreforms was carried out for both current and historic conditions at 1:24,000 scale for the approximately 121 lineal mi of the King County and southern Snohomish County study area.

Mapping Current Conditions

Specific mapping rules for feeder bluff delineation were developed by an advisory board that contained U.S. Geological Survey coastal and upland mappers, the Washington Department of Ecology coastal geologist, and Coastal Geologic Services (CGS) for one of the first modern feeder bluff mapping projects (Johannessen and Chase, 2005a). Field personnel working from a small boat throughout the King County and southern Snohomish County study area assigned segments of the shore to one of six different shoretypes on the basis of geomorphic evidence, as defined below and summarized in table 1.

Table 1. Mapping criteria for geomorphic shoretypes.

[Developed from Johannessen and Chase 2005a]

Presence of (priority in order)	Absence of
Feeder Bluff Exceptional (FBE)	
1. Bluff/ bank 2. Recent landslide scarps 3. Bluff toe erosion 4. Abundant sand/gravel in bluff 5. Colluvium/ slide debris 6. Primarily unvegetated or vegetated slumps 7. Trees across beach 8. Boulder/ cobble lag 9. Steep bluff (relative alongshore)	1. Shoreline bulkhead/ fill 2. Backshore 3. Old/ rotten logs 4. Coniferous bluff veg.
Feeder Bluff (FB)	
1. Bluff/ bank 2. Past landslide scarps 3. Intermittent toe erosion 4. Moderate amount sand/gravel in bluff 5. Intermittent Colluvium 6. Minimal vegetation 7. Trees across beach 8. Boulder/ cobble lag 9. Steep bluff (relative alongshore)	1. Shoreline bulkhead/ fill 2. Backshore 3. Old/ rotten logs 4. Coniferous bluff veg.
Transport Zone (TZ)	
1. Coniferous bluff vegetation 2. Apparent relative bluff stability 3. Gentle slope bluff (relative alongshore) 4. Unbulkheaded transport zone adjacent 5. Bulkhead may be present	1. Visible landslide scarps 2. Toe erosion 3. Backshore & backshore vegetation 4. Old/ rotten logs 5. Colluvium 6. Trees across beach 7. Bulkhead may be absent
Modified (MOD or MOD-BNSF)	
1. Bluff/ bank 2. Shoreline bulkhead (mostly intact) 3. Substantial shoreline fill	1. Backshore & backshore vegetation 2. Lagoon/ wetland/ marsh behind berm 3. Backshore “platform” 4. Old/ rotten logs 5. Fine, well-sorted sediment (relative alongshore)
Accretion Shoreform (AS)	
1. Backshore & backshore vegetation 2. Lagoon/ wetland/ marsh behind berm 3. Backshore “platform” 4. Old/ rotten logs 5. Fine, well-sorted sediment (relative alongshore)	1. Bank/ bluff in backshore 2. Toe erosion at bank 3. Landslide scarps 4. Boulders on beachface
No Appreciable Drift (NAD)	
1. NAD mapping (WWU-Ecology) 2. Embayment/ lagoon shore 3. Low wave energy	1. Active beachface 2. Accretion shoreform indicators

The **Feeder Bluff Exceptional (FBE)** classification was applied to bluff segments that were experiencing relatively rapid erosion/mass wasting (table 1, fig. 2). The **Feeder Bluff (FB)** classification was used for areas that had moderate erosion/mass wasting and sediment input into the littoral drift system. Feeder Bluff segments identified areas with a longer recurrence interval of sediment input as compared to Feeder Bluff Exceptional segments. **Transport Zone (TZ)** segments represented areas that did not appear to be contributing appreciable amounts of sediment to the system (not feeder bluffs) or showed evidence of past long-term accretion (not accretion shoreforms) and littoral sediment was generally transported alongshore. The **Modified (MOD)** classification was used to designate areas that had shoreline armoring (most commonly residential bulkheads) or that were otherwise altered by the modification such that the bank no longer provided sediment input to the beach system. The **Modified-by BNSF RR (MOD-BNSF)** classification was used to designate segments that had been altered specifically by the Burlington Northern Santa Fe railroad (BNSF) seawall. The **Accretion Shoreform (AS)** classification identified areas that were depositional in the past or present such as spits or broad no-bank deposits. The **No Appreciable Drift (NAD)** classification was used in areas where there was no appreciable net volume of sediment being transported, following the methods developed by Schwartz and others (1991).

Recent bank toe erosion and landsliding were mapped as ancillary data within/across these six different shoretypes. Sources of significant freshwater input, including seeps, springs, creeks and outfalls were also mapped and coded, and the approximate size of outfalls was noted. All features were mapped by using a GPS unit from a small boat at high tides, under conditions of good visibility. These methods were consistently applied in other study areas, although not all other areas mapped included historic analyses.

Figure 2. Examples of geomorphic shoretypes in the Puget Sound area. Mapping criteria are provided in table 1.

Figure 2.—Continued

Figure 2.—Continued

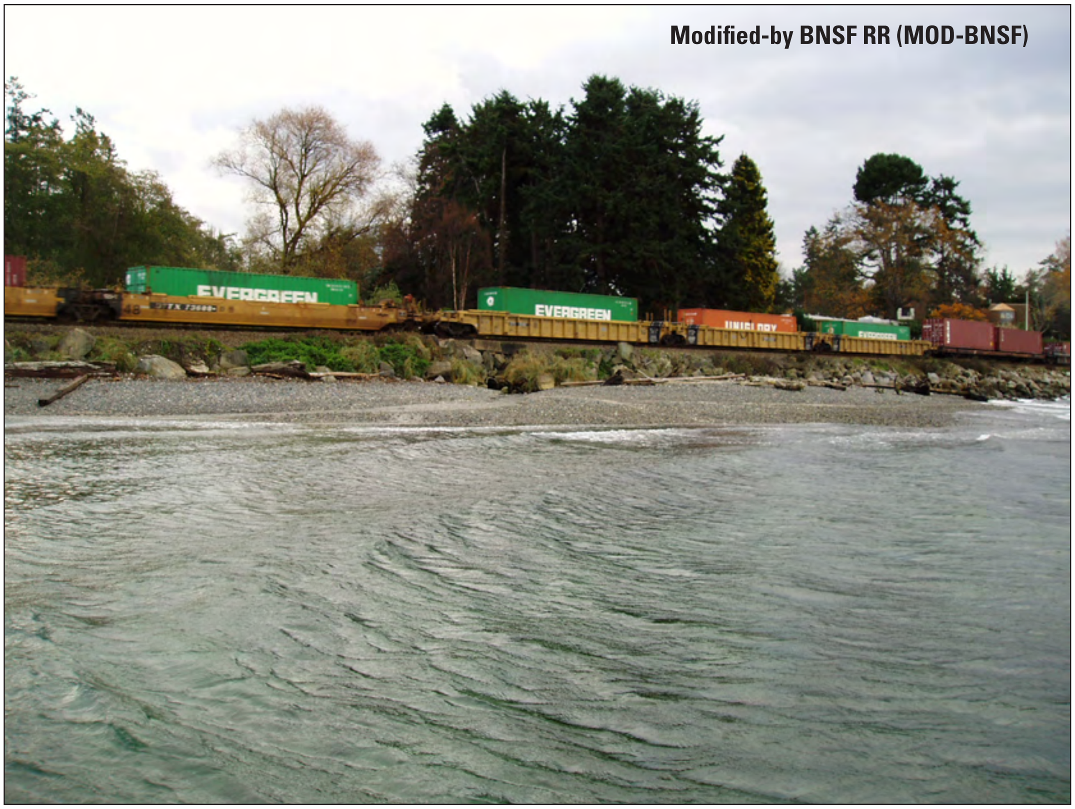

Figure 2.—Continued

Mapping Historic Conditions

Classification of historic sediment sources was conducted using historic information. Each segment of shore classified as "modified" in the current conditions mapping was scored using an index developed by Coastal Geologic Services, which required investigation of reach topography, surface geology, known landslide history, landscape and littoral drift context, historic topographic (T-sheet) maps, and historic air photos (in stereo-pairs where available). The new index was termed the **Historic Sediment Source Index (HSSI)**. Because of limitations in the pre-1930s data, a complete mapping of historic shoretypes to the accuracy of current conditions mapping was not possible; therefore the current conditions mapping was used as a starting point for historic sediment source mapping. Each shore segment was scored with an index that conveyed the relative likelihood that the segment was a feeder bluff (table 2). Full methods are described in Johannessen and others (2005). Historic shore segments were classified as Feeder Bluff Exceptional, Feeder Bluff, Potential Feeder Bluff, and Not Feeder Bluff based on the score of each modified segment. All areas characterized as Modified or Modified-by BNSF RR in the current conditions mapping were analyzed in detail to determine their historic character. All other segments mapped were assumed to be unchanged between historic to current periods. Most, but not all, datasets covered the entire study area.

The heavily modified shores of Elliott Bay (Seattle) were developed prior to much of the available mapping and presented a challenge as little data was available that would describe the pre-development geomorphic character. Therefore, additional supporting data were utilized for Elliott Bay, including historic drawings and maps, engineering drawings, text documents (reports and records), and historic vertical air and ground photos. Historic Accretion Shoreform mapping was conducted using slightly different methods, which consisted largely of traditional geomorphic air photo interpretation (1936–1948 photos) along with historic T-sheet maps, and interpretation of T-sheets based on surveyor's notes (Collins and Sheikh, 2005). Geologic maps (1:100,000 and 1:24,000, where available), and topographic quadrangles (1:24,000) were used to corroborate interpretation of the T-sheets and aerial photos. Historic accretion shoreform methods are not covered here but are found in Johannessen and others (2005).

Table 2. Historic sediment source index (HSSI) scoring criteria.

[From Johannessen and others, 2005]

Score	Question	Source
0-2-4-6	Relative fetch: longest fetch distance measured in GIS (0=0-<5 mi., 2=5-<10, 4=10-<15-, 6=15+) .	USGS 7.5-minute topo maps, DNR shoreline
0-3-6-9-12	Typical bluff height. First contour must be within 100 ft of Shorezone shoreline 0=0-80 ft, 3=81-120, 6=121-160, 9=161-200, 12=200+ ft.	USGS 7.5-minute topo maps
0-6	Surface Geology: dominant unit in segment. Unit scores reflect relative quantity of beach-forming material (coarse sand and gravel). 6=Qva; 3=Qls, Qsgo; 2=Qpom, Qtb, Qob, Qvt , 0=Other units	WADNR-Geology
10	Mapped as Rocky/Eroding/Bluff in T-sheet interpretations by Collins and Sheikh	Collins and Sheikh, 2005, University of Washington, Rivers History Group
10	1936/47 visual evidence of eroding bluff; including slides, slumping, scarps, trees in intertidal etc.?	Walker and Assoc., KCDNR&P and Snohomish County air photos
5	Recent landslides within 500 ft of segment?	City of Seattle, KC DNR&P BNSF
5	Older slides (Qls or Uos) within 500 ft of segment?	Qls=DNR surface geology; Uos=DOE, CZ Atlas
5	Landslides mapped by CGS within 500 ft of segment?	CGS current conditions mapping
5	Adjacent to Feeder Bluff in CGS current conditions mapping; or Historic Feeder Bluffs?	CGS current conditions mapping
2	Within 500 ft of divergent zone?	DOE with CGS edits, WA net shore drift
2	Within 1,500 ft of divergent zone?	Net shore drift mapping by DOE (with CGS edits)
1	Absence of low elevation backshore?	USGS 7.5-minute topo

Results of Current Conditions Mapping

A total of 858 individual shoreline segments were delineated for the study area (table 3), based on 1:24,000 mapping according to the rules described above (Johannessen and others, 2005). An example of mapping in a small portion of King County is shown in figure 3. The total length of modified shore was far greater than any other shoretype, representing 45.6 percent of the total study area length. In addition, the BNSF railway line and seawall north of Shilshole was mapped separately. “Modified-by BNSF RR” was the dominant mapped feature of the WRIA 8 portion of the study area, as it comprised an additional 13.4 percent of the entire study area shore. Cumulatively, modified shores (including those along Accretion Shoreforms (9.9 percent of the study area) and those along the BNSF railway) comprised 69 percent of the study area shore length. Only three drift cells in the study area remain completely unmodified.

Feeder Bluff Exceptional segments (highest sediment input into the nearshore) represented 3.3 percent of the study area and were mapped in only 29 individual segments in 10 drift cells under current conditions mapping (including Magnolia Bluffs, Maury Island, and southwest Vashon Island). Feeder Bluff segments were mapped along 15.1 percent of the study area shore cumulatively (table 3). Twenty-two drift cells (of 61 total cells and NAD areas mapped) had no intact sediment sources as a result of armoring. These represent a substantial number of drift cells generally considered as not properly functioning. Feeder Bluffs were more prevalent along the shores of Vashon and Maury islands as a result of a lesser extent of modification. Transport zone segments were mapped along only 4.1 percent of the study area (table 3) shore likely a result of the overall sediment-starved nature of most drift cells in the study area.

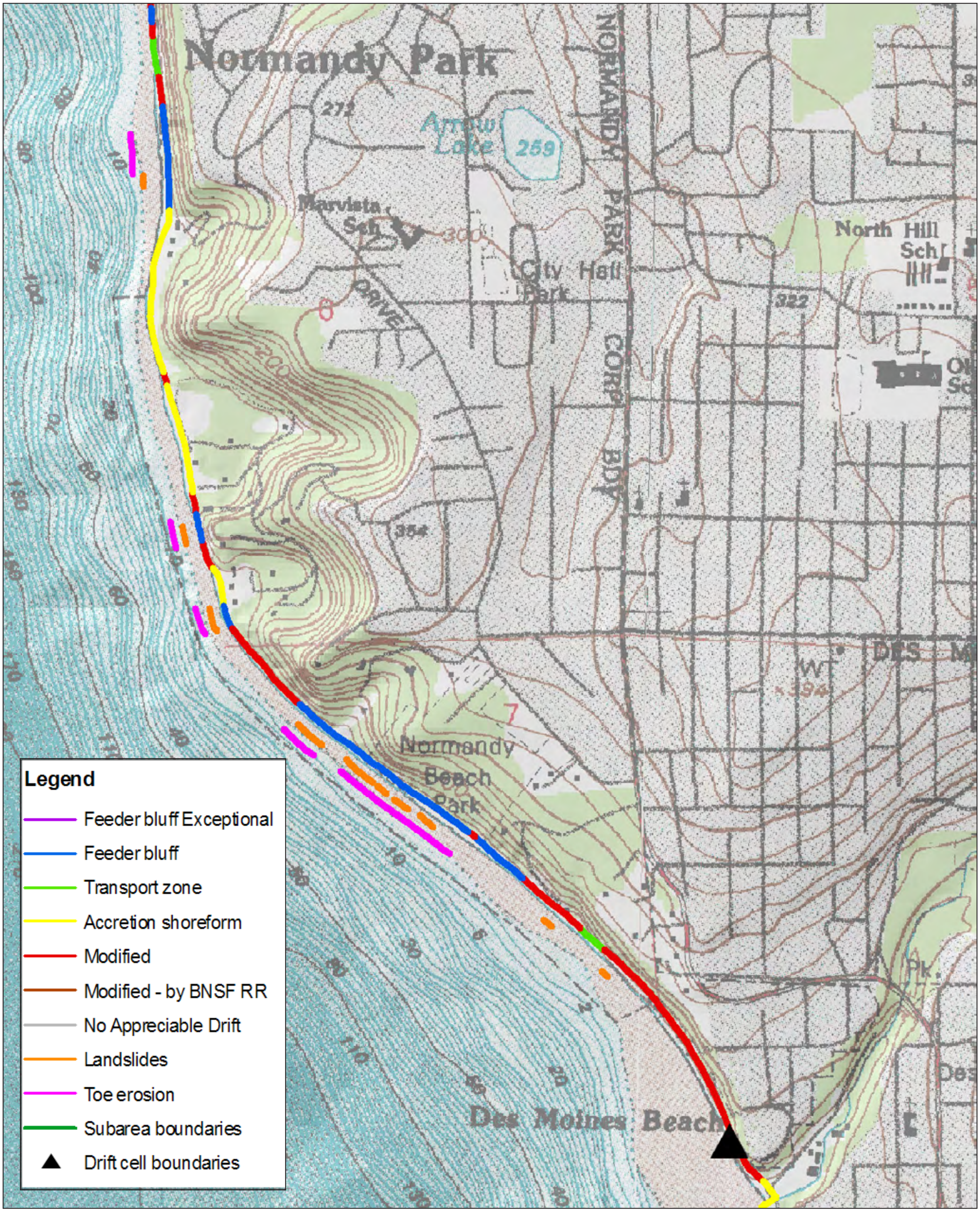

Figure 3. Example of current conditions mapping from Normandy Park in southern King County, Washington.

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Table 3. Coastal Geologic Services current conditions mapping summary for Watershed Resource Inventory Area 8-9 study area.

Shoretype	Number of segments	Length (feet)			Percentage of study area
		Minimum	Maximum	Mean	
Feeder Bluff Exceptional	29	61	2,861	709	3.3
Feeder Bluff	184	23	3,560	517	15.1
Transport Zone	95	19	1,808	274	4.1
Accretion Shoreform	247	55	2,930	473	18.5
Modified	287	21	29,986	1,004	45.6
Modified - RR	16	829	17,247	5,293	13.4

Mapped recent landslides most commonly occurred along the steep bluffs of Vashon and Maury Islands and in smaller high bluffs on the mainland, such as Magnolia and north of Des Moines (figs. 1 and 3). Extensive bulkheads, revetments, and fill along much of the mainland shore generally limited the occurrence of recent slides. The cluster of recent slides within the BNSF railroad revetment area, however, suggests that bluffs remain unstable and are subject to mass wasting, even though these bluffs have been bulkheaded for approximately 110 years. Mass wasting in this area is commonly triggered by saturated soils and seepage pressure (Tubbs, 1974; Baum and others, 2000). Slides occasionally occurred at other armored areas, with colluvium extending over bulkheads. Recent bluff toe erosion was mapped at numerous unarmored shores on the mainland. On the islands, recent toe erosion was fairly common on the west and east sides of Maury Island, and along the southwest and northwest shores of Vashon Island.

Results of Historic Conditions Mapping

Comparison of current conditions to historic conditions mapping revealed that widespread and far-reaching changes have occurred to the study area coast, altering geomorphic processes in numerous ways (Johannessen and others, 2005). An example of landslide datasets and historic mapping results for a section of the BNSF rail subarea is shown in figure 4. Historic analysis (combined with current conditions mapping) revealed that the most common shoretype mapped in pre-development conditions was Historic Feeder Bluff (table 4). Total historic sediment sources (Historic Feeder Bluff, plus Historic Feeder Bluff Exceptional) comprised one-half of the study area shoreline, as compared to only 18.4 percent in current conditions mapping. *Potential* Historic Feeder Bluffs were not counted as sediment sources because of the ambiguity of the data. When comparing current to historic sediment sources, there was a 63.4 percent loss for the entire study area, leaving only 36.6 percent of the historic sediment sources currently intact.

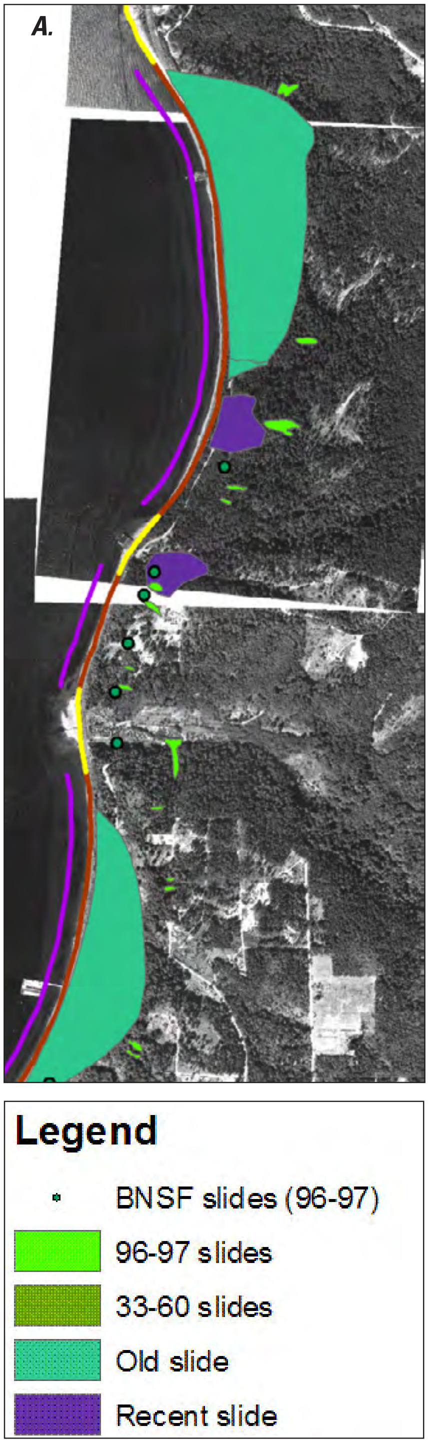
Historic Accretion Shoreform mapping was performed independently from the HSSI analysis of modified segments (Johannessen and others, 2005). Historic Accretion Shoreforms were mapped along almost 40 mi of the shore (33.2 percent). This was far more than the approximately 22 mi mapped during current conditions fieldwork. Detailed analysis and description of Historic Accretion Shoreforms is not included here because of the quantity and complexity of these features, but this information is found in Johannessen and others (2005).

Table 4. CGS current conditions mapping summary for WRIA 8-9 study area.

Shore segment	Total length (feet)	Approximate percentage of study area
Historic Feeder Bluff Exceptional	95,019	15.0
Historic Feeder Bluff	223,055	35.3
Potential Historic Feeder Bluff	54,555	8.6
Historic Transport Zone*	207,608	32.9**
Historic Accretion Shoreform**	209,842	33.2**

* Historic transport zone, Current Transport Zone segments + Historic Not Feeder Bluff.

** Percentages of current Shorezone shoreline length are greater than 100 percent as accretion shoreform mapping used different methods and historic accretion shoreforms and bluff/modified units mapping had some overlap.



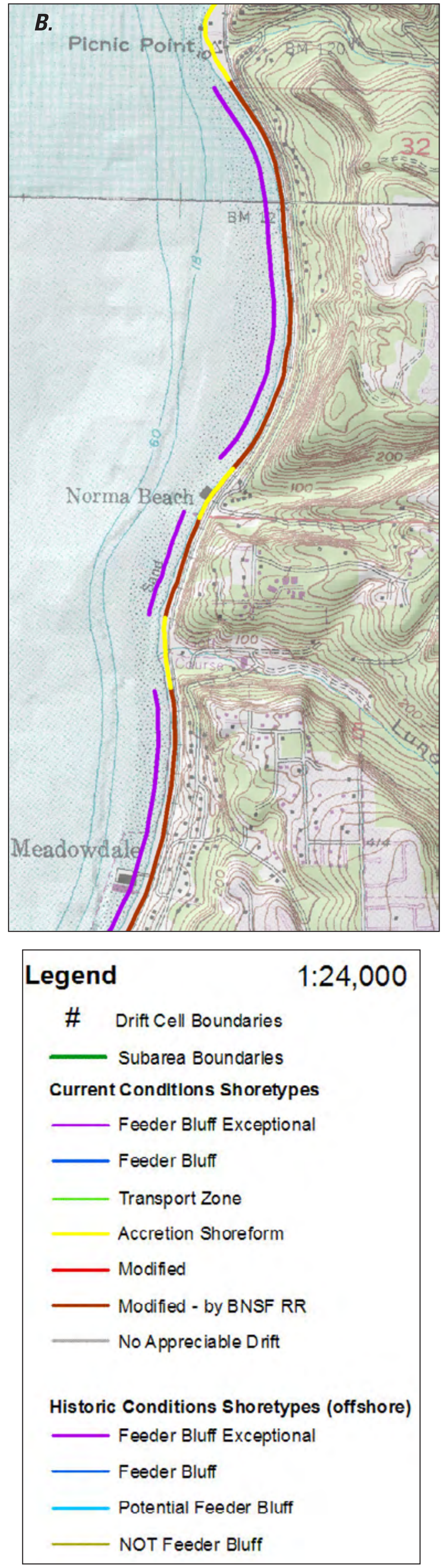


Figure 4. Comparison of landslide map (*A*) with feeder bluff map (*B*) developed in this study for a portion of the BNSF railroad line in southern Snohomish County. Current conditions are mapped at the shoreline whereas historic conditions are shown slightly offshore.

Restoration and Conservation Prioritization

Following the completion of current and historic conditions mapping, a study-area-wide prioritization of all potential restoration and conservation sites was performed at the segment, drift cell, and landscape scales. In each case historic and current Feeder Bluff and Feeder Bluff Exceptional segments were scored using the HSSI to determine the relative value of each segment as a source of littoral sediment. Drift cells were ranked by calculating the percent of intact sediment sources (relative to historic conditions) in the drift cell, and then weighting that number by the score(s) of the individual current and historic sediment source segments that make up that drift cell, as show below:

$$\text{Score} = \frac{\begin{array}{c}(\text{HFB score} * \%\ \text{HFB of total pre-dev.sed source})\\ +(\text{CFB score of total pre-dev.sed source})\end{array}}{(\text{CBC score} * \%\ \text{of total pre-dev.sed source})}$$

where CFB=Current Feeder Bluff, HFB=Historic Feeder Bluff. This prioritization was solely based on mapped geomorphic shoretypes and this work did not evaluate biological values. The value of the data for conservation and restoration prioritization could be enhanced by incorporating biological data.

The first prioritization approach ranked Historic Feeder Bluff segments for restoration potential. Highest priority segments were widely distributed, but the highest ranked segments were most abundant at high elevation bluffs in the BNSF railway area (fig. 5). Additional clusters of high priority bluff restoration segments were found at Magnolia Bluffs, between Normandy Park and Des Moines, and at the entrance to Quartermaster Harbor on Vashon Island (fig. 1). Drift cells of the highest priority for restoration were found along the entire Northern Railroad and Shilshole subareas. Additional drift cells of the highest priority include cell KI-7-2, located on the north side of Three Tree Point and cells KI-13-17 and KI-13-18 in Quartermaster Harbor.

The second prioritization approach compared HSSI segment scores and listed the top three scoring segments within each drift cell. This method of examining restoration and conservation potential is useful for drift cells where sediment supply is deemed critical locally, without relying on the total potential yield of particular bluff segments area-wide. This may be the case where estuaries are lost or threatened as a result of sediment supply in low wave energy environments. The third prioritization approach summarized and scored data for entire drift cells and compared the scores across the study area. Results of the restoration prioritization indicate that drift cells with the highest priority for restoration were found along the entire Northern Railroad and Shilshole subareas (fig. 1). Additional drift cells of the highest restoration priority include cell KI-7-2, located on the northern side of Three Tree Point and cells KI-13-17 and KI-13-18 in Quartermaster Harbor (fig. 6).

The results of the conservation prioritization of drift cells show that as a result of pervasive modifications, largely from the BNSF railway, cells with conservation potential were primarily in King County/WRIA 9. Drift cells with the highest conservation prioritization include cells KI-7-2 on northern side of Three Tree Point, and KI-13-18 in Quartermaster Harbor (fig. 1). Other high priority drift cells for conservation included southwest Shilshole Bay, east Vashon Island (cell 13-12), and the Burien to Duwamish Head cell as a result of the rarity of existing high-quality feeder bluff segments there.

Puget Sound Regional Feeder Bluff Mapping Synthesis

Current conditions mapping has now been completed for more than 800 mi of Puget Sound shore. Historic conditions mapping has been completed for more than 335 mi of Puget Sound shore, most recently along Bainbridge Island, most of northwest Skagit County, and in San Juan County. Historic conditions were recently mapped from Point Defiance to the Nisqually Delta. The Washington Department of Ecology is seeking funding to complete the data set Sound-wide.

Synthesis of all feeder bluff mapping data collected to date reveals the general status of Puget Sound bluffs and beaches. Data from 99 drift cells covering approximately 250 mi of shore is summarized here. Historic sediment sources were mapped over a cumulative length of 93 mi, with 42 mi currently remaining as feeder bluffs. This equated to a 55 percent loss of bluff-derived sediment sources. The average proportion of drift cells mapped as sediment sources dropped from 37 percent historically to 20 percent currently. Of the 99 drift cells, 14 drift cells no longer had any intact nearshore sediment sources, 29 drift cells had lost 50 percent of more of the (linear extent) of historic sediment sources, 23 drift cells had lost 1–50 percent of the (linear extent) of historic sediment sources, and 33 drift cells had not incurred a loss of nearshore sediment sources.

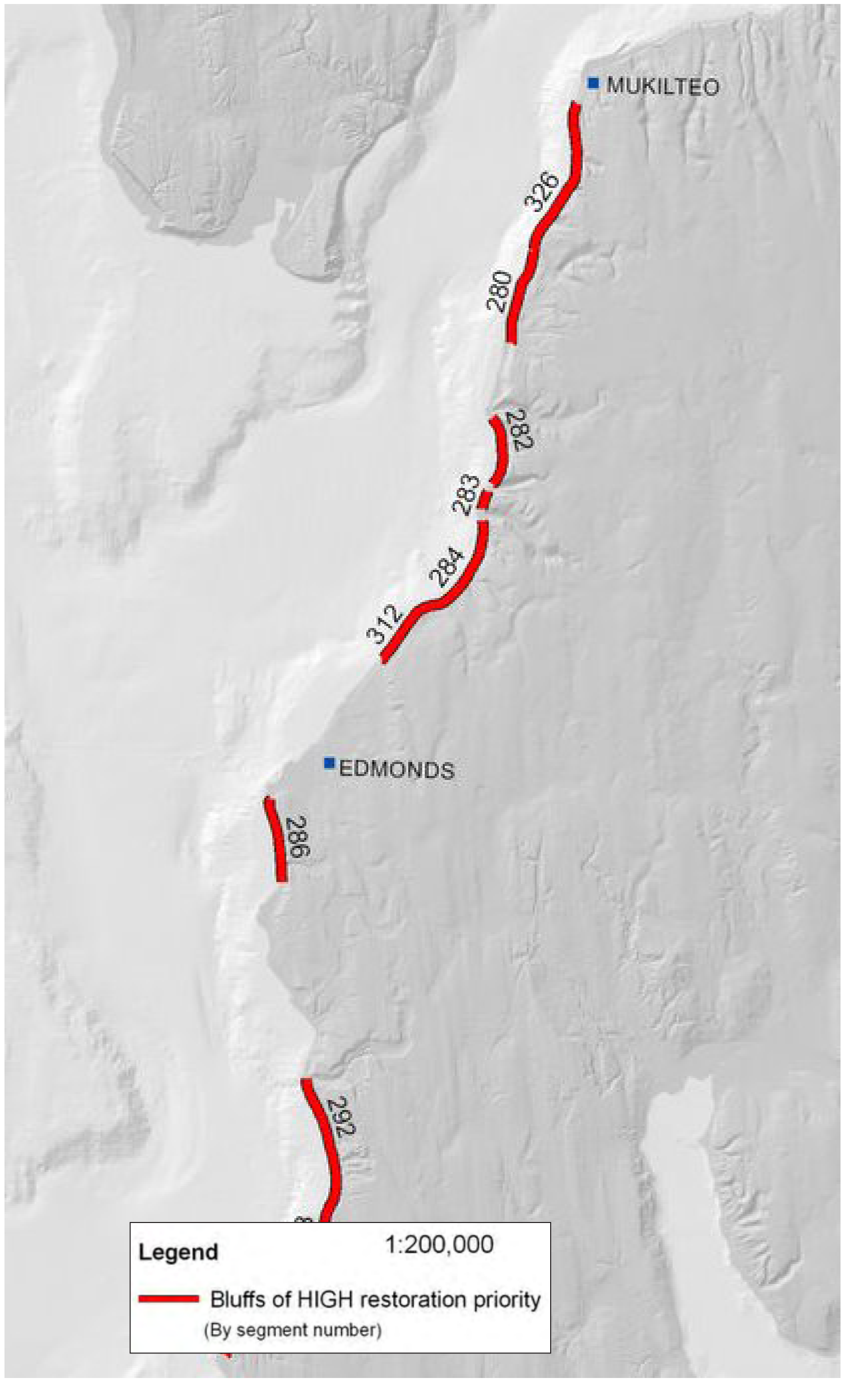
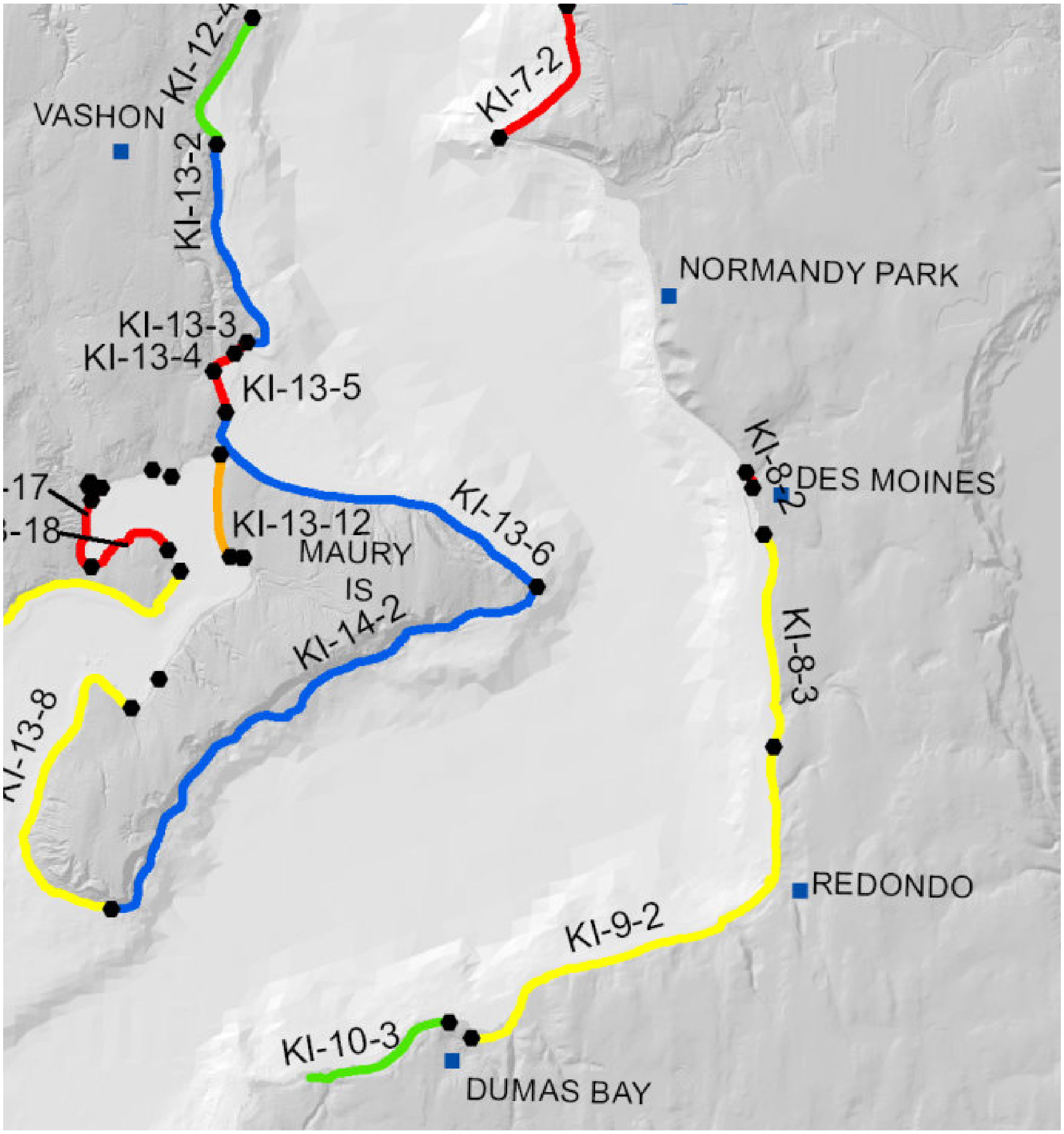


Figure 5. Example of restoration prioritization by segment in southern Snohomish County.



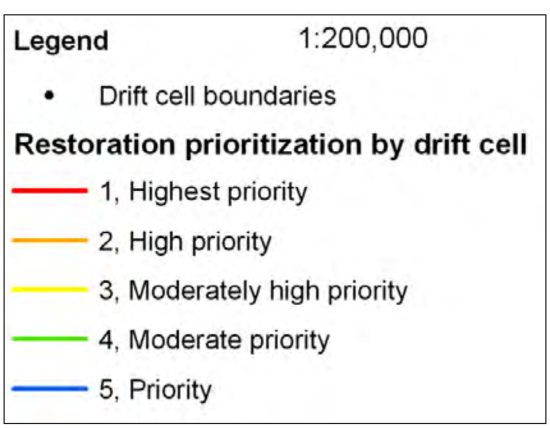


Figure 6. Example of restoration prioritization by drift cell in southern King County.

Summary and Discussion

Feeder bluffs refer to eroding bluffs that provide significant sediment to Puget Sound beaches and littoral cells (Bauer, 1976). Shore modifications such as bulkheads and fill have substantially changed Puget Sound sediment supply and nearshore habitats. Feeder bluffs were mapped in King and southern Snohomish counties for current conditions using field-based mapping rules based on Johannessen and Chase (2005a) and for historic conditions using a new Historic Sediment Source Index (HSSI) developed for the 121 mile coast of the Central Puget Sound study area (Johannessen and others 2005).

The total length of modified (armored residential/commercial shores) shore in the King County and Snohomish County study area was far greater than any other segment, representing 45.6 percent of the total study area length. In addition, the BNSF railway line and seawall north of the Shilshole comprised an additional 13.4 percent of the shore (Johannessen and others 2005). Twenty-two drift cells (of 61 total cells) currently have no intact sediment sources. When comparing current to historic feeder bluff mapping, there was a 63.4 percent loss of feeder bluff length over the entire study area, leaving only 36.6 percent of the historic sediment sources currently intact. This trend likely has lead to significant impacts such as increased shoreline erosion and a loss of beach and nearshore habitat area.

Feeder bluff mapping was completed to allow for in-depth prioritizing and planning for strategic protection of sediment supply (conservation) and for shoreline armor removal (restoration) to protect and restore self-sustaining physical processes, which then create and sustain valued nearshore habitats. By using the current and historic feeder bluff mapping in a GIS, a framework was developed for setting shoreline habitat conservation and restoration priorities based on sediment supply. This is the single most important process for maintaining, enhancing, or restoring nearshore habitat.

An example of restoration actions that apply feeder bluff data is the removal of shore armoring at important historic feeder bluffs (Clancy and others, 2009). Several of these efforts are underway at present, such as a bulkhead removal at the top scoring feeder bluff segment in King County. Beach enhancement efforts are underway as a direct result of feeder bluff mapping, including a large beach nourishment being designed for the east shore of Fidalgo Bay in Skagit County and several beach nourishment projects underway or about to begin along the BNSF railroad grade in Snohomish and Pierce counties. A number of smaller restoration projects have been identified as a result of the mapping and are working their way through the design and permit phases in Island and San Juan Counties. Feeder bluff data is being used for restoration planning in Skagit, Island, and San Juan Counties, with emphasis on sediment supply for estuaries.

As the majority of Puget Sound shores are in private ownership, and unmodified bluffs will gradually recede through erosion and landsliding, there likely will be a continued desire for landowners to build bulkheads. If carried out, this would lead to further sediment impoundment and further reduction of the natural sediment input to the nearshore system, as well as site-specific impacts to beaches. The possibility of further decreasing sediment supply for littoral cells along with the lag time of impacts from past modifications would likely lead to substantially-increased negative, cumulative impacts to nearshore habitats.

Aside from restoration, practical application of the data includes attempting to minimize additional long-term negative impacts to nearshore habitats by preserving the function of sediment source bluffs. This is occurring in the form of denial of permit applications by local jurisdictions based on existing codes and new feeder bluff mapping, and also by acquisition by NGOs. As an example of management that likely will become more common in the future, moving houses landward may be the only means to both preserve habitat and allow for preservation of houses in coming decades with predicted sea level rise (Clancy and others, 2009). Conservation actions underway that utilize feeder bluff data include acquisition of high priority feeder bluff parcels, such as those with high volume sediment input that are located near the origin of long littoral cells and/or those cells with critical habitats. Implementation of bluff sediment supply restoration and conservation has begun in the Puget Sound region but certainly will have to be accelerated for reactivation of physical processes to improve nearshore habitats. Completing the feeder bluff dataset Sound-wide would allow for systematic restoration and conservation planning across the region.

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Beach Processes and Ecological Response

Kelp and eelgrass on a rocky beach in northern Puget Sound. Photograph taken by Hugh Shipman, Washington Department of Ecology.

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Biological Effects of Shoreline Armoring in Puget Sound: Past Studies and Future Directions for Science

Casimir A. Rice[1]

Abstract. Human alteration of Puget Sound shorelines is extensive yet its biological consequences are largely unknown, in part because research and monitoring of the Puget Sound ecosystem (1) has usually not included anthropogenic disturbances such as shoreline armoring as explicit factors in sampling design and data analysis, (2) tends to not make direct measures of biological condition a top priority, and (3) has rarely sampled across the full range of natural physical and biological conditions within the system. Several recent site- and local-scale field studies have documented differences between modified and more natural beaches in terms of several biological attributes (for example, spatial extent and patch size of eelgrass; supratidal invertebrate abundance and assemblage composition; embryo condition of intertidally spawning fish; and taxonomic composition, size, behavior and diet in fish assemblages). Many of these results are equivocal and no large-scale biological field studies have resolved the uncertainty. However, combination and reanalysis of bird survey and shoreline attribute monitoring data from all of greater Puget Sound illustrate the value of landscape-scale studies focusing explicitly on biological responses to human influence across a range of natural ecological gradients (for example, season, year, oceanographic sub-basin, shoreform). Changes in the taxonomic composition of marine bird and waterfowl assemblages were related to urban land cover gradients along Puget Sound shorelines throughout greater Puget Sound, although specific effects of armoring itself were not detected. Together these studies demonstrate that armoring of Puget Sound shorelines affects abiotic attributes (for example, physical structure and microclimate), can adversely affect the biota at local scales, and suggest the potential for Sound-wide changes in biology as a result of shoreline armoring. But the cumulative, population and ecosystem level effects of armoring remain understudied and unknown. Expanded, systematic field studies that characterize biological attributes across a range of armoring, other anthropogenic disturbances, and natural ecological conditions (for example, geomorphology, exposure, landscape position) are necessary to improve our understanding and management of the biological effects of shoreline armoring in Puget Sound. Only one such study is planned for central Puget Sound but others increasingly are being proposed.

Introduction

Puget Sound is a large and ecologically diverse and dynamic fjord estuary system that has undergone major physical and biological transformation as a result of human activity (Bortleson and others, 1980; Collins and Sheikh, 2005; Ruckleshaus and McClure, 2007; Rice, 2007; Simenstad and others, 2010). At the interface between terrestrial and aquatic, and salt and freshwater environments, Puget Sound shorelines are a unique ecotone that is home to many species during at least part of their lives (Brennan and Culverwell, 2004). These include taxa that are the focus of considerable management, regulatory, and conservation concern: eelgrass (*Zostera marina)*, a dominant feature of the biota that provides habitat for many other species and significant detrital input to Puget Sound food webs; ESA-listed Puget Sound Chinook salmon (*Oncorhynchus tshawytscha*) and summer chum salmon (*O. keta*) that use estuarine shorelines for extended rearing as juveniles (Simenstad and others, 1982; Beamer and others, 2005); the small pelagic fishes (Pacific herring [*Clupea pallasii pallasii*], surf smelt [*Hypomesus pretiosus*], and sand lance [*Ammodytes hexapterus*]), all of which spawn on intertidal or subtidal Puget Sound shorelines (Penttila, 1995) and likely play key roles in the Puget Sound ecosystem as mid-level consumers and as prey for many species (Rice, 2007); and marine birds and waterfowl, several of which have undergone significant population declines in recent decades (Puget Sound Action Team, 2007).

Shoreline armoring is one of the more conspicuous and prevalent disturbances across the Puget Sound landscape (see Carman and Taylor, 2010), often cited as an important factor contributing to perceived declines in biological condition (Thom and Hallum, 1991; Thom and others, 1994; Ruckelshaus and McClure, 2007), yet few studies

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of its ecological consequences have been done, and still fewer conclusive data are available. This is consistent with the broader pattern in Puget Sound science of both limited biological monitoring and assessment in estuarine environments, and omission of anthropogenic stressors in sampling design and data analysis (Rice, 2007). Relying on random selection of sample locations in field studies, for example, is unlikely to encounter a representative range of anthropogenic disturbance simply because those disturbances are not randomly distributed.

With the partial exception of toxicology studies (see Puget Sound Action Team, 2007, and Rice, 2007, and references therein), biological monitoring in Puget Sound typically consists of tracking trends of single species abundance over time rather than evaluating the character of the biota along explicit human influence gradients. That is, we tend to ask, “How much is there and how is that changing over time?” rather than “What is out there and how does it reflect the various dimensions and degrees of human activity?” (Rice, 2007). Addressing this second type of question is critical for effective monitoring and assessment (Karr, 2006). Foundational studies (for example, Miller and others, 1980; Long, 1982) documenting the character of shoreline biota across natural ecological gradients are also rare and dated (but see Dethier and Schoch, 2005).

In addition to these common problems of focus and approach, the study of the biological effects of shoreline armoring presents considerable practical difficulties because of the heterogeneous and dynamic nature of shoreline environments, and the myriad combinations of material, elevation, and age of armored structures across diverse natural ecological contexts such as geomorphology, exposure, and landscape position (Williams and Thom, 2001; Simenstad and others, 2006). Extensive private ownership of shorelines in Washington State restricts access to shorelines and generates opposition to documenting adverse effects of armoring. Shoreline armoring also is typically one of many anthropogenic disturbances that often occur together; thus, isolating the effects (local and offsite) of armoring from a suite of individual stressors, evaluating its relative importance, and understanding cumulative effects at landscape and ecosystem scales is a major scientific challenge. All of these factors have slowed progress toward understanding the biological effects of shoreline armoring in Puget Sound.

The purpose of this paper is to briefly review the state of the science with respect to the biological effects of armoring in Puget Sound, including a summary of studies to date, and suggested directions for future research. Conceptual models of how shoreline armoring may affect coastal ecosystems in general, and the documented effects of armoring in systems outside of Puget Sound are reviewed elsewhere in this volume (for example, see Coyle and Dethier, 2010).

Puget Sound Studies

Several recent studies have addressed the biological effects of shoreline armoring within Puget Sound focusing on plants (Simenstad and others, 2008), invertebrates (Tonnes, 2008; Sobocinski, 2010), fishes (Rice, 2006; Toft and others, 2007; and see Toft and others, 2010), and birds (Rice, 2007). Although results are often equivocal, some clear patterns have emerged, and these studies provide useful foundation for future work by testing various methods, and by documenting biotic and abiotic attributes of armored and unarmored shorelines.

In a study of intertidal eelgrass landscape structure in Hood Canal and the eastern Strait of Juan de Fuca, Simenstad and others (2008) used extensively ground-truthed remote sensing to evaluate the spatial continuity and patch attributes of intertidal eelgrass across a range of natural and anthropogenic gradients, including drift cell position and shoreline armoring, respectively. Identifying relationships between the many potential effects proved complex. Natural beach geomorphology greatly affected eelgrass attributes, but extreme cases of shoreline armoring were identified as a potentially important effect on eelgrass landscape metrics. In addition, the authors suggest that their methods and approach may complement Sound-wide video transect surveys (Gaeckle and others, 2007), which are limited in their spatial resolution, and perhaps more importantly, do not factor in shoreline armoring or any other human influences in the sampling design.

Some of the clearest results documenting the biological effects of armoring have come from studies of supratidal invertebrates. Species richness and absolute abundance in benthic cores and fallout traps (compared between paired beaches) in central Puget Sound tended to be lower at the base of armored sites than on natural substrates (Sobocinski and others, 2010), but such differences were not apparent in a synoptic set of samples in the same study, possibly because of increased spatial variation in the synoptic versus paired samples, and the relatively high elevation of the bulkheads on the sites studied. This suggests that the extent of intertidal coverage of armoring is an important determinant of ecological effects. Armored beaches tend to have little or no wood, and less wrack, present on them (Tonnes, 2008; Sobocinski and others, 2010). Consequently, densities of talitrid amphipods, which are strongly related to the presence of driftwood and wrack (Tonnes, 2008), were orders of magnitude higher on unmodified than on modified beaches. One caveat to some of these results is the degree to which the armoring, or simply the removal of overhanging vegetation, affected the results (Rice, 2006; Tonnes, 2008).

Removal of armoring as part of ecological restoration actions seems to have beneficial effects on invertebrate assemblages. Ongoing monitoring of restoration projects at Olympic Sculpture Park and Seahurst Park in central Puget Sound (Toft 2009; Toft and others, 2008, and 2010) has documented, for example, increased taxa richness after armoring removal, and a convergence of assemblage composition on restored sites with that on unarmored reference sites. An expanded study of the Seahurst Park project that includes ten paired armored and unarmored sites will run from spring 2010 to winter 2013 (M. Dethier, oral commun., 2010).

Fish assemblage attributes associated with armoring in Puget Sound include changes in taxonomic composition, individual size distribution, behavior, and diet of fishes (Toft and others, 2007; Toft and others, 2010); and reductions in the abundance and condition of the embryos of surf smelt, a small pelagic fish that uses upper intertidal beaches to spawn (Rice, 2006). Changes in attributes of fish assemblages at armored sites seem to be related at least in part to beach slope and substrate type, and are more distinct the lower the armoring extends into the intertidal (Toft and others, 2007; 2010).

Because smelt embryos are affected by thermal and moisture conditions (Lee and Levings, 2007), microclimate conditions on the different beaches are the likely cause for the increased mortality on the altered beach, where, for example, summer substrate temperatures averaged nearly 5°C higher on the altered beach, and peak temperatures were 29°C on the altered beach versus 18°C on the natural beach. But while some site-level effects of shoreline modification in general are apparent, the degree to which the observed effects are specifically the result of armoring is less clear. Overhanging vegetation is commonly lost when a beach is armored and that loss likely is responsible for a significant portion of the changes in microclimatic (Rice, 2006; Tonnes, 2008) and biotic (Romanuk and Levings, 2003, 2006) conditions on armored beaches.

Moreover, because there is no evidence that Puget Sound fish populations are limited by shoreline rearing and spawning habitat (but see Beamer and others, 2005 for evidence of estuarine rearing habitat limitation in juvenile wild Chinook salmon), a better understanding of the population biology and status of Puget Sound fishes would be helpful in evaluating the true biological significance of shoreline armoring. For example, we have little information on the population status of most of the species potentially affected by shoreline armoring, let alone whether shoreline armoring is having a significant adverse effect on that status, or "how much" armoring it might take to be of serious concern. Better understanding of the physical attributes and spatial distribution of preferred spawning habitats of surf smelt, sand lance, and herring, and the relative importance of spawning habitat loss in the population dynamics of these species is a major knowledge gap.

In addition to these local- and site-level studies, a post-hoc analysis of aircraft-based marine bird surveys along shorelines provides an instructive example on how we might approach future research on armoring and other anthropogenic effects. Multiple populations of marine birds and waterfowl have undergone major declines in Puget Sound during recent decades (Puget Sound Action Team, 2007), presumably the result of many local and remote effects. Historical monitoring and assessment of these taxa did not attempt to relate changes in bird abundance or taxonomic composition to local environmental factors, including human influences such as the modification of shoreline ecosystems. The combination of aircraft-based bird census data with shoreline attribute data (Washington Department of Natural Resources, 2001), including land-cover data (Hepinstall-Cymerman and others, 2009), revealed that the taxonomic composition changes along anthropogenic gradients (Rice, 2007). For example, as the percentage of urban land cover alongshore increased, overall taxa richness declined, and the relative frequency of opportunistic and tolerant taxa such as large gulls, increased. Although no clear relationships between attributes of bird assemblages and shoreline armoring were apparent, this study demonstrates that, despite coarse lumping of disparate data sets across a large and heterogeneous natural landscape, relationships between integrative measures of biological condition and human activity can be detected, simply by framing the research question appropriately: that is, asking "What is out there and how does it reflect the various dimensions and degrees of human activity?" rather than just "How much is there and how is that changing over time?"

Conclusion

Despite widespread recognition of the potentially serious adverse biological effects of shoreline armoring, and several recent studies developing methods to study such effects and documenting impacts in Puget Sound, empirical evidence of biologically significant effects remains scarce, in part because of the lack of scientific studies focused explicitly on armoring effects, including underlying mechanisms. The study of the effects of shoreline armoring presents many challenges, but if our inferences about likely effects are correct, and armoring exists across over one third of the Puget Sound shoreline (Carman and Taylor, 2010), surely we should be able to detect those effects, and use that information to improve the understanding and management of Puget Sound ecosystems.

Several key efforts would be particularly informative:

- Conduct focused field studies on the biological and physicochemical character of armored and unarmored shorelines, alone and in combination with other anthropogenic disturbances. Subjects for biological response should include multispecies metrics in ecologically diverse taxa that are likely to be responsive to armoring, and amenable to scientific study. In addition to plants, supratidal invertebrates, fishes, and birds already mentioned here, consideration of effects on intertidal and subtidal infauna (see Dethier and Schoch, 2005, for an example of sampling methods and potential response variables) would be an informative focus. Because armoring effects may differ across the many local differences in, for example, substrate, exposure, shoreform, and landscape position, these studies should attempt to cover all major natural gradients. New shoreline typology (Shipman, 2008; McBride and others, 2009) and change analysis (McBride and others, 2005; Simenstad and others, 2010) can provide a useful basis for incorporating such factors into sampling design. Controlled, manipulative experiments such as restoration actions could provide invaluable insights into armoring effects and mechanisms.
- Seek opportunities to incorporate armoring and other forms of anthropogenic shoreline modification into existing monitoring and assessment programs such as those that are focused on vegetation (Gaeckle and others, 2007) and marine birds and waterfowl (Puget Sound Action Team, 2007).
- Improve our understanding of the population biology of key species of concern, such as small pelagic fishes. For example, characterizing physical attributes and spatial and temporal distribution of spawning habitats, and developing life cycle models for these species, would be useful tools in evaluating the true biological significance of shoreline armoring.

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Fish and Invertebrate Response to Shoreline Armoring and Restoration in Puget Sound

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Abstract. Puget Sound shorelines have been heavily modified, especially those associated with urban centers. Understanding the degree to which anthropogenic modifications affect nearshore fish and invertebrates, and how to best evaluate and enhance ecological functions, are key to restoring the health of Puget Sound and must be addressed by integrating science and management. The goals of this paper are (1) to summarize existing knowledge of armoring effects on shoreline biota, (2) to examine the ecological function of two case study restoration sites, and (3) to discuss the role of science in urban shoreline restoration and implications for management. Past research suggests that armoring removal could help restore shallow water ecosystems of nearshore intertidal beaches and re-connect aquatic and terrestrial realms. We present a synopsis of recent research, describing shoreline armoring removal and beach rehabilitation at the Olympic Sculpture Park (City of Seattle) and Seahurst Park (City of Burien). Riprap or seawalls at these sites were removed with the goal of enhancing shallow water habitats for juvenile Pacific salmon (predominantly Chinook and chum) whose populations are of special concern in Puget Sound. Results indicated that these sites showed ecological improvements compared to armored or pre-restored conditions, most noticeably in the intertidal elevation range where armoring was removed as compared to lower elevations affected only by beach regrading and sediment nourishment. Understanding such linkages between abiotic and biotic features of a beach ecosystem is vital to planning rehabilitation efforts along degraded shorelines, and will help guide the restoration of salmon habitat. Given the context and findings discussed in this paper, we advocate that science can be useful in restoration planning (1) prior to restoration in helping to define project goals, (2) during project design by incorporating data to optimize the likelihood of desirable ecological responses, and (3) after completion of restoration to illustrate successes and failures and allow for adaptive management.

Introduction

Shoreline modifications are prevalent in many aquatic systems worldwide, especially in urban areas dominated by humans. The effects of shoreline modifications on flora and fauna have recently expanded as a research topic, designed to help understand the impacts that shoreline developments have on the ecotone between aquatic and terrestrial realms (Chapman, 2003; Alberti and others, 2007; Toft and others, 2007; Bilkovic and Roggero, 2008; Defeo and others, 2009). An average of 27 percent of Puget Sound's natural shoreline is armored by retaining structures, increasing to approximately 65 percent near urban centers (Simenstad and others, 2010). Such structures usually consist of vertical seawalls and riprap boulder fields. The resulting changes along modified shorelines should be an important focus of research and management, and are key to understanding the current biotic health and potential for maintaining and restoring diverse shoreline ecosystems.

The workshop "Puget Sound Shorelines and the Impacts of Armoring: State of the Science" that generated these proceedings brought together a diverse array of scientists and managers to address the state of knowledge about the physical and ecological effects of shoreline armoring. As a contribution to better understanding the ecological effects, the goals of this paper are (1) to briefly summarize the knowledge about effects of armoring on shoreline biota, (2) to focus on the ecological function of two case study restoration sites, and (3) to discuss the role of science in restoration of urban shorelines and implications for management. We focus on the "marine shorelines" of Puget Sound proper, excluding those of deltas and river sub-estuaries that enter Puget Sound (for example, Duwamish, Skagit, Nisqually) that are dominated by marshes and mudflats. We summarize recent research and highlight monitoring results of shoreline armoring removals and beach rehabilitation at the Olympic Sculpture Park (City of Seattle) and Seahurst Park (City of Burien). These shorelines have had either riprap or seawalls removed, with different restoration approaches employed to enhance shallow water environments that are recognized to be important habitats of juvenile pacific salmon (*Oncorhynchus* spp., predominantly Chinook, *O. tshawytscha*; chum, *O. keta*; pink, *O. gorbuscha*; and coho, *O. kisutch*) (Simenstad and Cordell, 2000). We recognize that although it is not always possible in extremely modified habitats to technically "restore" original conditions, it is feasible to effectively rehabilitate or enhance habitats within urban constraints (Simenstad and others, 2005). We use the term "restoration" to describe a general goal, and the terms rehabilitation and enhancement for actions that are intended to make progress toward that goal.

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Armoring Impacts on Shoreline Habitats and Biota

Shallow water intertidal habitat in Puget Sound is an important ecosystem feature and is the main location of aquatic shoreline armoring and its associated impacts. Efforts to restore or enhance nearshore areas recently have increased, in part driven by the listing of Chinook salmon as threatened under the Endangered Species Act in 1999. Juvenile Chinook salmon in the Pacific Northwest use estuarine and nearshore habitats during outmigration and rearing, as do other salmonids such as juvenile chum salmon (Simenstad and others, 1982). Surf smelt (*Hypomesus pretiosus*) and Pacific sand lance (*Ammodytes hexapterus*) also use beaches as habitat for spawning. Consequently, shoreline armoring in Puget Sound can affect nearshore fish abundance, distribution, and behavior patterns (Toft and others, 2007), as well as survival of eggs in beach spawning surf smelt (Rice, 2006). Also, removal of supralittoral vegetation can affect some nearshore fish species, demonstrating that terrestrial processes interact with aquatic ecosystems (Romanuk and Levings, 2006).

Invertebrates that are important prey for nearshore fish can be negatively affected by shoreline armoring (Romanuk and Levings, 2003; Sobocinski and others, 2010). Shoreline modifications affect aquatic community patterns in other systems as well, usually decreasing densities or altering assemblage structure (Peterson and others, 2000; Chapman, 2003; Cruz Motta and others, 2003; Moschella and others, 2005), but occasionally somewhat positive effects are detected because of added unique structures that attract some different organisms than what occurred naturally (Glasby, 1998; Davis and others, 2002). However, it is also important to note that these additional species can be non-indigenous (Glasby and others, 2007). Mechanisms causing negative effects are often related to physical alterations associated with truncating the intertidal zone, such as degrading habitat and shoreline vegetation, creating a steeper physical profile, limiting the sediment supply, and reflecting wave energy (Williams and Thom, 2001); however, many of these causal linkages remain untested in their specific effects on biota. Nearshore restoration often emphasizes improving habitat conditions for invertebrates that are important food for fish, but whether altered systems can be restored by removal of the modifications and enhancement of the intertidal beach remains poorly investigated.

The scale of the direct effects of armoring is related to the tidal elevation to which the armoring footprint extends: (1) within terrestrial and supralittoral, (2) into intertidal, and (3) across the entire beach profile into subtidal waters. Impacts to shoreline biota can often be more extreme where shoreline armoring extends into deeper subtidal areas, severely truncating the nearshore and destroying the natural gradual slope of the intertidal zone. Where this happens, pelagic fish that typically spread out along the intertidal area at high tide must inhabit deep water directly along shore (Toft and others, 2007). However, shoreline armoring at higher tidal elevations can still affect fish feeding. For example, 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). Invertebrate assemblages also are negatively affected by the amount of seaward armoring, as shoreline modifications that encroach into intertidal beach elevations below Mean Higher High Water (MHHW) have a greater impact on benthic macroinvertebrates than those installed higher than MHHW (Sobocinski and others, 2010).

Two main points are implicit in these studies: (1) armoring that extends into the subtidal affects pelagic fish distributions, and (2) armoring at any elevation affects fish feeding and the aquatic-terrestrial connection. This suggests that urban restoration within Puget Sound should mainly focus on:

- Restoring shallow water ecosystems of nearshore intertidal beaches.
- Restoring connectivity across aquatic and terrestrial realms.

Alleviating impacts of armoring through restoration will be examined using two case studies, which offer insight into the types and benefits of rehabilitation that are feasible along modified Puget Sound shorelines. The studies are briefly described here, and an overview of the results is summarized from methods and analysis presented elsewhere (Toft and others, 2008; Toft, 2009).

Case Study 1: Olympic Sculpture Park

The Olympic Sculpture Park was created by the Seattle Art Museum on 3.4 ha of waterfront property along Elliott Bay in downtown Seattle, Washington. A main design goal was to improve habitat along the shoreline that would provide public access and benefit wildlife resources, including outmigrating juvenile salmon. Before the site was constructed, the shoreline consisted of seawall and riprap with minimal upland vegetation, which severely truncated available intertidal habitat and access to riparian resources. Two shoreline enhancements were created: (1) a pocket beach was excavated from the riprap, and (2) a compacted-sediment "habitat bench" was created along the seawall (fig. 1). Both features extend from shore to a tidal elevation of approximately 0.0 m Mean Lower Low Water (MLLW). Dunegrass (*Elymus mollis*) and riparian vegetation were planted along the pocket beach, and riparian vegetation also was planted along the walkway above the habitat bench.

Monitoring at this site is ongoing, and data have been analyzed from pre-restoration (2005) and post-restoration (2007) periods, bracketing construction in 2006 and opening of the park in January 2007. Monitoring has included quantitative surveys of fish, epibenthic invertebrates, and terrestrial insects pre- and post-restoration, with additional

Figure 1. Photographs of the Olympic Sculpture Park (*A*) pre-restoration, (*B*) post-restoration at the pocket beach, and (*C*) habitat bench. The pocket beach replaced riprap armoring, and the habitat bench is a shelf that projects from the base of the seawall. The habitat bench is not visible in (*B*) as it is inundated at high tide; (*C*) shows the habitat bench at low tide with kelp beds on the seaward side.

inclusion post-restoration of benthic invertebrates, algae, riparian vegetation, and physical beach structure (Toft and others, 2008). Pre-restoration monitoring showed that several species of juvenile salmon (mostly chum and Chinook) occupied the urban shoreline, with peak abundances occurring from April through July. Given the presence in the area of juvenile salmon, it was hoped that shoreline habitat improvements would benefit them.

Initial results from pre- and post-restoration fish monitoring indicated that the pocket beach and habitat bench had significantly higher densities of juvenile salmon in shallow water transects than the adjacent stretch of riprap (table 1; Toft and others, 2008). Also, 94 percent of fish captured in the pocket beach were juvenile salmon, showing that the target salmon habitat was utilized effectively. Epibenthic invertebrates and terrestrial insects showed improvements, generally with increased taxa richness, densities, and shifting assemblage structure compared to pre-restoration conditions and to adjacent stretches of armored shorelines (table 1). Overall, monitoring has indicated that although there is significant public use of the park and restoration activities were constrained by urban features, the beach structure is relatively stable and there has been a rapid development of aquatic and terrestrial biota.

Table 1. Summary of biological monitoring post-restoration compared to pre-restoration and to reference beaches at the Olympic Sculpture Park (Habitat Bench and Pocket Beach) and Seahurst Park.

[Data summarized from technical reports (Toft and others, 2008; Toft, 2009) with analysis by univariate ANOVA and multivariate ordination techniques. Symbols represent statistical differences: + increase, “nd” no difference, – decrease, blank = not measured]

Olympic Sculpture Park:

Results after 1 year restoration compared to pre-restored (Pre) and reference armored shorelines (Ref).
Assemblage structure represents taxonomic composition change away (+) from armored shorelines.

	Olympic Park – Habitat Bench					
	Insects		Epibenthic invertebrates		Juvenile salmon	
	Pre	Ref	Pre	Ref	Pre	Ref
Density	nd	+	+	+	nd	+
Taxa richness	nd	+	+	+		
Assemblage structure	+	+	+	+		

	Olympic Sculpture Park – Pocket Beach					
	Insects		Epibenthic invertebrates		Juvenile salmon	
	Pre	Ref	Pre	Ref	Pre	Ref
Density	nd	+	+	nd	nd	+
Taxa richness	+	+	+	+		
Assemblage structure	+	+	+	nd		

Seahurst Park:

Results after 3 years restoration compared to pre-restored (Pre) and reference natural beach (Ref).
Benthic invertebrates monitored at three tidal elevations: +12, +8, and +5’ MLLW.
Assemblage structure represents taxonomic composition change towards (+) or away (-) from reference natural beach.

	Benthic invertebrates + 12		Benthic invertebrates + 8		Benthic invertebrates + 5	
	Pre	Ref	Pre	Ref	Pre	Ref
Density	+	nd	+	–	–	–
Taxa richness	+	+	+	+	nd	+
Assemblage structure	+	nd	nd	–	–	–

Case Study 2: Seahurst Park

Seahurst Park is within the city of Burien, approximately 15 km south of downtown Seattle, Washington. Restoration completed in February 2005 replaced a 300-m section of seawall with a more gradual and natural slope, added gravel and cobble to the beach, and planted riparian vegetation in the uplands (fig. 2). Monitoring at the restored site and at an adjacent reference beach is ongoing, and data have been analyzed from pre-restoration (2004) and two post-restoration periods (2006 and 2008). Benthic macroinvertebrates have been the focus of biological monitoring (Toft, 2009) because they are closely linked to physical characteristics of beaches (Dethier and Schoch, 2005), and talitrid amphipods in the supralittoral are impacted by armoring and may be a good predictor of beach health (Dugan and others, 2008; Sobocinski and others, 2010). Sampling was conducted at tidal elevations that spanned the face of the former seawall (+12 ft MLLW), the base of the seawall (+8), and the lower beach regrade (+5).

Compared to the reference site, benthic invertebrate densities typically were lower at the restored site, whereas taxa richness was higher (table 1; Toft, 2009). Compared to pre-restoration armored conditions, densities and taxa richness improved at the restored site at the higher tidal elevations specific to where armoring was removed (+12- and +8 ft MLLW). Invertebrate assemblages were distinct from each other at lower tidal elevations where the beach regrade and sediment nourishment occurred, which could either be a response to the early restoration stage or to possible physical differences between the sites. The results from initial monitoring reported by Toft (2009) and other studies at Seahurst Park are conceptualized in figure 3. Negative biotic responses as a result of armoring and positive responses as a result of restoration are most apparent at higher tidal elevations of direct armoring location and removal, with fewer impacts of armoring and benefits of restoration occurring below armored locations, where restoration activities included beach regrade and sediment nourishment.

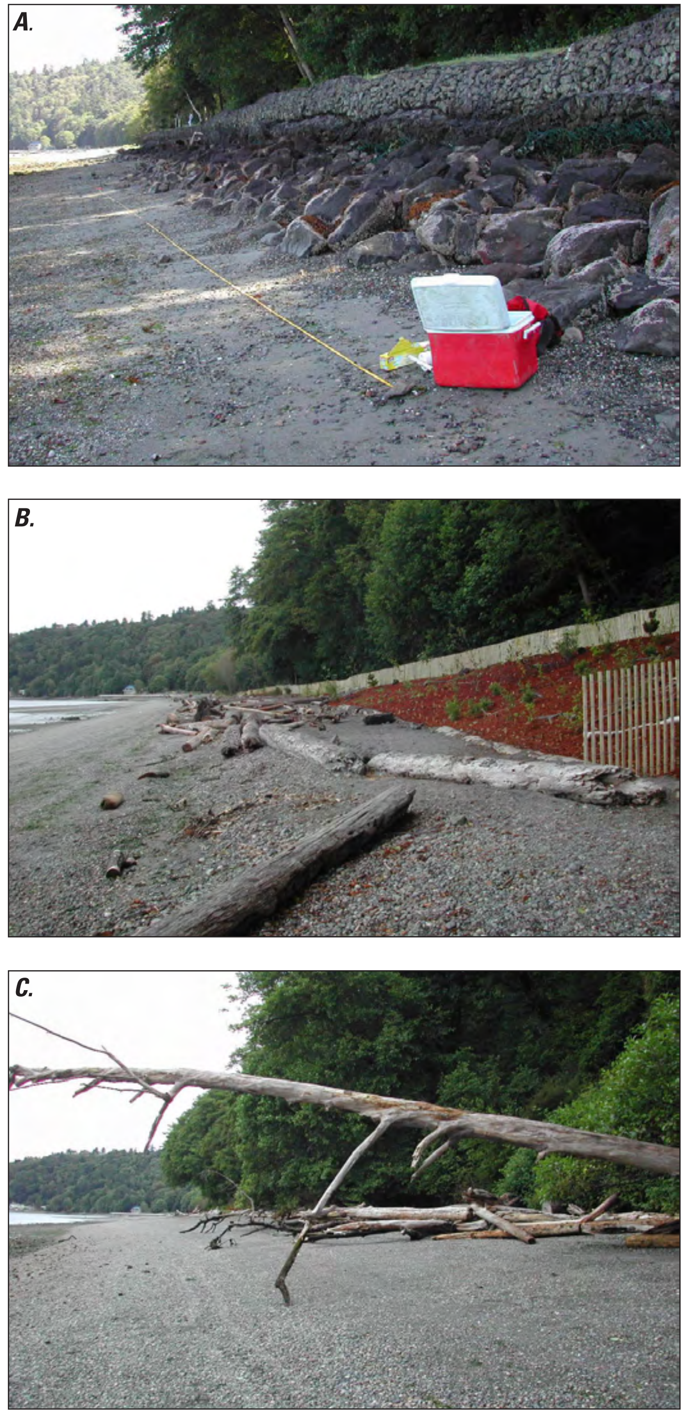

Figure 2. Photographs of Seahurst Park (*A*) pre-restoration, (*B*) post-restoration, and (*C*) reference beach. Location of the transect in (*A*) is at a tidal elevation of approximately +8 feet MLLW.

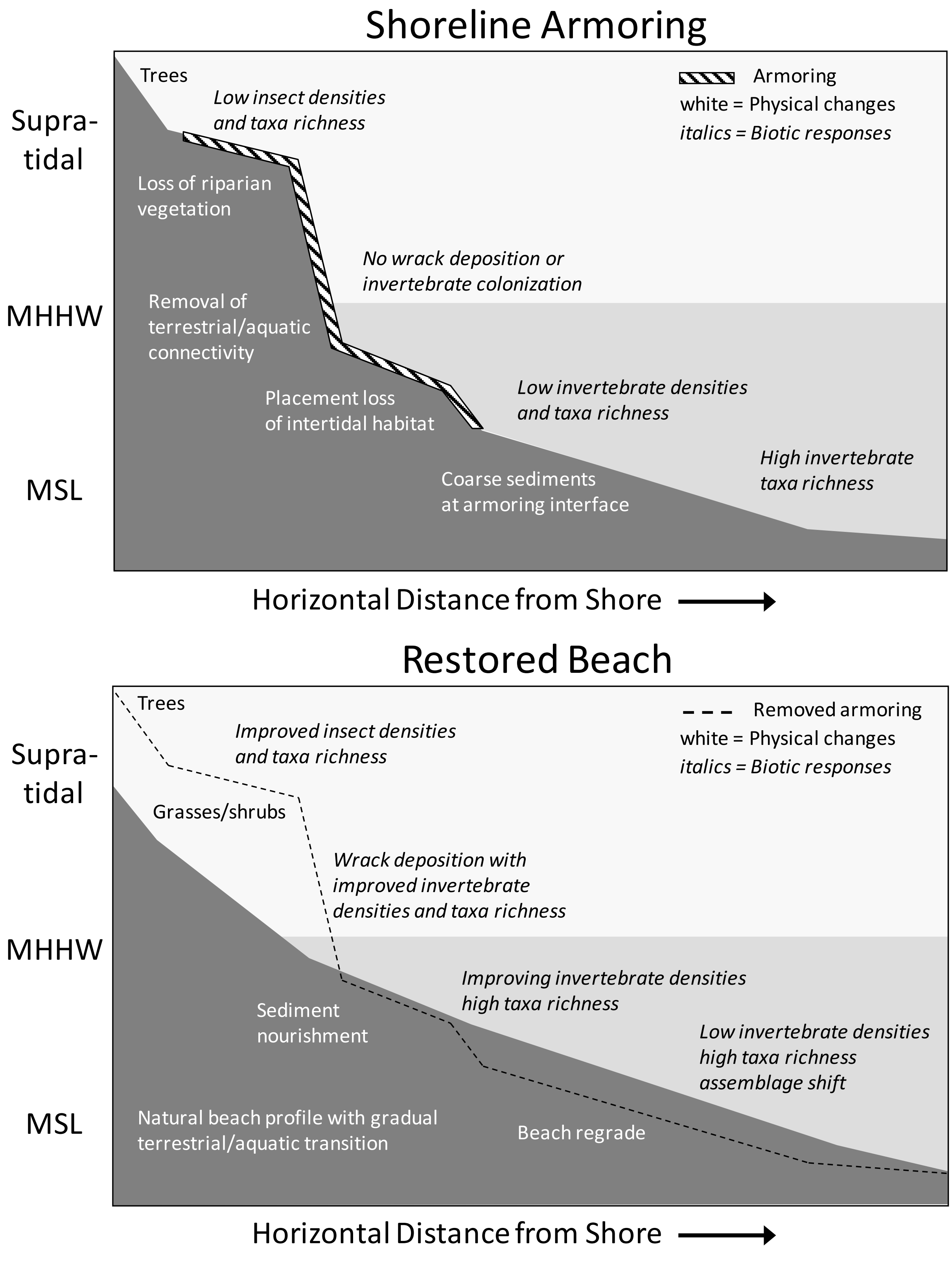

Figure 3. Conceptual diagram of Seahurst Park (Burien, Washington) monitoring summarized from data collected during armored and restored conditions. Mean Higher High Water (MHHW) represents the approximate high-tide line, and Mean Sea Level (MSL) the approximate mid-tide elevation on the beach profiles. Main invertebrate datasets summarized from Toft, 2009, with ‘armored’ insects and sediments from Sobocinski and others, 2010, ‘restored’ insects from Armbrust and others, 2009, and physical profile outlines based on Johannessen and Waggoner, 2009.

Conclusions and Future Opportunities

The Olympic Sculpture Park and the Seahurst Park have shown ecological improvements attributable to the restoration actions, but questions about longer-term restoration effects will remain unanswered until the sites become more stable in ecological and physical structure (Simenstad and Thom, 1996). At the Olympic Sculpture Park, the first year of post-restoration monitoring showed general improvements compared to adjacent armored shorelines. In this instance of beach enhancement in a constrained urban setting with no reference natural beaches, we have documented short-term benefits. At Seahurst Park, the first 3 years of post-restoration monitoring have shown mixed results compared to an adjacent reference natural beach. Measures of the invertebrate community improved at higher tidal elevations where the armoring directly impacted the beach, but have been somewhat degraded at lower tidal elevations where the beach was regraded and nourished with sediments. Attention should be given in similar restoration designs to maximize improvements at armored locations, and minimize them at non-armored locations that may be affected by construction or beach nourishment activities. These problems might be alleviated if long-term monitoring shows that beaches stabilize through time, although this will probably depend in part on site and local processes (Dethier and Schoch, 2005).

By examining these two case studies and the relation between nearshore biota and shoreline armoring, it becomes clear that restoring shorelines in Puget Sound can help establish and maintain connections between terrestrial riparian and aquatic intertidal zones, even in extensively modified urban settings. Understanding the impacts of shoreline armoring and the potential for restoration can improve our ability to manage the interactions between human development and nearshore ecosystems. Within this context and given our early findings at the two case study sites discussed in this paper, we detail our understanding of the role of science in urban restoration and implications for management based on the following questions:

How can science be most useful to managers? Linking scientific knowledge about endangered juvenile salmonid use of nearshore ecosystems to policy decisions on habitat use and restoration goals is imperative for successful habitat restoration. In restoration planning, science can be useful (1) prior to restoration in helping to define project goals, (2) during project design by incorporating data to optimize the likelihood of desirable ecological responses, and (3) after completion of restoration to document performance, to identify problems, and to provide critical information for adaptive management.

What can monitoring restoration actions/projects tell us? Pre- and post-restoration monitoring gives valuable information on the status of site development. Without this information, it is not only impossible to assess the performance and ultimate outcomes of restoration or rehabilitation, but also impossible to determine what changes to incorporate to ensure improved performance and likelihood of beneficial outcomes in the future. Even in urban environments where natural “reference” shorelines are rare, monitoring can be effective if it compares conditions at restored sites before and after restoration and to adjacent habitats. This places the restored site in context to its surroundings and measures if it has accomplished management goals of improvement. With the large amounts of money often spent to restore habitats, it seems errant not to adequately fund monitoring to measure restoration performance and achievement of goals.

How can data on completed projects benefit restoration designs throughout Puget Sound? Verifiable data is an essential component for developing future restoration designs, guiding shoreline armoring removal, and restoring beach processes. This is especially applicable to supplying creative solutions in cases where original habitat cannot be restored, but rehabilitation or enhancement from altered conditions is desired (Simenstad and others, 2005). Predicting the amount of active management required to maintain created habitats such as the beaches described here is difficult, because they are developing within urban landscapes that lack some natural flexibility and resilience to storms and other physical processes (Nordstorm, 2000), and have sediment supplies reduced by shoreline development (Komar, 1998). However, research on the two case studies described here has shown that the sites are initially stable, with minimal sediment transport and no immediate needs for re-nourishment (Toft and others, 2008; Johannessen and Waggoner, 2009).

How can experimental designs be optimized to assess restoration and urbanization? Without data, unknowns remain unknown. With data, knowledge is gained, but the extent gained depends on the data quality. The power and strength of data are optimized when focused experimental designs produce precise data that can overcome weaknesses due to natural variation. We recommend paying particular attention to statistical power, development of testable hypotheses, inclusion of multiple reference/comparison sites, and long-term monitoring. In urban restoration settings this kind of data, coupled with clearly developed questions and potential outcomes, will be of the most use to scientists and managers (Michener, 1997).

What questions and practices are most important for the future? Basic questions still remain on the mechanisms and degree to which shoreline armoring affects ecological and physical beach processes. Questions examining spatial and temporal variability will require focused research to assess the functioning and resilience of these systems under alternative restoration and rehabilitation actions. Connectivity across the terrestrial-aquatic interface must be highlighted as a vital component of the shoreline ecosystem, and should not be separated into different parts but rather combined as one ecological unit. Integrating physical and biological datasets from the experimental design phase onward should be emphasized in order to provide a more complete understanding of system function.

One overarching question should be considered when issues of shoreline armoring and restoration arise: In another decade's time, what information are you going to wish you had collected? If that question is not continually addressed, progress will be limited. This is important to consider, as current rates of new shoreline armoring substantially exceed removal rates in Puget Sound (Randy Carman, Washington Department of Fish and Wildlife, presentation at workshop of these proceedings, May 12, 2009); therefore, we are not even dealing with the status quo because restoration is not keeping up with development. This will increasingly be an issue because of the "coastal squeeze" of sea-level rise with shoreline development, placing more pressures on the aquatic-terrestrial ecotone on sheltered coasts (National Research Council, 2007; Defeo and others, 2009). Discussion of these issues in the scientific literature focuses on sandy beaches instead of the more atypical mixed sediment beaches of Puget Sound (Nordstrom, 2000; Defeo and others, 2009), and warrants more research. The workshop that generated these proceedings was a key step in furthering our understanding of shoreline armoring and its effects on nearshore ecosystems, and continued dialogue will be necessary in attempts to improve the health of Puget Sound shorelines.

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Anticipated Effects of Sea Level Rise in Puget Sound on Two Beach-Spawning Fishes

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Introduction

The shoreline of Puget Sound provides habitat for many species, including surf smelt (*Hypomesus pretiosus*) and Pacific sand lance (*Ammodytes hexapterus*); two fishes that spawn in the intertidal zone. Surf smelt and Pacific sand lance (hereinafter sand lance) are key parts of the Puget Sound food web (Simenstad and others, 1979), providing food for many sea birds, marine mammals and fishes, including economically and culturally important Pacific salmon (*Oncorhynchus* spp.). By integrating climate change predictions and their expected effects on intertidal geological processes and subsequent ecological processes, we hope to inform policies to protect surf smelt and sand lance spawning habitat while addressing legitimate private property concerns regarding shoreline armoring.

Shoreline armoring might be the most important threat to surf smelt and sand lance spawning habitat (Thom and others,1994), and a little studied threat to sand lance winter rearing habitat (Quinn, 1999). Griggs and others (1994) and Williams and Thom (2001) identify many detrimental effects of shoreline armoring, and more than one-third of Puget Sound's shoreline is armored (Puget Sound Water Quality Action Team, 2002), including many locations where surf smelt and sand lance spawn. Since 1974 shoreline armoring has been regulated where spawning has been documented. However, many beaches have not been surveyed and the spawning behavior of sand lance was not well known until 1989 (Penttila, 1995), so much of the shoreline of Puget Sound was armored prior to regulation or documentation of beach spawning. Furthermore, existing regulations do not consider cumulative or off-site impacts of armoring, cannot prohibit armoring in most cases (see Carman and others, 2010), and do not address likely future environmental conditions such as higher sea level.

Sea level is expected to rise substantially in this century, which likely will profoundly affect the structure and function of the Puget Sound ecosystem (National Wildlife Federation, 2007). As sea level rises the spatial extent of intertidal beaches might contract, which would reduce the extent of intertidal habitat and thus the amount of suitable spawning habitat. Where the upward extent of beach migration is limited by shoreline armoring (Griggs and others, 1994; Griggs, 2005), loss of spawning habitat might be exacerbated (Thom and others, 1994). However, the question of whether sea level rise will result in a loss of surf smelt and sand lance spawning habitat on armored shorelines has not been addressed quantitatively. Our goals were (1) to describe the geographic and temporal distribution of surf smelt and sand lance spawning in Puget Sound, including discontinuities in occurrence and egg abundance; (2) to describe associations between beach elevation and egg abundance; and (3) to determine the potential for spawning habitat contraction and egg loss as a result of sea level rise on armored beaches.

In this paper, we address our goals by describing some results and conclusions (1) of a long-term survey to detect beach spawning in Puget Sound, (2) of a one-year survey of beach spawning density on Camano Island, WA, and (3) of the first year of a study of the spatial distribution of eggs on central Puget Sound intertidal beaches.

Study Methods

Puget Sound Survey

To describe the geographic and temporal distribution of surf smelt and sand lance spawning occurrence we analyzed survey data collected by the Washington Department of Fish (WDFW) since 1972. These data included visual observation of egg presence and results of analyses of standard samples consisting of four subsamples of about 500 mL of the upper approximately 5 cm of substrate that were collected about 6 m apart at approximately +10 ft mean lower low water (MLLW). Sampling locations were selected haphazardly, to maximize efficiency at detecting presence of spawning. The Washington Department of Natural Resources has delineated and mapped morphologically homogeneous shorelines and maintains a GIS

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layer (Washington State Department of Natural Resources, 2010, Washington ShoreZone Inventory at http://www.dnr.wa.gov/ResearchScience/Topics/AquaticHabitats/Pages/aqr_nrsh_inventory_projects.aspx) that identifies them. We plotted spawning sample results onto Washington ShoreZone Inventory beaches. Some ShoreZone beaches were sampled more than once. Surveyed beaches were attributed with presence of surf smelt or sand lance spawning if one or more samples detected their eggs. Spawning absence was attributed to beaches where all samples failed to detect eggs. Spatial patterns of spawning were presented graphically using a GIS, and frequency of spawning occurrence is described by tallying data by survey and ShoreZone beach.

Camano Island Survey

To describe the spatial and temporal distribution of surf smelt and sand lance egg abundance, we conducted surveys every 2 weeks from September 2007 through August 2008 at 51 locations on Camano Island, Washington. Samples were collected at locations that were evenly spaced around the island. Sampling procedures were similar to those used for the Puget Sound survey. In this preliminary analysis, we summarized egg counts by location and through time for both species.

Intertidal Egg Distribution

To describe the distribution of eggs relative to beach elevation we collected samples at approximately 4, 6, 8, and 10 ft above MLLW on 28 beaches in central Puget Sound. Each sample consisted of 4 subsamples of 500 mL, similar to the standard samples collected in the Puget Sound survey. Subsamples were taken 6 m apart from the top approximately 5 cm of sediment. Samples were collected in 2005 and 2006 to assess the sufficiency of the sampling method developed by WDFW (Moulton and Penttila, 2001; Krueger and others, 2007). Sampling locations were selected haphazardly as part of the Puget Sound survey.

To assess the likely effect of sea-level rise on forage fish spawning on armored beaches, we estimated the proportion of eggs likely to be lost as a result of a range of potential sea-level rise scenarios. We assume that the morphology (for example, shape and substrate) of armored beaches will remain unchanged as sea level rises. We used estimates of sea-level rise of 0.13 to 0.69 m (5.1 to 27.3 in.) within this century made by the Intergovernmental Panel on Climate Change (2001) and used by the National Wildlife Federation (2007) to guide analysis. Because expectations for sea-level rise are highly uncertain for specific locations and differ among locations (National Wildlife Federation, 2007), we estimated loss of eggs as a proportion of beach lost. Beach elevations were standardized between MLLW and mean higher high water (MHHW) plus 1.5 ft. We used the latter elevation as a conservative (that is, high) estimate of the elevation of shoreline armoring, because data describing the elevation of armoring was not available. To describe the distribution of egg abundance in relation to beach elevation, we fit a 2-parameter gamma distribution to each of the 13 (of 28) beach locations that had sufficient data. We then calculated the cumulative gamma distribution over all sites using proportions of surf smelt eggs and standardized beach elevations. The cumulative density function estimates the proportion of eggs lost as a result of sea level rise on armored beaches as a proportion of the beach is lost as a result of sea- level rise, given no change of beach morphology. That is, given the difference between MLLW and MHHW + 1 ft, estimates of sea level rise can be used to estimate the proportion of beach inundated and subsequently the proportion of eggs lost on a beach.

Results

Puget Sound Survey

Surf smelt and sand lance have broad geographic distributions, and spawn throughout much of Puget Sound (fig. 1). More than 20,000 samples have been collected to document spawning locations (Washington Department of Fish and Wildlife, 2010, at http://wdfw.wa.gov/mapping/salmonscape). Surf smelt eggs were found in 6,574 samples and sand lance eggs were found in 1,540 samples. To date, 3,689 of 6,956 ShoreZone beaches have been surveyed. Spawning by one or both species was observed on 37 percent of sampled beaches. Spawning by both species is spatially discontinuous. Spawning by either surf smelt or sand lance has not been detected on many sampled beaches where habitat seems suitable.

Camano Island Survey

On Camano Island, surf smelt and sand lance egg abundance was highly variable among locations and through time within a year (Quinn and others, 2009). Most of the surf smelt eggs were collected from 20 percent of the locations sampled during a few late summer and early fall sampling sessions. Similarly, most sand lance eggs were collected at a few locations during a few early winter sampling sessions. Surf smelt eggs were much more abundant than sand lance eggs on Camano Island, but eggs of both species were found at many locations (Quinn and others, 2009).

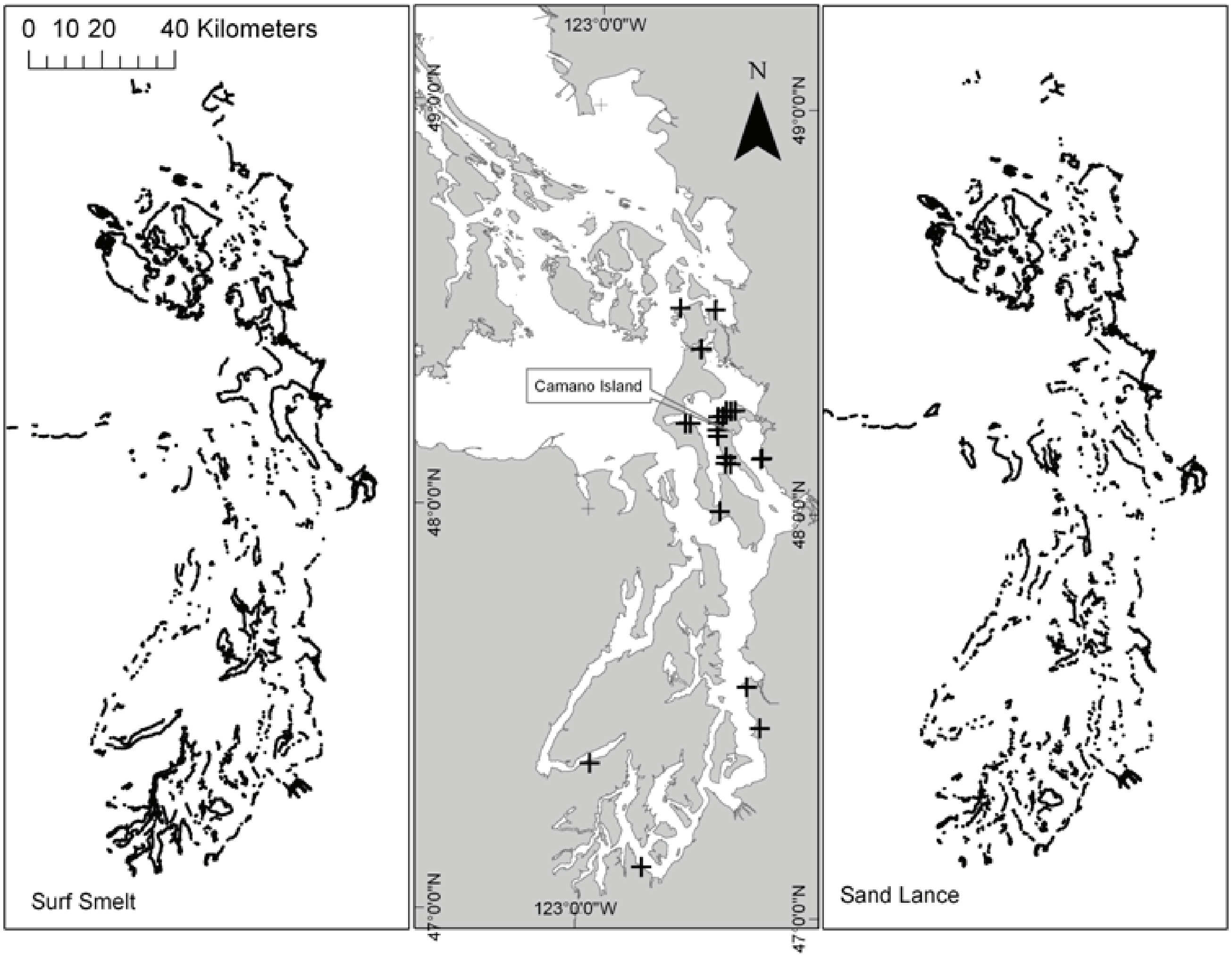

Figure 1. Geographic distribution of samples with observations of surf smelt (left) and sand lance (right) occurrence in Puget Sound. Large + indicates sampling locations (center) where data describing the relation between surf smelt egg density and beach elevation were collected.

Intertidal Egg Distribution

Only 13 locations had sufficient data on surf smelt to fit gamma distributions to quantify the relation between egg abundance and beach elevation. Locations with the highest number of eggs tended to have those eggs at higher elevation than at other sites (fig. 2) and on most beaches a high proportion of eggs were found at high beach elevations (fig. 3). Only 2 locations had sufficient data for sand lance to fit gamma distributions to quantify the relation between egg abundance and beach elevation, precluding subsequent analysis (Krueger and others, 2009). Sand lance seem mostly to spawn at lower elevations in the intertidal zone than do surf smelt. Examination of the cumulative gamma distribution suggests that on beaches where the tidal range plus 1.5 ft is about 10 ft, the low estimate of sea level rise (about 5.1 in.) will inundate about 3.5 percent of beaches and 5 percent of surf smelt eggs, whereas the high estimate of sea level rise (about 27.3 in.) will inundate about 23 percent of the beach and about 75 percent of surf smelt eggs (fig. 3).

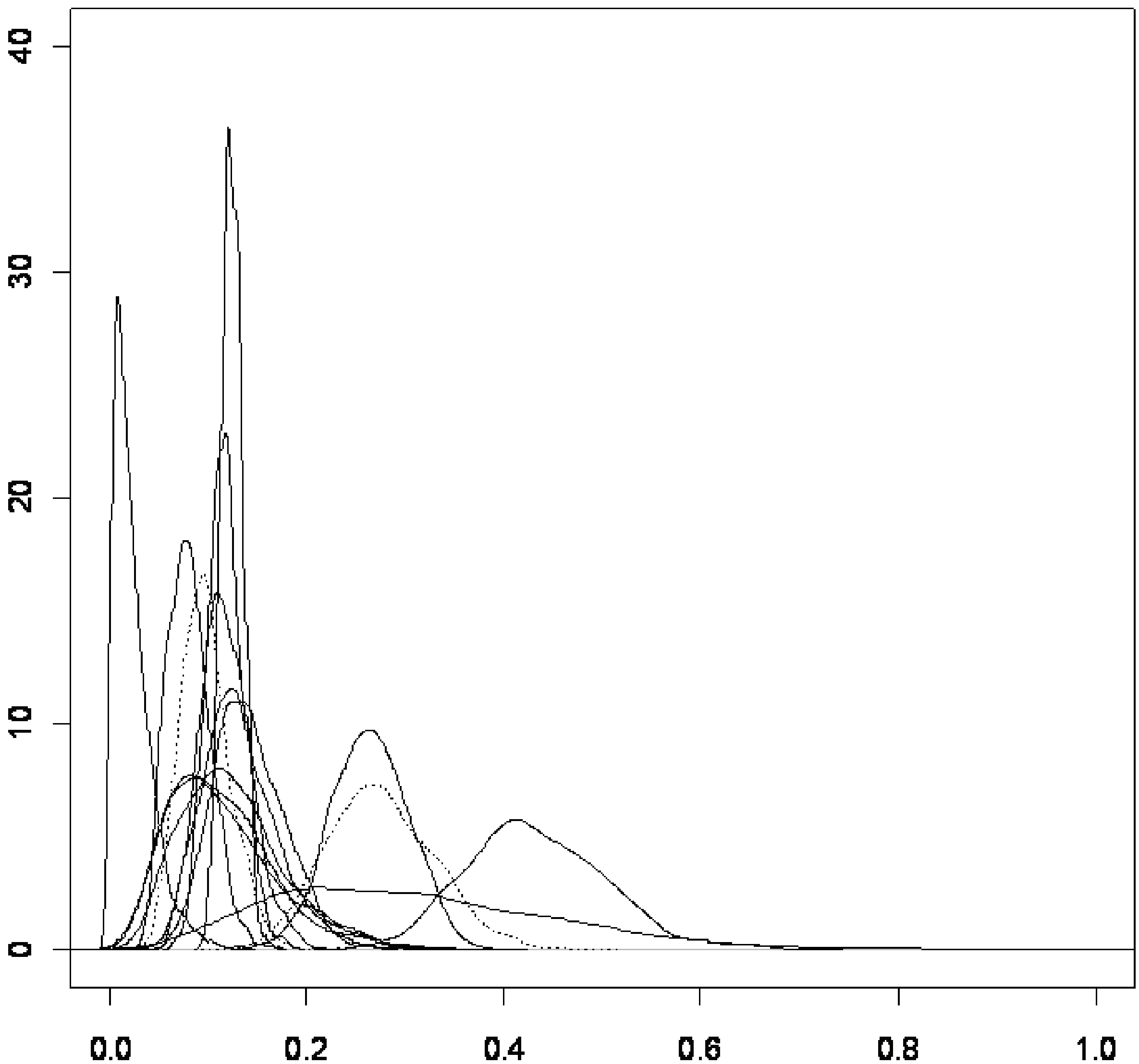

Figure 2. Gamma distributions that describe the relation between surf smelt (n = 13 beaches, solid lines) and Pacific sand lance (n = 2 beaches, dashed lines) egg density and beach elevation. Beach elevation (x-axis) is standardized between 0 (MHHW + 1.5 feet) and 1 (MLLW). Egg density (y-axis) is presented as a percentage of the total number of eggs collected at each beach.

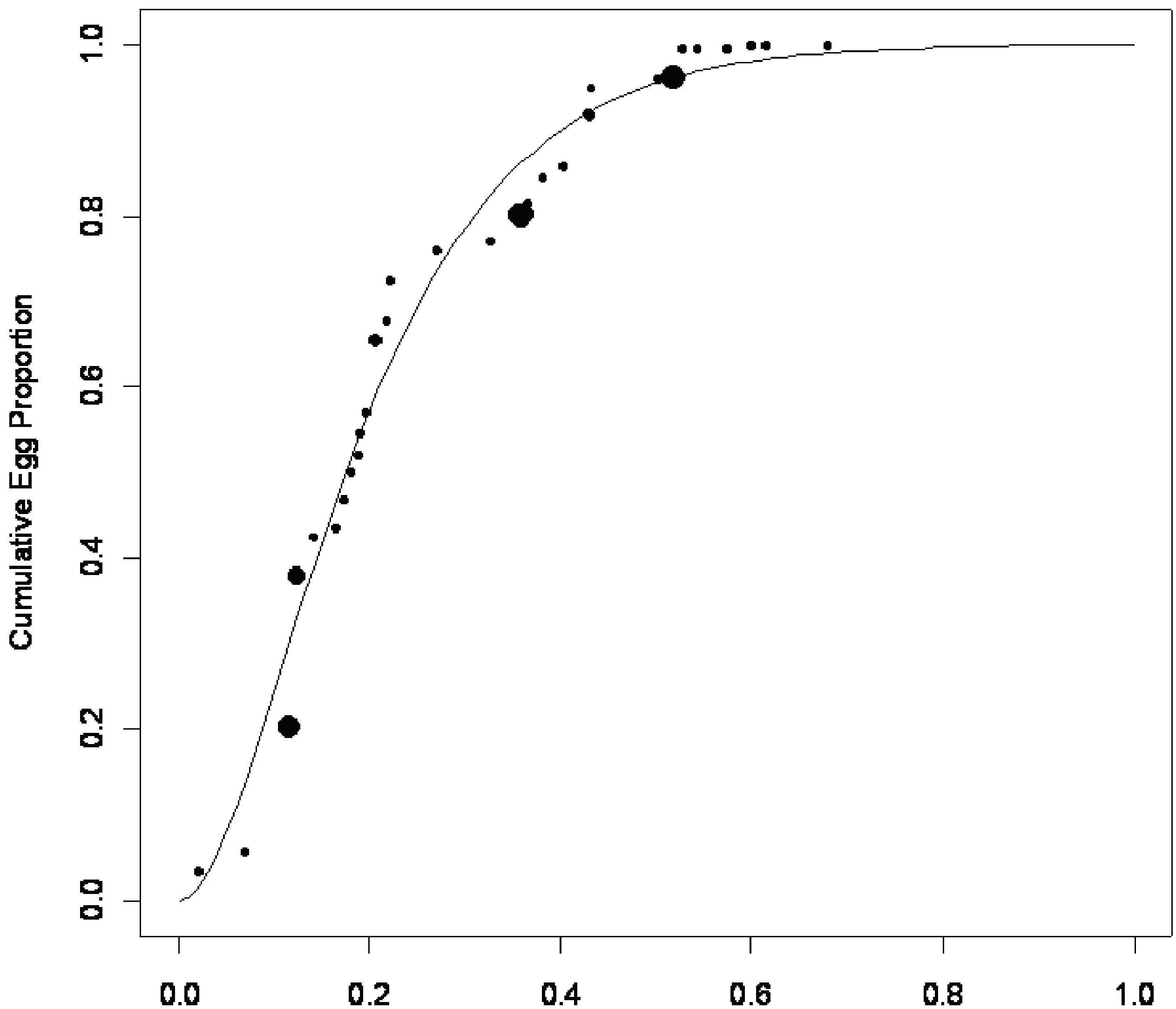

Figure 3. Cumulative gamma distribution describing the proportion of surf smelt eggs found (y-axis) in relation to beach elevation. Beach elevation (x-axis) is standardized between 0 (MHHW + 1.5 feet) and 1 (MLLW). Points identify the position of samples in relation to the fitted line. Larger points identify two samples. Note that loss of a small proportion of the higher beach elevation (for example, 0 to 0.2) affects a large loss of eggs (about 55 percent of those found on the beach). These analyses assume that armoring is at MHHW + 1.5 feet and that beach morphology is static.

Discussion

Maintaining abundant surf smelt and sand lance in Puget Sound is a conservation imperative, but current regulations do not consider cumulative or off-site impacts of armoring, cannot prohibit armoring in most cases (see Carman and others, 2010), and do not address likely future environmental conditions such as sea-level rise. Conserving surf smelt and sand lance is an opportunity to proactively manage for expected environmental conditions by integrating knowledge of geological and ecological processes into policy decisions that address legitimate private property concerns. Although much remains to be learned about Puget Sound beaches, the effects of management actions, and the ecology of surf smelt and sand lance, sufficient information is available to provide sound advice to policy makers and to suggest precautionary management.

The broad geographic distribution of surf smelt and sand lance in Puget Sound likely requires different management actions among regions where environmental conditions, fish behavior, and population structure differ. Robards and others (2002) found differences in the growth and abundance of populations of sand lance in Cook Inlet, Alaska, that were subject to different environmental conditions, and Moore and others (2008) describe some patterns of oceanographic properties in Puget Sound that likely affect fish growth, abundance, and behavior. The presence of several populations (stocks) in Puget Sound seems likely a result of observed differences in spawn timing among locations and consistent timing of spawning at some locations. Small discrete populations have been found for similar species at a similar spatial extent (Bradbury and others, 2008), but their delineation is an unaccomplished prerequisite for efficient monitoring and management in Puget Sound. Further, within Puget Sound, regional differences in effective fetch and tide range and local differences in beach morphology (Finlayson, 2006) suggest that the effects of practices such as shoreline armoring differ among locations. Management of beaches and species should account for these spatial patterns.

Monitoring and management should also account for the spatial and temporal discontinuity of spawning. Observed discontinuity likely is a result of differences in environmental conditions, population size, and sampling errors (Angermeier and others, 2002). Spawning surf smelt and sand lance seem to have preferred sediment sizes on beaches (Penttila, 1995), and adult and juvenile sand lance have sediment size preferences (Haynes and others, 2008) that might affect where spawning occurs. Although predicting the effects at a location is difficult, shoreline armoring can coarsen beach sediment (Kraus and McDougal, 1996) and cause degradation, possibly making beaches less suitable for spawning. Management to establish and maintain large populations of these species should ensure abundant suitable spawning sediment.

Discontinuity might be a result of small population size. The abundance of these species is not known, but such information is necessary for monitoring and management. False absence sampling errors also can produce observed discontinuity. The sampling procedure used to collect most of our spawning data has a low false absence error rate (Krueger and others, 2007), suggesting that most observed absences are correct. However, it should not be assumed that the locations of spawning do not change. Although repeated selection of a beach for spawning has been observed for surf smelt (D.E. Pentilla, written commun.) and Japanese smelt (*Hypomesus japonicas*, Hirose and Kawaguchi, 1998), capeline (*Mallutus villosus*), another beach spawning fish, has altered its geographic distribution of spawning in Newfoundland, Canada, in response to changing water temperature (Nakashima and Wheeler, 2002). Changing environmental conditions might affect where and when spawning occurs. Research that better describes the spatiotemporal distribution of spawning will facilitate more efficient management, but failure to detect spawning should not preclude conservation of beaches that might be suitable for spawning now or in the future.

Spawning surf smelt, and perhaps sand lance, have strong preferences for specific beach elevations (Krueger and others, 2007) and among beaches where spawning is observed, the number of eggs often differs by several orders of magnitude (Quinn and others, 2009). These patterns have profound monitoring and management implications. Importantly, spawning success might be disproportionate to the length or area of beach affected by armoring or other disturbance. That is, loss of spawning on a small proportion of beaches might affect a large loss of spawning if the disturbed beaches have many eggs. We know little about the relative importance of specific beaches for spawning; therefore, precautionary management that assures suitable spawning habitat on known and likely spawning beaches is warranted. Further, impacts to a small part of the upper beach might result in a large loss of eggs because surf smelt eggs are most abundant at high beach elevations.

Sea-level rise is likely to cause substantial loss of surf smelt spawning habitat on beaches with armored shorelines because armoring prevents beach migration inland (Griggs and others, 1994), thereby reducing the area of beach with elevations preferred for spawning. On some beaches loss of surf smelt spawning habitat is likely to occur soon with moderate sea level rise because many eggs are deposited at high beach elevations (fig. 3). Estimates of sea-level rise suggest that on beaches with armored shoreline substantial surf smelt spawning habitat might be lost in the next few decades and most spawning habitat might be lost by 2100.

Several limitations of our study should be noted to prevent misapplication of our results. First, our beach spawning elevation and beach form data likely do not fully describe conditions on many Puget Sound beaches because our data are from few beaches that are mostly in central Puget Sound. Second, sufficient data to describe the distribution of sand lance eggs in relation to beach elevation are not available because data were not collected during their peak spawning period (that is, winter). The effects of sea-level rise and shoreline armoring on sand lance might be similar to those we describe for surf smelt, but we have little data to support that conjecture. Also, because we use a surrogate to estimate the elevation of shoreline armoring we might have underestimated the effect of sea-level rise on spawning where armoring is below our surrogate elevation. Further, our analyses did not account for likely changes to beach profiles or sediment size likely to occur with elevated sea level. Failure to account for these effects might underestimate the effect of sea-level rise and shoreline armoring on spawning habitat. Finally, estimates of sea-level rise are uncertain, especially for specific locations (Mote and others, 2008). We used a range of sea-level rise estimates to address this problem. Because we make conservative assumptions (for example, beach profile and substrate remain suitable) for our analyses, our detection of substantial loss of spawning habitat likely is robust.

Our analyses suggest that addressing shoreline armoring effects on beach morphology and surf smelt and sand lance spawning habitat is an important and urgent management concern. Loss of beach spawning habitat as a result of sea-level rise and shoreline armoring is likely to be widespread because much of the shoreline of Puget Sound is already armored and the desire to armor shorelines is expected to increase as additional shoreline is developed (Quinn, 2010) and as sea level rise speeds beach migration (Griggs and others, 1994; Johannessen and MacLennan, 2007). Further, the discontinuous geographic distribution of spawning occurrence and egg abundance suggest that loss of a relatively small number of spawning beaches might have a large detrimental effect on egg abundance. Importantly, some regulatory protection of surf smelt and sand lance spawning habitat exist, but those measures fail to take into account the expected environmental change and spatiotemporal variation in spawning. Further, existing regulatory protection fails to consider the cumulative or off-site effects of projects and provides no ability to deny projects for single-family residences, even if the project might exacerbate losses on other beaches. Effective conservation of surf smelt and sand lance should address such regulatory shortcomings.

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Impacts of Shoreline Armoring on Sediment Dynamics

Peter Ruggiero[1]

Abstract. The shores of Puget Sound rapidly are being hardened and covered with artificial structures. Although shoreline armoring often succeeds in protecting upland investments, shoreline armoring activities are hypothesized to represent a significant source of nearshore morphodynamic and marine habitat modification in Puget Sound. Shoreline armoring is believed to affect physical processes in many ways, primarily by causing beach narrowing, sediment coarsening, and a decrease in the natural sediment supply from eroding bluffs. Shoreline armoring also is thought to affect biological processes through loss of upper intertidal habitat, changes in sediment composition, and decreased organic input. However, it has not been conclusively confirmed in the field or the laboratory whether currents and sediment transport rates will increase or decrease in front of a hardened shoreline, as compared to a non-armored section of beach, and whether the sedimentary environment will be significantly modified. The effect of seawalls on beaches has been found to be most sensitive to the position of the seawall within the surf zone, the beach slope, and the reflection coefficient. This paper will review various studies exploring seawall impacts on sediment dynamics and suggest pilot investigations specific to the Puget Sound consisting of beach monitoring, field experiments, and modeling efforts.

Introduction

The effect of seawalls on beaches has been a topic of considerable research and controversy for many years, and recent reviews of the available literature (Kraus, 1987; Griggs and Tait, 1990; Kraus and McDougal, 1996; Coyle and Dethier, 2010) have demonstrated the need for still more study. Beaches have been reputed to respond to wave-seawall interactions in many ways, including; the formation of scour troughs, beach lowering, end scour, up-coast accretion, down-coast erosion, far down-coast shoals, reflection bars, and delayed post-storm recovery. Processes identified as having contributed to these possible responses include those such as sediment impoundment (groin effect), removal of upland sand from the sediment budget, wave reflection (fig. 1), acceleration of longshore currents, and increased sediment mobilization. Controls on how these processes affect beach change also have been discussed: long term shoreline change (passive or background erosion), storm events (active erosion), position of the seawall relative to the surf zone, width of the surf zone, sediment supply, and specific characteristics of waves and the seawall.

Figure 1. Seawalls impact nearshore hydrodynamics in many ways, including wave reflection. Photo Credit Carl Schoch (Homer, Alaska).

Confusion and disagreement in the literature is compounded by the lack of sufficient field data and confounding results from physical and theoretical models. In this (non-exhaustive) review we highlight a variety of recent efforts aimed at understanding the impacts of seawalls on sediment dynamics. We then offer a suggestion as to why such confusion remains and suggest some areas where studies specific to the Puget Sound can shed light on this difficult problem.

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Classifying the Problem

It generally is accepted that on beaches experiencing **passive erosion** (for example, beaches eroding because of relative sea-level rise) the beach fronting a seawall will eventually disappear. As an example, the armoring of shorelines in Oahu, Hawaii, has been quantitatively shown to cause narrowing and the loss of sandy beaches over an approximately 50- year period on a coast experiencing 1.55 mm/yr of relative sea-level rise (fig. 2; Fletcher and others, 1997). In contrast, three long-term field studies have documented seawall-backed beaches experiencing no significant negative impacts. These studies, in California (Griggs and others, 1994), Oregon (Hearon and others, 1996), and Virginia (Jones and Basco, 1996), each extend over time scales on the order of a decade. No measurable or significant differences between profiles for seawall-backed and non-armored beaches were found in these studies, suggesting little long-term effect of seawalls on the beaches. Because these studies spanned periods of only about a decade, however, sea-level rise, and therefore passive erosion, was relatively unimportant. These studies were assessing the impacts of seawalls on beaches that intermittently were experiencing **active erosion**. The confusion, and sometimes controversy, is about the impacts of seawalls on beaches during episodes of active erosion.

The aforementioned results are in part attributable to the position of the walls relative to mean sea level and the frequency and intensity with which they are impacted by waves. In the California and Oregon studies, the walls were impacted by waves only during the largest winter storms. Weggel (1988) suggested a classification of seawall types based on the seawall's position on the beach and the water depth at the toe of the structure (table 1). The beaches in the Oregon and California field studies would be classified as Type I to Type III, depending on the season and storm condition, whereas the seawalls studied in Virginia can be classified as Type III to Type IV, depending on season and location. In this context, the Weggel (1988) classification helps to explain why the Oregon and California study sites experienced few decadal scale impacts as a result of armoring but sheds little light on the minor impacts experienced in the Virginia study. Data on the Oahu study sites are insufficient to enable their classification (Fletcher and others, 1997).

Table 1. Weggel's Seawall Classification.

Type	Location of Seawall
I	Landward of maximum storm runup – never impacted by nearshore hydrodynamics at present sea level stage
II	Above the still water line associated with maximum storm surge but below the level of the maximum runup
III	Above Mean High Water and below the still water line of storm surge
IV	Within the normal tide range; base is submerged at high water
V	Seaward of MLLW; base is always submerged; subjected to breaking or broken waves
VI	So far seaward that incident waves do not break on or seaward

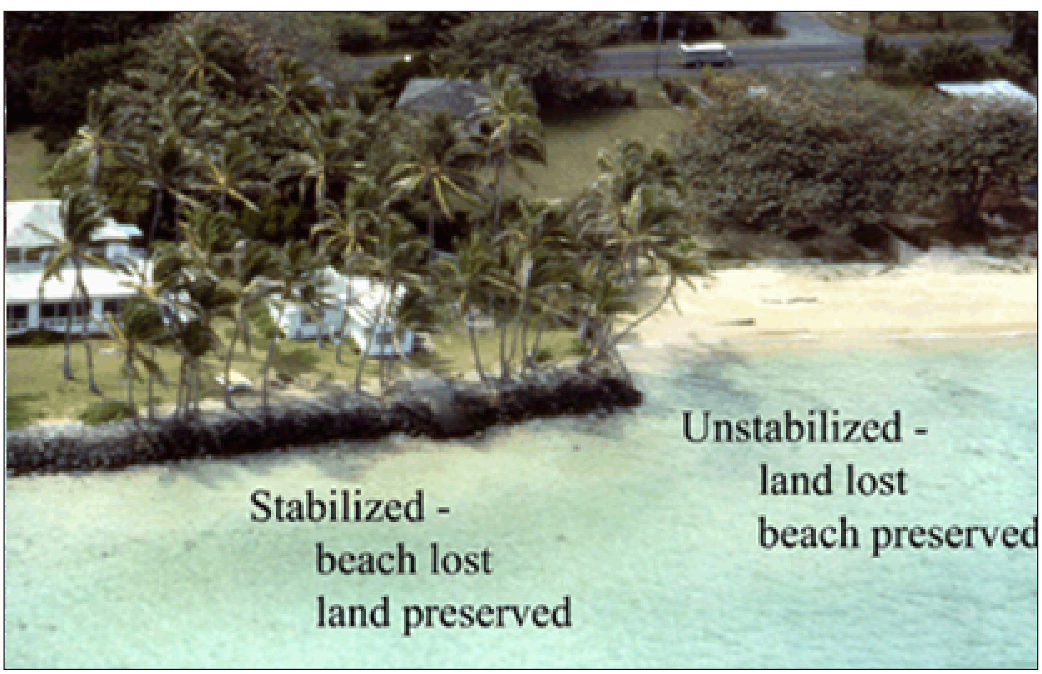

Figure 2. Example of the impact of seawalls on beaches under conditions of 'passive' erosion. Photo Credit Chip Fletcher (Hawaii).

Recent Studies on the Impact of Seawalls

Cross-Shore Processes

A recent study developed a modified version of the cross-shore profile model SBEACH, which explicitly includes wave reflection from the seawall and its affect on wave breaking and setup (McDougal and others, 1996). This study yielded two surprising results. The first is that the beach change predictions including reflected waves were not substantially different from those neglecting reflection (that is, the standard SBEACH model with a no transport condition at the location of the seawall). The second was that a large scour trench did not always develop at the toe of the seawall, even for very energetic waves. These numerical results were confirmed in the 'large-scale' model tests conducted as a component of the SUPERTANK experiments (Kraus and others, 1992). The agreement of these two-dimensional numerical and physical models indicates that alongshore processes may be significant in event-scale seawall related effects (Kraus and McDougal, 1996). Unfortunately, there is much less understanding of the important alongshore processes in front of seawalls.

It should be noted, however, that in a recent 'medium-scale' wave flume experiment, El-Bisy (2007) physically simulated toe scour in front of seawalls and found that the scour depth increased with increasing distance of the seawall relative to the surf zone and with increasing wave steepness. Recent work, such as that by Lawrence and Chadwick (2005), who apply Boussinesq wave models to analyze the hydrodynamics of the partial standing wave in front of seawalls, are beginning to provide more rigorous insight on the processes and mechanisms involved in cross-shore sediment transport in front of seawalls, but significant work remains

Longshore Processes

Two recent studies provide the most detailed discussion of alongshore processes in front of seawalls available thus far, yet disagreement about the impact of seawalls remains. Rakha and Kamphuis (1997a and 1997b) developed a numerical model that includes the effect of a seawall on wave-transformation, wave-induced currents, and morphological evolution. Their numerical analyses, which were validated with small-scale physical model tests, suggested that seawalls had only a minor effect on the longshore current and beach profile evolution. In fact, the volume of erosion for beaches backed by seawalls was nearly the same as that for a beach without a seawall. Miles and others (2001) report on the first detailed field measurements of sediment transport processes in front of a seawall from an experiment on the southern coast of England. During the relatively low energy conditions measured, suspended sediment and longshore currents were observed to be stronger in front of a seawall than on an adjacent natural beach, resulting in a longshore sediment transport rate that was on the order of a magnitude greater in front of the wall. These results taken in combination suggest that it has not yet been (conclusively) confirmed in the field or the laboratory whether currents and sediment transport rates will increase or decrease in front of a hardened shoreline, as compared to a non-armored section of beach.

Ruggiero and McDougal (2001) developed a simple analytic model to estimate longshore currents and littoral transport on planar beaches backed by seawalls, the objective being to better understand the effect of seawalls on nearshore processes. The model is based on the depth- and time-averaged equations of motion in the nearshore, assuming no longshore gradients. Once the waves, incident and reflected, and the total water depth including setup are determined, the longshore equation of motion is used to calculate a mean longshore current. Once the longshore current in front of a seawall is known, an estimate of the longshore sediment transport profile is possible. Ruggiero and McDougal (2001) used a Bagnold-type energetics model (Bagnold, 1963), which simulates bed load and suspended load. The model assumes that the orbital wave motion mobilizes the sediment, wave power is expended maintaining the sediment in motion, and the presence of a mean current, regardless of how small, transports the sediment. In calculating the sediment transport, the same set of assumptions is employed as when determining the wave setup and the longshore current.

This model is an extension of the classical no seawall derivations of wave setup, longshore currents and longshore sediment transport on planar beaches (for example, Bowen and others, 1968; Bowen, 1969; Longuet Higgins, 1970a, 1970b; and McDougal and Hudspeth, 1983a, 1983b) and the standard assumptions are made. This model is developed for a beach backed by an infinite vertical seawall within the surf zone. The seawall must be located between the point of maximum setup on the beach face and the breaker line. Therefore, the model is valid for three of the six types of seawalls—Type-3, Type-4, and Type-5, described in Weggel's (1988) classification system—based on the seawall's location with respect to the shoreline (fig. 3). The model assumes shallow water, small angle of wave incidence, spilling breakers, and conservation of reflected wave energy flux. A partial standing wave develops in front of the seawall, causing modulations in the bottom shear stress, radiation stress, setup/setdown, longshore current, and longshore sediment transport (fig. 4). Modulations associated with the total water depth and bottom stress are relatively small and can be neglected. The modulation of the radiation stress is retained and forces longshore current and sediment transport profiles, which behave quite differently than no seawall formulations.

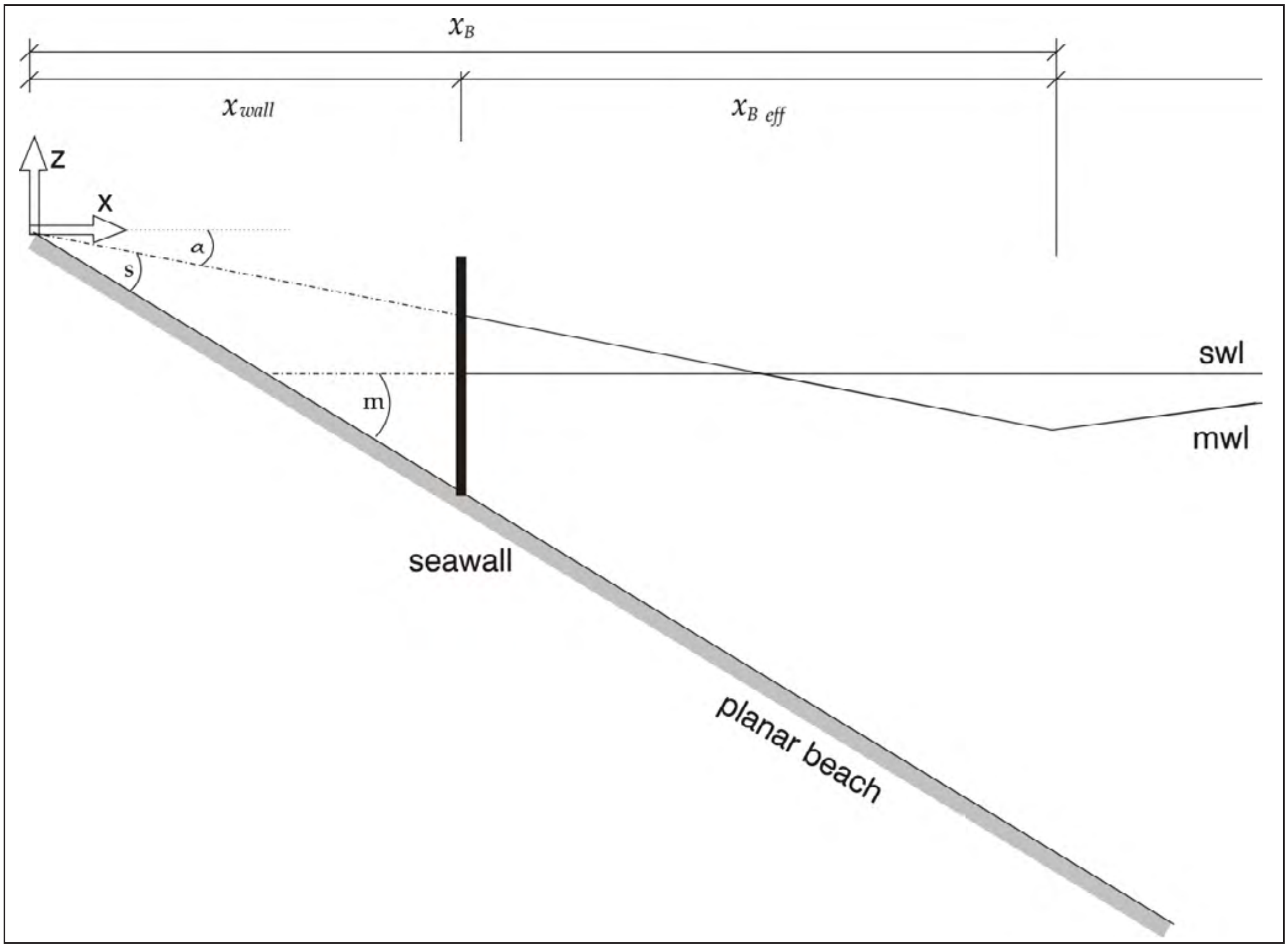

Figure 3. Profile view definition sketch of the analytical model of Ruggiero and McDougal (2001), where *m* is the planar beach slope, α is the slope of the wave setup, *s* is the total slope, x_{wall} is the cross-shore location of the seawall, x_B is the surf zone width, $x_{B\ eff}$ is the effective surf zone width with the seawall, *swl* is the still water line, and *mwl* is the mean water line accounting for wave setup/setdown.

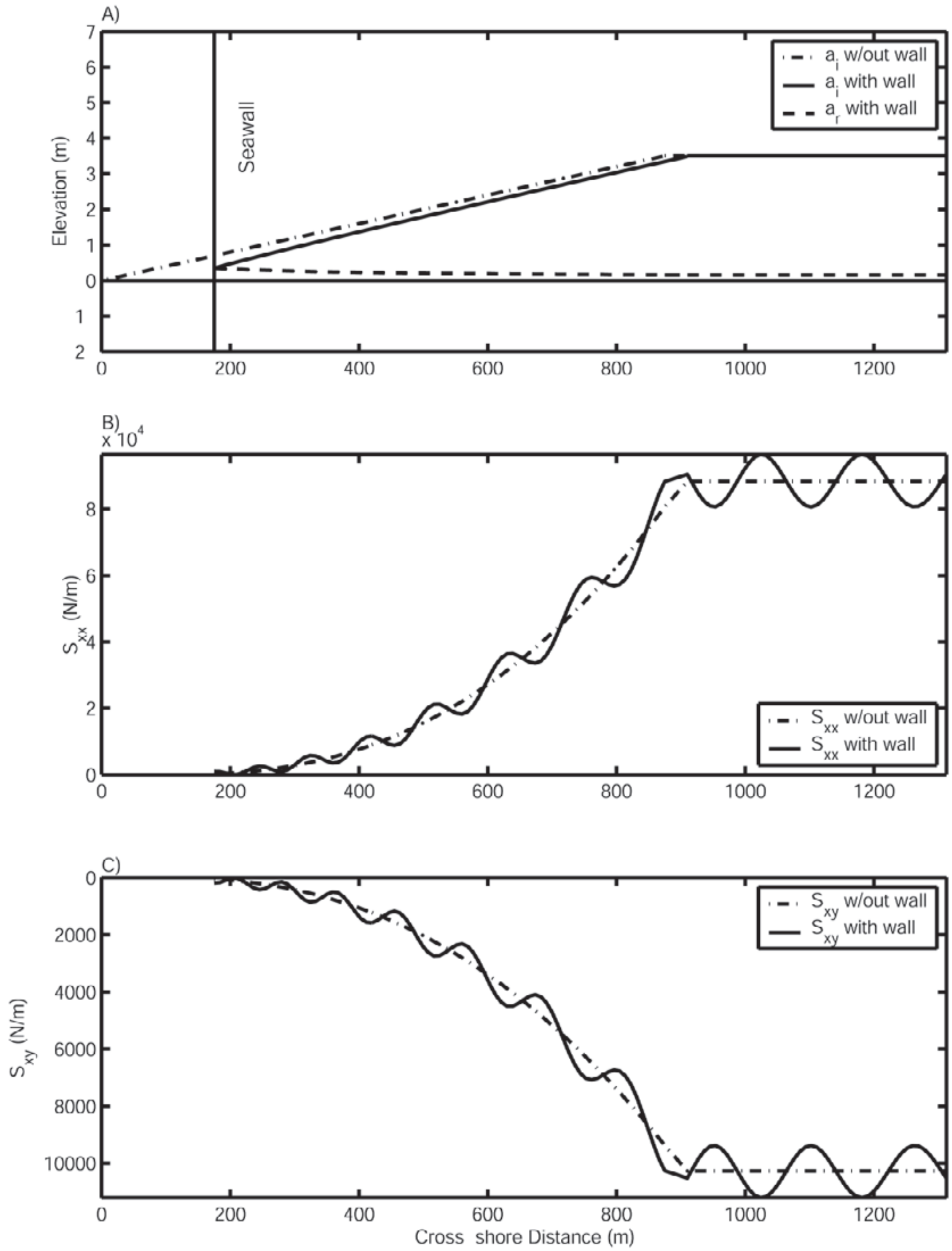

Figure 4. Cross-shore variation of (*A*) incident, a_i, and reflected, a_r, wave amplitudes, (*B*) onshore component of the onshore directed radiation stress, S_{xx}, and (*C*) alongshore component of the onshore directed radiation stress, S_{xy}.

Reflection from a seawall causes waves to break further seaward, resulting in a steeper total water depth slope. However, the effective width of the surf zone (the distance from the seawall to the break point) is actually less than the surf zone width without a seawall. As the reflection coefficient goes to zero, the model collapses to the classical no-seawall solutions for wave setup, longshore current, and sediment transport on planar beaches. The magnitudes of the longshore current and sediment transport in front of a seawall can be either greater than or less than a similar beach without a seawall depending on the location of the seawall in the surf zone for particular choices of beach slope and wave conditions (figs. 5 and 6). A comparison with the solution to the linear long wave equation suggests that the position of the seawall serves to tune the surf zone with some positions forcing a resonant condition, causing local maxima and minima in the behavior of the integrated longshore current and sediment transport.

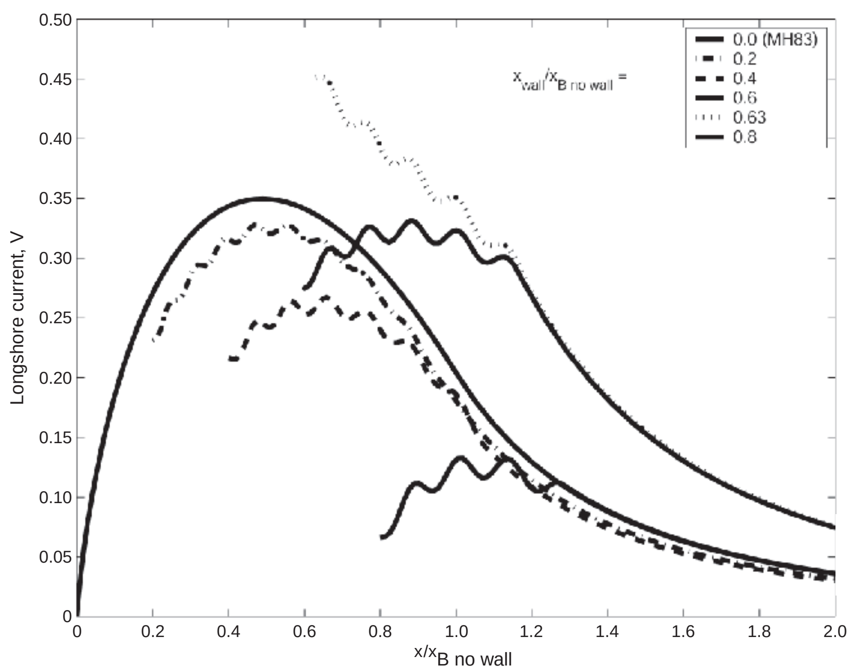

Figure 5. Longshore current profiles fronting a seawall for model case 3d (H_s = 7m, T_p = 15s, and beach slope = 1V:100H) and several positions of the wall across the surf zone. The thick solid line represents the classical longshore current solution with no seawall. The longshore current, V, has been non-dimensionalized by the longshore current at the break point and the cross-shore coordinate is non-dimensionalized by the width of the surf zone for the no-wall condition, $x_{Bnowall}$.

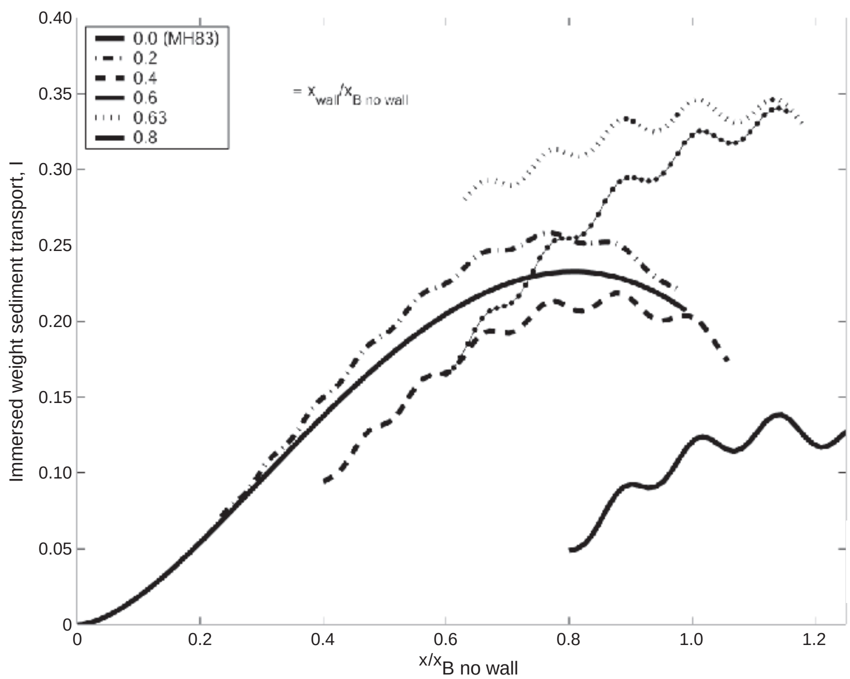

Figure 6. Sediment transport profiles fronting a seawall for model case 3d (H_s = 7m, T_p = 15s, and beach slope = 1V:100H) and several positions of the wall across the surf zone. Symbols are the same as figure 5. The non-dimensional immersed weight sediment transport, I, has been non-dimensionalized by the no seawall sediment transport evaluated at the breaker line.

Summary and Suggestions for Future Research

What remains clear is that the debate about the effect of seawalls on beaches has not been fully resolved. However, the results of the Ruggiero and McDougal (2001) study indicate potential mechanisms resulting in the contradictions in the available seawall literature. The effect of seawalls on beaches seems to be most sensitive to the position of the seawall within the surf zone, the beach slope, and the reflection coefficient, and future work should investigate these parameters in detail. Rigorous field measurements at a variety of sites with differing morphologic and hydrodynamic characteristics as well as physical and numerical modeling efforts are still necessary to provide much needed insight into the seawall problem. Therefore, testing the hypothesis that shoreline armoring activities represent one of the most dramatic sources of nearshore morphodynamic and marine habitat modification in Puget Sound is not only important locally but worldwide to beaches backed by seawalls.

To address the impacts of seawalls in the Puget Sound, we make the following suggestions regarding further study; investigations that include beach monitoring, field experiments, and numerical modeling:

5. Synthesize existing inventories of armoring trends; identify field sites for monitoring, field experiments, and modeling efforts; quantify the percentage of Puget Sound shoreline suffering from passive erosion; attempt to quantify rates (volume) of sediment source reduction as a result of shoreline armoring. (Desk Studies).

6. Develop a nearshore morphology monitoring program along walled/no-walled sections of coast. Separate short-term morphodynamic variability (active) from interannual or longer-term shoreline change trends (passive). (Field Studies).

7. Investigate the interactions between seawalls and active nearshore processes via detailed examination of the following: random high frequency fetch limited waves, complicated beach morphology and mixed sediment environment, and variable water levels changing position of seawall relative to surf zone. (Field Studies and Numerical Modeling).

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Ecological Effects of Coastal Armoring: A Summary of Recent Results for Exposed Sandy Beaches in Southern California

Jenifer E. Dugan[1] and David M. Hubbard[1]

Introduction

The use of coastal armoring is already widespread on developed coastlines and is expected to escalate in response to the combination of expanding human populations, coastal erosion, and sea level rise. Although there is an extensive literature on the physical effects of armoring on open coast beaches (see reviews by Kraus and McDougal, 1996; Griggs, 2005a, 2005b; Weigel, 2002a, 2002b, 2002c), relatively few studies have investigated the ecological implications. This is true even though sandy beaches harbor distinctive ecological communities and provide critical foraging and nesting areas for threatened wildlife, such as sea turtles and shorebirds (for example, Schlacher and others, 2007). Consequently, ecological impacts of armoring have been largely overlooked in coastal management and conservation and rarely are considered in decision-making or policy (Dugan and others, 2011a). However, results from recent studies suggest that the ecological effects of armoring and other coastal defense structures on open coast beaches could be important (Martin and others, 2005; Dugan and Hubbard, 2006; Dugan and others, 2008).

In this paper, we provide a summary of the conceptual model we developed for predicting potential ecological responses to coastal armoring. Our model framework incorporates the presence, extent, and functioning of multiple intertidal zones, as well as changes in beach width in general. Using available information on ecological communities of exposed sandy beaches, we hypothesized that changes in the width and extent of intertidal zones could affect the diversity, abundance, and structure of the intertidal community with strongest effects on the upper zones of the beach. We predicted that these effects could in turn reduce the prey resources available to shorebirds and their use of beach habitats. We summarize the results of our investigations of a number of the ecological responses expected from the loss of intertidal and supralittoral beach habitat associated with coastal armoring, including the reduction or loss of intertidal zones and associated invertebrates, reduced accumulation of macrophyte wrack and decreased shorebird use.

Conceptual Framework

Coastal armoring, including seawalls and rock revetments, has been shown to reduce intertidal beach widths through the processes of placement loss, passive erosion, and increased erosion directly seaward of structures (Griggs, 1998, 2005b; Hall and Pilkey, 1991; Tait and Griggs, 1990). The most widely documented initial effect of coastal armoring is placement loss, whereby the footprint of the armoring structure and any backfill material covers or replaces existing coastal habitat (Griggs 2005a, 2005b). The magnitude and relative importance of passive erosion and active erosion effects on beach widths are subject to more debate. To provide a conceptual framework for assessing biological effects of armoring, we developed hypotheses concerning patterns of beach habitat loss associated with coastal armoring and its consequent effects on biota (table 1). We propose that a number of ecological impacts of coastal armoring could be predicted using changes in the widths of different zones of the beach (for example, McLachlan and Jaramillo, 1995) as proxies for habitat loss (fig. 1). As beaches become narrower in front of armoring structures and as the intensity of interaction between structures and coastal processes (for example, wave reflection) increases, our model predicts habitat is lost disproportionately from the upper beach. Our model predicts the effects of armoring to be greatest on the landward-most coastal strand (for example, Feagin and others, 2005; Dugan and Hubbard, 2010) and supralittoral "dry sand" zones of the beach (fig. 1) in response to placement loss and passive erosion. Habitat near the driftline (fig. 1) also may be greatly reduced or eliminated; this is the primary zone for a diversity of wrack-associated and scavenging invertebrates, such as burrowing talitrid amphipods, ghost crabs, isopods and beetles, as well as for grunion, sea turtle and shorebird nesting. As the driftline shifts from the sandy beach to the armoring structure, the rich, three-dimensional habitats characteristic of this zone are replaced with the steep, reflective, two-dimensional habitat of the seawall. Although this manmade hard substrate may support a low diversity of rocky shore organisms (for example, Chapman, 2003; Chapman and Bulleri, 2003; Moreira and others, 2006), foraging opportunities for shorebirds would be greatly reduced.

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Table 1. Framework of hypotheses on the ecological effects of coastal armoring.

As beach width narrows in response to armoring structures:
Upper intertidal, supralittoral and coastal strand zones are lost disproportionately,
Loss of upper beach zones decreases number of habitat types available and room for migration of habitats/zones and macroinvertebrates with changing ocean conditions,
Reduction in habitat types reduces diversity and abundance of macroinvertebrates, particularly on the upper shore,
Loss of upper beach habitat eliminates nesting habitat for sea turtles, fish, birds etc.,
Lack of dry sand habitat and increased wave reflection associated with structures alters deposition and retention of buoyant materials, (e.g., macrophyte wrack, driftwood) further affecting upper shore biota and processes, including nutrient cycling,
Intertidal predators, such as shorebirds, respond to the combination of habitat loss, decreased accessibility at higher tides, and reduced prey resources.

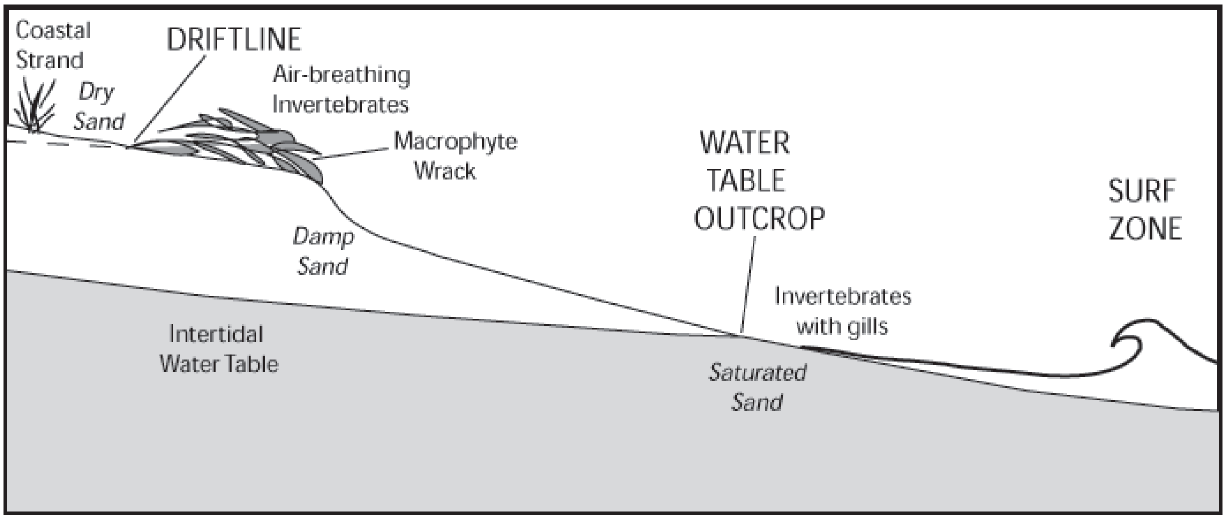

Figure 1. Profile of an exposed sandy beach showing the intertidal and supralittoral zones investigated. The relative locations of invertebrate types, driftline, macrophyte wrack and coastal strand vegetation are indicated.

Increased wave reflection and the loss of upper beach zones also could affect the retention of macrophyte wrack and other drift material in front of seawalls (Dugan and Hubbard, 2006), thereby reducing the primary support for the wrack-based component of the beach food web (see review by Colombini and Chelazzi, 2003; Dugan and others, 2003). The distribution and survival of mobile invertebrates of the lower shore (for example, donacid bivalves, whelks, isopods and hippid crabs) also may be reduced by restrictions on tidal migration (Klapow, 1972; McLachlan and others, 1979; Jaramillo and others, 2002b) imposed by seawalls. In addition, changes in concentrations of suspended sediment and altered littoral current velocities and sediment transport rates in front of seawalls (Miles and others, 2001) could affect the distribution of intertidal animals as well as that of sand. These projected ecological effects of armoring on invertebrates, wrack, and beach zones could reduce prey resources, accessibility, and the amount of foraging and nesting habitat available to shorebirds, thus diminishing the value of armored beaches for wildlife.

Research Approach

To investigate predictions from the conceptual model outlined above, we compared (1) widths of intertidal zones, including the distance to the driftline and the water table outcrop (see fig. 1), (2) standing crop of macrophyte wrack, (3) distribution and abundance of mobile upper beach invertebrates, and (4) distribution and abundance of birds on paired armored and unarmored segments of four beaches in southern California (Dugan and Hubbard, 2006; Dugan and others, 2008). These studies were conducted on wave-exposed intertidal beaches in Santa Barbara County, California, where the coastline consists primarily of narrow, bluff-backed beaches perched on wave-cut bedrock platforms. At each of the four study beaches we studied (1) a segment of shoreline immediately seaward of an intertidal concrete seawall (hereinafter armored segment) and (2) an adjacent unarmored bluff-backed segment of shoreline of the same length and with similar orientation (hereinafter unarmored segment). The seawalls we studied are 60-plus-year-old massive concrete structures ranging from 170 to 1,050 m long, with nearly vertical concave faces that interacted with high tides year-round (for example, waves were reflected off the seawalls at least daily) during our studies. The toes of all the seawalls were located at a low intertidal level but the degree of interaction of the seawalls with waves and tides on any particular sampling date depended on the sand levels. The elevations of the sand surface at the seawalls varied by an average of 0.98 m (range: 0.83 to 1.16 m) during the 1-year study with an average change of 0.36 m between subsequent months. When sand levels were low and waves were large, swashes or surf interacted with the seawalls even during low tides. Our study methods and statistical analyses are described in more detail in Dugan and Hubbard (2006) and Dugan and others (2008).

Results

Study results generally supported the predictions of our conceptual framework and revealed some unexpected effects of armoring on roosting birds (gulls, seabirds and others; table 2; see Dugan and Hubbard, 2006, and Dugan and others, 2008, for more details). Overall, armored shoreline segments supported significantly less habitat area, lower macrophyte wrack biomass, and fewer invertebrates and birds than did unarmored segments (table 2). Intertidal zone widths on armored beach segments were narrower than on adjacent unarmored segments. The uppermost zones, from the driftline to the upper beach limit, were lacking altogether, and mid beach zones (upper beach limit to the water table outcrop) were narrower (greater than two times) year-round on armored than on adjacent unarmored segments. The biomass of macrophyte wrack was significantly lower (1 to approximately 3 orders of magnitude) on armored segments. The abundance, biomass, and size of upper intertidal invertebrates (including talitrid amphipods and isopods) were significantly lower on armored segments. No difference was detected in the species richness of upper shore invertebrates between armored and unarmored shoreline segments; however, only a few species were found and sampling effort was relatively limited. Foraging shorebirds and roosting birds, including gulls and a variety of other species, responded with significantly lower species richness and abundance on armored segments. The result for roosting birds was not predicted by our model.

As hypothesized, the scale of effects we observed was strongest for the upper shore (table 2). Large differences (greater than tenfold) were found for extent of upper beach zones, macrophyte wrack, and the abundance and biomass of upper shore macroinvertebrates. The scale of effects for other ecological variables we measured ranged from 1.6 to 7.7-fold.

Table 2. Scales of ecological effects of armoring detected on open coast beaches, expressed as the ratio of mean values from the pairs of unarmored and armored beach segments for each parameter listed.

[* $p \leq 0.05$, ** $p \leq 0.01$, *** $p \geq 0.001$, n.d. not detected]

Ecological characteristic	Scale of effect
Intertidal zone widths	
Upper beach: upper beach limit to driftline	36x***
Mid beach: upper beach limit to water table outcrop	2.1x***
Macrophyte wrack (standing crop)[1]	374x*
Macroinvertebrates (upper shore)	
Species richness	n.d.
Abundance	10.6x*
Biomass	16.1x***
Mean individual size	1.6x*
Shorebirds	
Species richness	2.0x***
Abundance	3.7x*
Gulls	
Species Richness	2.0x
Abundance	4.8x***
Other birds	
Species richness	3.3x***
Abundance	7.7x***

[1] Values from Dugan and Hubbard, 2006; Dugan and others, 2008.

Discussion

Habitat loss resulting from coastal armoring structures and the narrowing of beaches in front of such structures was evident year-round for the seawalls we studied in on open coast beaches of southern California. Our results supported the prediction that upper intertidal beach zones would be lost and mid-intertidal zones reduced in front of coastal armoring structures. Armoring affected the “dry” upper beach zones most strongly, with all the zones above the driftline missing on armored segments in almost every survey. The reduction in width of the highest beach zones (above the driftline) observed for the armored segments compared to adjacent unarmored segments (average = 3.5 m) was consistent with the scale of placement loss expected for the seawalls in the study and demonstrates the relative importance of this armoring impact on narrow beaches. However, the overall narrowing of the mid beach above the water table outcrop (see fig. 1) on armored segments (11.4 m) was much greater than expected from placement loss alone, suggesting that the effects of passive erosion were also present in this zone. The contrast between our results on armoring effects on the widths of mid-beach zones and those of Jaramillo and others (2002a) for a newly constructed seawall may be related in part to the differences in age of the armoring structures studied (20 months versus 60-plus years). No comparisons are possible for upper beach zones because their study did not compare zone widths above the driftline.

Predicted ecological effects of the observed loss and reduction in beach zones, including declines in intertidal invertebrate communities, were supported by the differences in abundance and biomass of mobile upper beach invertebrates that we observed on open coast beaches. In a study of sheltered beaches on Puget Sound, the abundance of talitrid amphipods and insects also was significantly higher on natural beaches than on armored beaches (Sobocinski, 2003; Sobocinski and others, 2010). In contrast, a well-designed study of short-term responses (20 months) of beach invertebrates to a newly constructed seawall in Chile did not find significant effects of armoring on the overall macroinfaunal invertebrate community (Jaramillo and others, 2002a) or on populations of two abundant invertebrates (the cirolanid isopod, *Excirolana hirsuticauda* and the anomuran decapod, *Emerita analoga*) that inhabit lower intertidal zones of open coast beaches. However, upper beach invertebrates, such as talitrid amphipods, were not compared separately in their analyses. This contrasting result is quite valuable in the context of understanding ecological effects of armoring because it indicates that additional factors, including the age and the position of the structure on the beach profile, may be important in predicting impacts.

Effects of armoring on upper beach invertebrates may be associated in part with impacts to wrack retention on armored beaches. As found here for open coasts, wrack abundance also was significantly lower on sheltered beaches with armoring (Sobocinski, 2003). The majority of invertebrates in our samples were talitrid amphipods, a group known to respond to wrack availability on beaches (for example, Dugan and others, 2003) and which play a major role in the processing and breakdown of wrack (Lastra and others, 2008). Therefore, the significant reductions in wrack biomass associated with armoring are likely to affect abundance and distribution of these key taxa, as well as wrack breakdown and nutrient cycling on beaches (for example, Dugan and others, 2011b). Impacts to wrack-associated invertebrates, which make up more than 35 percent of the species on most beaches in the region (Dugan and others, 2003) have clear implications for intertidal biodiversity. In addition, wrack-associated invertebrates, such as talitrid amphipods, often are an important prey resource for shorebirds and, importantly, are available to avian predators on a wider range of tide levels than many of the suspension-feeding invertebrates found lower on the beach. Declines in the abundance of upper-intertidal invertebrates thus results in reduced prey availability and reduced foraging windows for shorebirds on armored beaches.

In addition to the macroinvertebrates we studied, the high intertidal zone around the driftline is nesting habitat for several ecologically and commercially important marine fish and invertebrate species, including the California grunion (*Leuresthes tenuis*) on open coastlines, and surf smelt (*Hypomesus pretiosus*), Pacific sand lance (*Ammodytes hexapterus*), and American horseshoe crabs (*Limulus polyphemus*) on protected shores. These animals lay their eggs in this zone during spring high tides to incubate in the sand through the neap tides and hatch on a subsequent spring tide series. Negative effects of armoring on embryo survival already have been reported for the surf smelt in Puget Sound (Rice, 2006, 2010) and could be expected for California grunion on open coasts. The reduction or loss of this high intertidal zone resulting from coastal armoring has clear consequences for the success of reproduction in beach-dependent fish and crab species. The importance of Pacific sand lance and surf smelt as forage fish for salmon and seabirds and of horseshoe crab eggs to migrating shorebirds (for example, Red Knot) has stimulated efforts to identify and protect spawning beaches from coastal armoring and other human impacts in the Puget Sound area (Reeves and others, 2003; Rice, 2006, 2010; Krueger and others, 2010) and in Delaware Bay (Jackson and others, 2010).

The prediction that shorebirds would respond to the presence of coastal armoring was strongly supported by our results. Of note, the significant effects of armoring on shorebirds were found during low-tide surveys when the greatest amount of intertidal habitat was available to the birds. During higher tides, bird use including foraging and roosting would be eliminated in front of these seawalls. The response of shorebird abundance to coastal armoring (greater than threefold) exceeded that predicted by the overall loss of beach habitat area alone (twofold) (table 2), suggesting that other factors, including prey abundance, availability of high tide feeding habitat, and refuges, as well as other landscape factors, may have contributed to the observed responses. Shorebird diversity and abundance have been correlated with prey availability on California beaches (for example, Dugan and others, 2003). The habitat and invertebrate prey resources of sandy beaches may be increasingly critical to the survival and success of these avian predators in developed coastal regions (Hubbard and Dugan, 2003). Our results suggest that further investigations of relationships between coastal armoring and shorebird conservation are worthy of consideration on open coasts.

Our finding that gulls and seabirds also responded negatively to armoring indicates ecological implications that extend beyond prey resource availability for coastal birds. In fact, the responses of gulls and other birds (both greater than fourfold) to armoring were stronger than that of shorebirds overall (greater than threefold) (table 2). This result suggests that armoring affects the use of beach habitat preferred for roosting or loafing by gulls and seabirds that are not using the beach for foraging. The addition of effects of armoring on roosting habitat to the suite of predictions in the conceptual framework is supported.

Significant ecological impacts to several components of the beach community were associated with the old, nearly vertical seawalls that interacted daily with tides and waves in our study (table 2). Ecological responses to other types of coastal armoring structures may differ (for example, Martin and others, 2005) and likely would scale with the physical effects of these structures on beach zones; however, further investigation is needed. An important consideration relative to our results is the location of the armoring structure on the beach profile, which affects the amount of interaction with waves and tides. Generally, the lower the structure on the beach profile, the greater the physical impacts associated with that structure (Weigel, 2002a, 2002b, 2002c). The ecological impacts of any armoring structure would be expected to be similar, whether location on the profile is a result of initial placement of the structure or subsequent erosion of the beach. Predicted sea level rise will not only increase beach erosion and lead to expansion of the use of coastal armoring, it will effectively shift the location of existing armoring structures to lower positions on the beach profile, hence increasing the physical and ecological impacts of existing armoring to beach ecosystems.

Conclusions

The combination of rising sea levels predicted by climate change models and the increasing extent of coastal development and armoring (for example, Griggs, 1998) will accelerate beach erosion and loss and increase ecological impacts to sandy beach ecosystems on a scale that is unprecedented. Loss of habitat resulting from coastal armoring was associated with significant impacts to mid- and upper-beach zone widths, macroinvertebrates, foraging shorebirds, and roosting gulls and seabirds on open coast beaches (table 1). Further investigation of ecological responses to coastal armoring is needed to inform the management and conservation of these threatened ecosystems. We suggest that this research include studies designed to evaluate the effects of extreme events, which may have important interactive effects on morphodynamics and ecological processes. Longer term studies that lead to a greater knowledge of the trade-offs between the quantifiable and immediate impacts of placement loss and other potential impacts occurring over longer time scales, including passive and active erosion, clearly are needed. In addition to developing a better understanding of the potential ecological impacts of individual structures, it is crucial to develop an approach for evaluating the cumulative impacts of coastal armoring for coastal regions.

Relevance to Puget Sound Ecosystems

This review summarizes our recent research on the effects of large (greater than 100 m), old (greater than 60 years) seawalls on the ecology of open coast, sandy beaches. Although it may not be possible to apply the results of this research directly to the various types and sizes of armoring structures constructed on the tide-dominated sheltered shores in Puget Sound, the framework we developed for investigating ecological effects may be of use. The ecology of all soft sediment shoreline habitats, sheltered and open-coast, is strongly affected by sediment supply, wave-energy, exposure and tidal regime. In all systems, the installation of coastal armoring structures can directly alter shore habitats through placement loss, passive erosion, and perhaps other mechanisms (for example, active erosion, depth of activation). Assessments of possible ecological impacts of armoring to open coast and sheltered soft shore ecosystems may be more effective if the relative widths and distributions of key shore zones are quantified. Impacts may be most immediately apparent and strongest in high shore zones where the direct effects of placement loss reduce or eliminate habitats and high tide refugia and alter physical or biological processes (for example, retention and processing of wrack). Large armoring structures may also fragment habitats, reduce connectivity with adjacent habitats, and inhibit significant ecotone processes and exchanges. Animals at higher trophic levels (for example, shorebirds, seabirds, turtles, fish) that use soft shores may be affected by alterations or reductions in habitat availability and quality (for example, area and type of habitat available, nesting areas, roosts, high tide refuges) and by bottom-up effects resulting from changes in prey assemblages (food resources) associated with habitat alteration as a consequence of coastal armoring.

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

Nancy L. Jackson[1], Karl F. Nordstrom[2], and David R. Smith[3]

Introduction

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

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

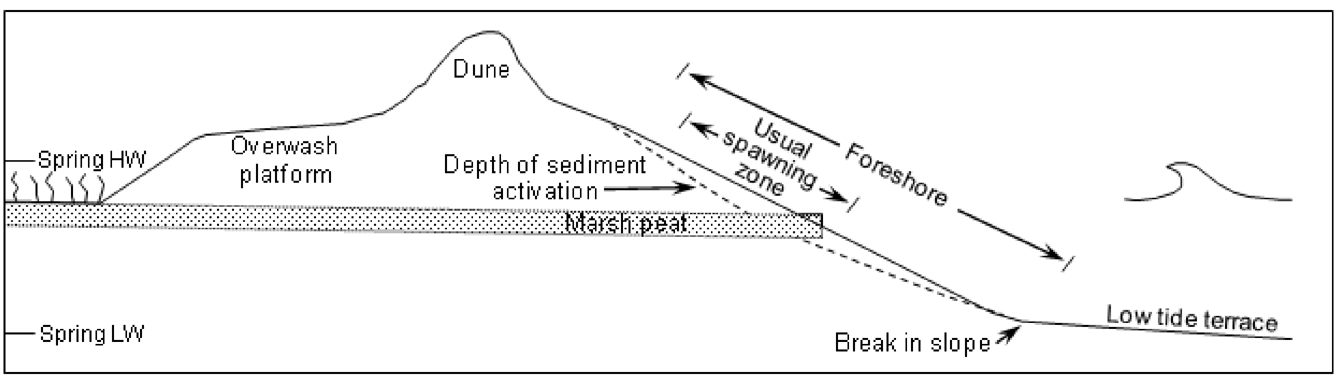

Figure 1. Schematic of an estuarine barrier transgressing over a marsh and exposing peat on the foreshore.

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

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

Horseshoe Crab Habitat on the Delaware Bay Shoreline

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

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

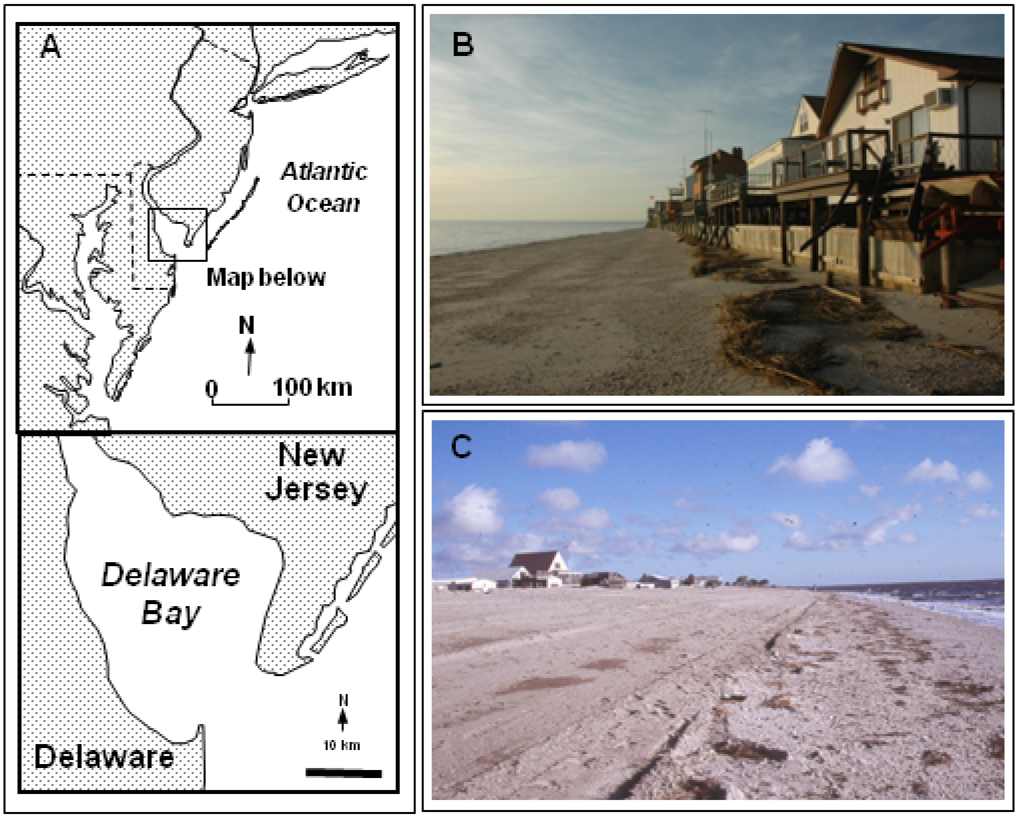

Figure 2. Locator maps (*A*), east side (*B*), and west side (*C*) of Delaware Bay.

Effects of Bulkheads on Sediment and Biota

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

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

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

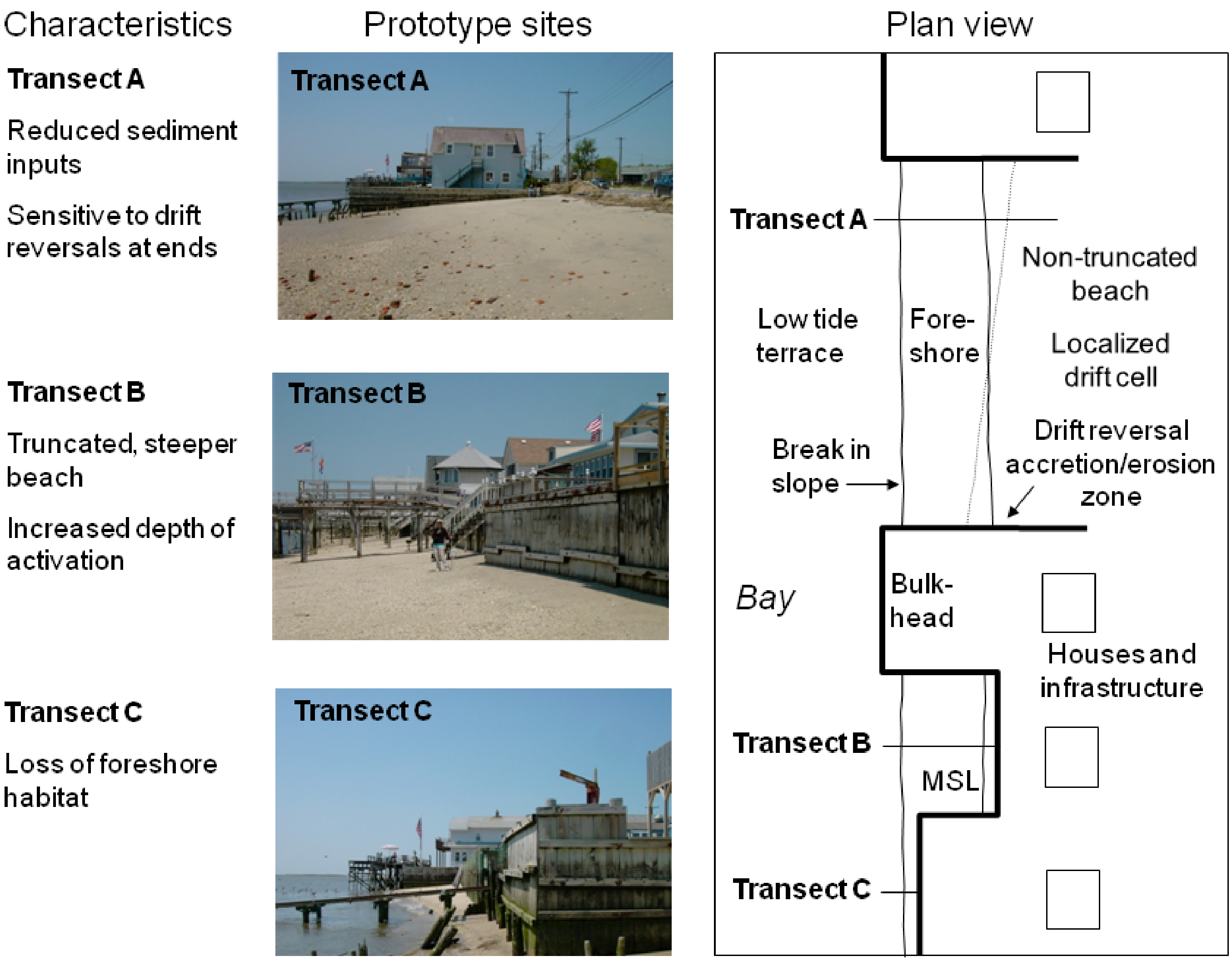

Figure 3. Complex platform configuration and differences in beach width resulting from incremental bulkhead construction.

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

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

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

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

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

Conclusions

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

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

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Management Needs

Armored railroad grade along the high bluffs north of Carkeek Park in Seattle. Photograph taken by Hugh Shipman, Washington Department of Ecology.

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Developing a Guidance Document for Puget Sound Marine Shorelines

Bob Barnard[1]

Introduction

Shoreline armoring—the construction of bulkheads and seawalls—has become a significant environmental issue on Puget Sound. Armoring influences beaches on the shoreline, alters coastal ecology, and reduces the resilience of the coast to rising sea level (Williams and Thom, 2001). The Aquatic Habitat Guidelines (AHG, a consortium of federal, state, and local stakeholder groups) document "Protecting Nearshore Habitat and Functions in Puget Sound" (Environ Vision and others, 2007) states that planners should enforce or encourage the use of alternative design methods in nearshore development projects to avoid and minimize environmental impacts. Currently, there is no comprehensive document to provide a technical foundation for the design of alternatives to rock and concrete bulkheads and the myriad of other projects, including restoration, that are proposed for our shorelines. The audience for this document would be the restoration, regulatory, and marine shoreline community who are looking for help to protect nearshore resources while permitting development. A proposed Marine Shoreline Design Guideline (MSDG) would build on the scientific background developed at the Shoreline Armoring Impacts Workshop. This guideline would integrate assessment, risk analysis, mitigation, and site requirements into the design processes, similar to the approach taken in AHG's Integrated Streambank Protection Guidelines (Cramer, Bates and others, 2002).

Aquatic Habitat Guidelines

The Aquatic Habitat Guidelines program is a group of agencies and stakeholders whose mission includes the promotion, protection, and restoration of fully functioning marine, freshwater, and riparian habitat through comprehensive and effective management of activities affecting Washington's aquatic and riparian ecosystems. Project participants include the Washington Departments of Fish and Wildlife, Ecology, Transportation, and Natural Resources; the Interagency Committee for Outdoor Recreation; the United States Army Corps of Engineers; and the United States Fish and Wildlife Service. Recently the Washington State Association of County Engineers and the Washington Forest Protection Association were added to the list of contributing agencies. This broad group produces guidance that has become essential in the design and permitting of aquatic projects. The composition of workgroups changes with the task, and participation in the MSDG development might include only a portion of the mentioned groups.

AHG has produced a number of successful guidance documents. Most relevant in this context is the Integrated Streambank Protection Guidelines (ISPG). The floods of 1996-97 caused catastrophic bank failures along many Washington rivers. The response of landowners was to use traditional rip rap countermeasures, resulting in serious environmental consequences. Natural resource agencies found themselves without viable alternatives to rip rap and without a rational mitigation strategy to compensate for the impacts. At the same time, certain salmon species were listed under the Endangered Species Act. This required a coordinated and consistent approach to the regulation of development that affected these fish.

AHG documents begin with a set of guiding principles to focus and direct them. There are AHG General Guiding Principles for Project Planning and Implementation that cover all the guidelines. These include using the best available science; recognizing and maintaining geomorphic processes; encouraging responsible land use practices that maintain natural processes and avoid adverse cumulative effects; providing compensatory mitigation to restore historical ecological functions; considering the project impacts over time and across the landscape; and recognizing that monitoring and adaptive management are critical components of restoration, mitigation, and management activities (Cramer, Bates and others, 2002). Without guidance documents, the designers do not have these principles in front of them to guide their decisions, and the permit writers or planners do not have a rationale for stewardship.

For example, a landowner's riverbank is washed away in a flood and part of his yard is gone. Before ISPG was published, the landowner might hire an engineer who refers to a time-honored U.S. Army Corps of Engineers (Corps) bank stabilization manual and designs a fractured rock revetment composed of rock of a certain size, laid at a certain thickness and slope, all determined from quantitative design methods and criteria. The landowner and designer feel confident that they have followed reliable advice. To a regulator charged with preserving and protecting natural resources, it is obvious that this is the worst possible alternative, but there is no comprehensive method to evaluate it and no alternatives to suggest that might mitigate impacts. ISPG provides those methods and alternatives, and this document has become

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a respected resource and the industry standard for environmental design of bank protection.

Present-day conditions along Washington's marine nearshore are similar to those in the late 1990s on Washington's rivers, and the need for a Marine Shoreline Design Guidance is nearly identical to the one that brought about ISPG. Thirty percent of the Puget Sound shoreline is already armored, and every year approximately 1.5 mi of new bulkheads are built and about 2.5 mi are replaced (R. Carman, Washington Dept. of Fish and Wildlife, oral communication concerning the number of Hydraulic Project Approvals written in Washington State for bulkheads on Puget Sound, May 2010). There are alternative techniques but no comprehensive monitoring to document their success, or standard of care for their proper design. MSDG will develop the science and design methodology for integrated shoreline protection.

Current Marine Shorelines Design Guidance

The structural approach to marine shore protection has been used and studied for generations and reached a highpoint in the Army Corps of Engineers' Shore Protection Manual (U.S. Army Corps of Engineers, 1984), in which engineers were given the tools to design marine shoreline protection. The underlying physical processes were analyzed and the design of seawalls, bulkheads, and revetments explained. The concepts of "protective beaches" and dunes were discussed as alternatives that supplied the aesthetic, recreational and dynamic characteristics lost in the structural approaches, although only in broad terms. This document has been superseded by the Coastal Engineering Manual (U.S. Army Corps of Engineers, 2008). This exhaustive work still contains the hard armoring design methods, but discusses environmental issues in planning and design, some alternative methods such as vegetated revetments, and extensively explores beach fill design (beach nourishment), and the creation or enhancement of berms, dunes, feeder beaches, nearshore berms, dune stabilization, and groins. Beach nourishment, in this context, is the construction of a wider protective beach, and/or a more substantial berm, using materials found in the backbarrier, offshore, or from navigation channel dredging. Largely, this design method is suited for open coast settings utilizing sand-sized sediments. The other alternative methods receive little attention, understandably, considering the generally large scale of Corps projects and the higher energy environments of many coastal developments.

The unique nature of Puget Sound beaches, and the challenges of protecting them, have been recognized for some time (Downing, 1983; Terich, 1987). Puget Sound has a glacial heritage, with beaches that generally are coarse grained, in a fetch-limited environment, and subject to large tidal ranges (Finlayson, 2006). This setting is distinct from the sandy, high energy open coast more common in the rest of the United States.

To adapt to the unique conditions on Puget Sound, some shoreline protection techniques, mostly hard armoring, but also a variety of soft methods, have been employed (table 1). Some variations on these techniques could be used anywhere, but local practice has modified their application in Puget Sound.

Rock and concrete bulkheads are probably the most commonly used techniques for shoreline protection, with new projects often fitting into an already established line of similar structures. Although some sites with high wave energy require aggressive, structural approaches, in many areas of Puget Sound rock bulkheads are really more like retaining walls for landscaping features or toe protection for bluffs than for dissipating wave energy with runup, as we might see them used on the coast. Similarly, vertical concrete bulkheads create an architecturally pleasing line and allow a lawn right up to the edge, rather than serving as a wave barrier. It has been argued that these methods are not essential and do not serve the common

Table 1. Marine shore protection techniques.

[Techniques adapted from Downing, 1983 and Zelo and others, 2000. Ecosystem impacts are the net sum of the advantages and disadvantages to the habitat and natural processes at the site: (-) indicates a negative impact, (+) a positive impact. Erosion control is the ability of the technique to stop upland erosion (+) in a given time frame, or (-) does not actively stop erosion. Fetch length characterizes the relative wave energy at the site from (L) a long fetch with high energy to (S) a short fetch with low energy]

Method of erosion control	Ecosystem impacts	Erosion control	Fetch length
Hard shoreline stabilization			
Sloping rock (rip rap) bulkhead	−	+	L
Vertical concrete or wood bulkhead	−	+	L
Rock groin	−	−	S
Soft shoreline stabilization			
Gravel beach nourishment	+	+	L/S
Berm and hillslope revegetation	+	−	S
Reslope, drift logs, anchored logs	+	+	S
Accommodation and avoidance			
Bulkhead removal, restoration of natural bank	+	−	S
Allow erosion of non-structural improvements	+	−	L
Drainage control	+	−	S
Zoning (SMA/GMA)	+	−	L
Move structure from harm's way	+	−	L

good (Terich, 1987), although the desires of landowners can be a powerful political influence, which, in an extreme case, resulted in the single-family residence exemption to saltwater bulkhead and bank protection rules in Washington State (Chapter 77.55.200, Revised Code of Washington). Washington Administrative Rule 220-110-285). These structural approaches are really the only active ways to protect high energy shorelines, although the success rate can be low depending on the quality of the design and construction. Accommodation and avoidance are the best alternatives in truly challenging high energy situations (Terich, 1987).

Groins are not commonly used on Puget Sound, and cause many problems when they are used. The intended effect is for transported sediment to fill up-drift of a groin over time, deepening the beach and protecting the upland development from wave attack (U.S. Army Corps of Engineers, 2008). Longshore drift on our coarse, fetch limited beaches is low and the effects of groins are reduced (Downing, 1983), as compared to the situation on rapidly moving sandy beaches. Breakwaters (not shown in table 1) are used worldwide to reduce erosion, but on Puget Sound breakwaters are used almost exclusively at marinas to reduce wave height to protect moored boats.

Gravel beach nourishment on Puget Sound is practiced in small scale projects using coarse sediment from upland sources (Shipman, 2002), as opposed to the large beach-fill projects mentioned above. The goal is to use indigenous materials to mimic natural processes, with the expectation that the nourished beach will perform much as a natural one (Johannessen and Chase, 2005), which is different from beach fill that increases the width and height of the existing beach (U.S. Army Corps of Engineers, 2008). Puget Sound beach nourishment probably is a more subtle undertaking than beach fill, which amounts to moving massive quantities of native materials about on the beach; careful planning and design are required for Puget Sound projects. It is now widely accepted that the design community needs more data to refine this technique for more general use (Shipman, 2002). Figures 1 and 2 show two examples of beach nourishment projects on Puget Sound. The Port Peninsula project (fig. 1) replaced a vertical bulkhead with a sloping gravel/cobble beach. It is, more or less, an artificial beach that creates a transition between a subtidal bench and the supratidal fill supporting Port of Olympia development. Figure 2 illustrates a finer grained beach nourishment project at a Superfund site in a protected harbor. The nourishment here is really a cap over contaminated sediments, but functions as a beach.

Considering the low-energy character of most shoreline sites in southern Puget Sound, bank revegetation and resloping should be much more common than they are. These techniques are inexpensive to implement and utilize natural materials and processes to manage unstable areas through site drainage and vegetation management (Myers, 1993). Further design development, with a reference to accepted geotechnical engineering practice and example projects, may be all that is necessary to make these techniques more acceptable to shoreline owners.

Figure 1. Port Peninsula beach nourishment, Budd Inlet, Washington.

Figure 2. Wycoff Superfund site beach nourishment, Eagle Harbor, Washington.

Wood is a plentiful, naturally occurring material in the upper intertidal and supratidal zones of Puget Sound beaches, and has found its way into many alternative shoreline protection projects here. The projects illustrated in figures 2–6 all have a wood component, either as slope stabilization features, to have a groin-like effect, for its habitat value as substrate for organisms, for accumulating finer sediment, or as a nutrient source. Drift logs and anchored logs are used frequently in Puget Sound alternative bank protection techniques to retain sediment and absorb wave energy during storms (Zelo and others, 2000). These logs can have both a stabilizing and destabilizing influence, however, depending on the severity of the storm. They remain stranded at high elevations or partly buried in beach sediments during low water events, but may become mobile at high water, working the upper shore and digging into otherwise stable sediments (Finlayson, 2006). This dual nature of large wood makes the design of bank protection measures complex under sensitive conditions. Anchoring is one alternative, although there are liabilities associated with the anchoring mechanism and uncertainty about the magnitude of wave energy, both of which would be remedied through monitoring and reliable guidance.

As the public and government agency attitudes toward responsible stewardship of natural shorelines improve, the accommodation and avoidance alternatives (table 1) should become more common. It is significant that the conservative Coastal Engineering Manual (U.S. Army Corps of Engineers, 2008) clearly outlined the continuum of response to erosion, flood surge, and sea level rise from do-nothing to rigid seawall, with all the possibilities in between. There are many points at which a landowner and natural resource agency can enter into this continuum, expressed in the range of projects listed in table 1. As landowners come to understand the value and benefits of the natural Puget Sound beach, they are more likely to consider bulkhead removal and restoration to natural conditions. In a given year, three to four bulkheads are removed in Puget Sound This represents only 2 percent of permitted projects, a number that can be increased with proper guidance to designers and landowners.

Figure 3. Turnbull large wood placement, Fox Island, Washington.

Figure 4. Frye Cove County Park, large wood and cobble slope stabilization, Eld Inlet. Washington.

Figure 5. Mercer large wood placement, Key Peninsula, Washington.

Figure 6. Suquamish Tribal Natural Resources large wood and bank resloping, Agate Pass, Washington

Washington's Shoreline Management Act, local Critical Areas Ordinances, and other local zoning laws govern activities on the shore. The effect of these laws varies with the county, although the intention is to limit activities, to reduce impacts, and to mitigate for the loss of natural function and values. The most powerful tool is the construction setback, which keeps development away from the dynamic shoreline environment (Terich, 1987). Finally, when all else fails and costs outweigh any benefits, the landowner must consider moving the structure or the dedicated use out of harm's way—physically moving the structure beyond the reach of expected erosion.

Through time, certain design techniques and construction details provide the basis for an engineering "standard of care." This standard is fairly well established for the traditional approaches, rock and concrete bulkheads. Soft armor techniques mentioned above are relatively new in the Puget Sound area and no standard of care has been established. This especially is true in high bank settings, where very risk-averse geotechnical assessments have recommended "hard" solutions in almost every case. We have for too long been working under the weight of past practices, which have weighed in favor of rigid structures regardless of their short- and long- term habitat impacts. Rip rap and concrete bulkheads have well-established design equations, standard sizes, and established sources of uniform materials. A similar body of knowledge and reliable sources of materials must be developed for alternative shoreline protection techniques (Johannessen and Chase, 2005).

Project design incorporates a factor of safety determined, in part, by the certainty inherent in the design, construction and materials. The other part of this factor concerns risk. The higher the risk, the higher the factor of safety, which influences not only the size and strength of the components, but also the technique used. Often, very high safety factors create heavy, overbuilt, rigid structures, which have corresponding high environmental impacts. Better guidance, more monitoring data, and more experience with multiple projects will lower this factor and improve the performance of alternative marine shoreline protection methods.

New Marine Shorelines Design Guidance

Approximately 200 times each year, someone in Puget Sound applies for a permit to either build a new bulkhead or replace an existing one (Carman and others, 2010). For each of these cases, one might ask the following questions: Given conditions in the drift cell and at the site, is a particular bulkhead necessary? If it were built, what would be its impacts to biota and natural processes at the site? How would you determine those impacts? Would an alternative protection technique be as effective and have a lesser adverse impact? Can we use beach nourishment in this instance? How could you improve a traditional bulkhead design to reduce its impacts? How do you mitigate for lost functions? These are the sort of questions that would be answered by the MSDG.

For example, a shoreline property owner wishes to replace his failing concrete bulkhead – the footing has been undermined and the wall has fallen over onto the beach. He hires an engineer, or a marine contractor, to design a replacement. His consultant determines, through standard calculations, the instability of his unprotected bank under the soil and wave conditions present at the site, and the proper design of a new footing and wall to replace the failed one. These are accepted procedures in the industry. When MSDG becomes commonly available, the landowner can obtain a copy, his consultant should already have a copy, and the permit writer has a medium to communicate the important concerns and alternatives to simple replacement of the failed structure. For instance, this is a high energy beach (MSDG has criteria for determining this) and a structural solution is necessary, but a rock bulkhead has fewer impacts (MSDG has tables to associate techniques with impacts) and requires less mitigation than concrete, the height of the rock can be reduced (MSDG has design criteria for rock revetments), and riparian vegetation can be planted on the top portion of the bank to partly mitigate for the wall. MSDG also might help the owner and his contractor determine that a structural alternative is not necessary and that restoring a natural bank with native vegetation might be effective, acceptable, and attractive.

With the publication of MSDG, we would expect the percentage of bulkhead removal projects to increase, beach nourishment to become more common, and rock and concrete bulkheads to become less common.

MSDG will follow an outline similar to that used in the successful ISPG. ISPG begins with the concepts of bank protection and moves through site and reach assessments. With this background, the designer is led through a selection process that weighs benefits and impacts of different techniques. Finally, the techniques themselves are described in detail with engineering criteria, drawings and example projects. The remaining one-third of the document is devoted to appendixes that provide the scientific and technical underpinnings of effective and environmentally responsible design. MSDG will reverse this order of considering topics somewhat by placing the scientific background up front.

MSDG will be a comprehensive assessment and design methodology, not simply a catalog of techniques or best management practices. One must understand the context in order to properly apply a technique, and MSDG would provide the Puget Sound perspective. The following is a description of the proposed document. Aquatic Habitat Guidelines documents have sought to integrate the civil engineering design with its environmental context. MSDG will cover coastal science relevant to Washington’s marine shorelines in order to establish the background for a process-based approach to shoreline modification design.

The permitting process is one way through which society protects natural resources and the rights and property of those affected by an activity. MSDG will describe how the proposed project fits into this regulatory framework at the federal, state, and local level. It will list relevant permits and regulations that apply to marine shoreline projects, and make the connection between regulation and the protection of natural resources. A goal of the guideline is to properly design projects that have the greatest likelihood of meeting permit requirements and mitigating for impacts.

Successful hydraulic projects begin with a good grasp of the conditions at the site. A site assessment describes the conditions that create the need for the project and the mechanisms that underlie it. Site assessments also describe the natural resources and the human infrastructure within the project area and their respective risks. Effective project plans also must consider how the project fits in a broader geomorphologic and ecosystem context, the process unit. A process unit consists (longitudinally) of the drift cell, and in elevation extends from the upland extent of the drainage system down to -10 m depth. The process unit assessment thus looks at the project site in the context of larger processes, such as the source, transport, and deposition of beach sediment. A single project may have profound influence on an entire drift cell, and it is this sort of project that will be closely examined in this assessment. The process unit assessment also needs to be part of larger planning processes, both at the county level and in the Puget Sound, to coordinate restoration and planning activities and to consider issues of cumulative impacts.

A complete project design integrates the assessment with risk management, mitigation for impacts that cannot be avoided, and the specific requirements of the proponent. MSDG will offer alternative approaches or techniques to solve the engineering problems at the site in an environmentally responsible way. Any given technique has costs and benefits, impacts, and enhancements. The goal of a project designed through this guidance is to balance these factors such that the project avoids or minimizes impacts and maximizes benefits to the owner with the lowest level of risk and overall cost.

Case studies of existing projects will show the shoreline community specific examples of tested alternatives to current techniques as well as well-constructed traditional bulkheads with compensatory mitigation. The alternatives may not be ones that one can be directly used at a given site, but they will help to develop confidence in the design approach selected for the example projects.

Conclusions

Design guidance documents, like those produced by the Aquatic Habitat Guidelines group, have been successfully used to improve the outcomes of aquatic projects. The conditions in Puget Sound are unique when compared to those on the open coast setting , which underlies the bulk of current coastal engineering experience. Putting all the information necessary for an environmentally responsible design process in one volume is an effective way to coordinate assessment, permitting, design, and construction. Although there is probably no perfect time to compile a document such as that proposed here, the amount of our marine shoreline that has been stabilized and the pace of bulkhead construction is high enough that we should start now to stem the tide.

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Considerations for Puget Sound Restoration Programs That Restore Beach Ecosystems

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Abstract. Ecological goods and services provided by Puget Sound beaches are threatened by loss of sediment supply caused by the armoring of eroding bluffs and banks—a compelling crisis that pits private property protection against public trust resources. Armoring impacts are broadly distributed and increasing, research on the precise impacts of sediment starvation in Puget Sound is limited, and beach systems are large in scale and overlap complex shoreline ownership patterns. These factors challenge the effectiveness of traditional restoration funding programs that focus on funding small sequential projects on individual parcels. Restoration programs implement beach projects despite ongoing degradation, substantial knowledge gaps, and weak stakeholder appreciation for ecosystem dynamics. On-the-ground restoration actions are implemented through networks of stakeholders. To compensate for these factors an effective beach restoration program integrates planning, stewardship, learning, and communication activities with project implementation. Restoration program performance typically considers acres of treatment and rapidity of implementation, sometimes discouraging activity beyond that necessary to deliver those measures. An effective beach restoration program thus is challenged to quickly deliver performance measures, while also meeting planning, learning, stewardship, and communications objectives necessary to actually achieve long-term restoration outcomes. This challenge may be most efficiently met by integrating planning, learning, stewardship, and communications into the more traditional restoration activities of project development and funding, with the intent of developing an effective restoration system that spans organizational boundaries. Boundary-crossing networks allow restoration systems to pool limited resources, and integration allows programs to capture opportunities that arise out of project work. This article proposes a skeletal framework for organizing restoration program activities along these lines.

Introduction

Restoration projects are not typically implemented by government funding agencies, but rather by external project sponsors. On-the-ground projects result from an elaborate series of transactions among stakeholders involving solicitations, applications, competitions, negotiations, contracts, permits, and communications. No one actor is singularly responsible for the complete action. Thus, on-the-ground restoration is the result of the function of a collective restoration 'system,' rather than the function of an individual restoration program. Yet, because of their fiduciary obligations, public funding programs are uniquely responsible for the outcome of public investments in restoration, and have a unique and powerful role in shaping collective restoration systems. Throughout this analysis, 'restoration program' refers to a public funding entity that funds restoration projects, whereas 'restoration system' is the entire program of interagency activity created by the distribution of public funds.

This paper attempts to provide a wide-ranging but logical analysis of the role of public restoration programs in the context of Puget Sound beach ecosystem restoration. This requires consideration of the character of Puget Sound beaches and the traditional structure of restoration programs, only then concluding with a potential policy framework and approach.

The Risk of Armoring Puget Sound Beaches

The Puget Sound can be divided into approximately 812 'beach systems' or 'littoral drift cells' (Simenstad and others, 2010). Each cell is a largely self-contained physical system in which sediment, supplied by erosion, is moved by waves along a reach of shoreline, resulting in a slow-motion sediment 'conveyor belt' that we call a beach. If sediment supply is high, or transport slows, sediment accumulates as barrier beaches, spits, and other physical shoreline structures (Finlayson, 2006; Shipman, 2008). These structures create diverse wave energy environments, and in turn a diversity of physical environments in which shoreline biota live. The wave energy environment and resulting sediment characteristics drive the structure of shoreline biological communities (Dethier, 1990). Thus, shoreline structural complexity resulting from transport and deposition of sediment creates a range of protected and exposed environments and varied substrates that strongly determines the composition and configuration of nearshore biological communities.

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Publications by the Puget Sound Nearshore Ecosystem Restoration Project present a generalized profile of the risks of shoreline armoring on Puget Sound beach ecosystems[2]. Construction of bulkheads is increasing (Gabriel and Terich, 2005) and reduces sediment supply from bluffs and banks. This supply of sediment from coastal bluffs is necessary to sustain Puget Sound beach ecosystems (Downing, 1983). Although armoring may reduce sediment supply, wave-driven transport of sediment is likely to continue unabated, increasing beach slope, reducing beach elevation, and coarsening beach texture over time, resulting in the loss of valued ecosystem goods and services, including forage fish spawning, backshore and down-drift wildlife habitats, and mitigation of wave erosion (Johannessen and MacLennan, 2007). Ultimately, the absence of sediment supply may result in the eventual loss of depositional features like spits and barrier beaches, reducing the diversity of habitat services. Global sea level rise and increased storm energy associated with climate change are anticipated to further increase sediment transport and erosion (Pilkey and Wright, 1988; Pethick ,2001; Johannessen and MacLennan, 2007). Increasing erosion risk creates short-term incentives to increase armoring, which would further reduce sediment supply. A recent Pacific Northwest sea-level rise scenario estimates the loss of 48 percent of existing estuarine beach area by 2050 in the absence of beach system evolution (Glick and others, 2007). Sediment provided by increased bluff erosion provides the only feasible mechanism for recovering this scale of lost beach area.

Although the logic of this scenario is compelling, the precise impact of a particular bulkhead has seldom been studied, making it difficult to associate specific injuries with specific actions, or to identify regulatory thresholds. The dependency of a particular drift cell on bluff-derived sediment as opposed to alluvial sediment may vary. Rates of sediment transport, and therefore the responsiveness of the system to changes in sediment supply, are likely to vary with orientation of the shoreline and wave energy regime. Some beaches are naturally sediment poor, whereas others are sediment rich, and the texture of sediment source can vary. The ecologies of many beach-dependent species are poorly understood. These uncertainties create opportunities for weak and uncoordinated public and governmental support for beach conservation. Although management of sediment supply seems to be an important element of ecosystem restoration, restoration programs to date have had difficulty evaluating the specific nature of project benefits, or identifying the relative importance in an ecosystem context of restoration of sediment supply and transport as compared to other ecosystem restoration activities.

[2]A series of technical publications cited herein can be accessed at www.pugetsoundnearshore.org.

Regardless, few argue that sediment supply is not critical to beach ecosystem function, or that systematic armoring of eroding bluffs will not result in the systematic reduction of sediment supply. Concern over coastal erosion, sediment supply, armoring effects, and sea level rise is not unique to Puget Sound (Pilkey and Wright, 1988; Pethick, 2001; Cooper and McKenna, 2008; Cai and others, 2009; Defeo and others, 2009; McKenna and others, 2009). Although most shoreline parcels and tidelands in Washington are owned by private landowners, national laws like the Endangered Species Act describe a public interest in the condition of shoreline habitats, which are in turn dependent on some undefined level of sediment supply. This public interest in sediment supply is exemplified by the concept of ‘sand rights’ wherein sediment supply is considered a public resource under the ‘doctrine of public trust’ (Dean, 1991; Stone and others, 2005), and has provoked debate within regulatory agencies (Canning and Shipman, 1995; Titus, 1998).

Private/Public Tradeoffs in Shoreline Development

Bulkheads are designed and installed where there is a perceived or real risk of property loss from toe erosion of shoreline banks, bluffs, and beaches. Washington State Hydraulic Code specifically requires the Washington Department of Fish and Wildlife to issue permits for shoreline armoring “in order to protect the property of marine waterfront shoreline” (Chapter 77.55.141 RCW). An analysis of permit data indicates a rate of new bulkhead construction of approximately 100 sites per year, not including reinforcement of existing bulkheads, and new construction outstrips removal by approximately 30 to 1 (Carman, Washington Department of Fish and Wildlife, oral commun., 2009). Given the incidence of unpermitted armor installation, these rates likely underestimate the annual increase in shoreline armoring. Recent history provides dramatic examples of rapidly increasing armoring along developing shorelines (Gabriel and Terich, 2005). Approximately 27 percent (1,070 km) of Puget Sound’s shoreline has been armored to date (Simenstad and others, 2010). In the more developed Central Basin, 62.8 percent has been armored (Simenstad and others, 2010).

Bluff erosion is a different name for the phenomenon of beach sediment input. Those bluffs that are eroding rapidly are providing greater quantities of sediment, and preventing bluff erosion is the same as preventing sediment input. Assuming that bulkhead construction on bluff-backed beaches is a response to risk of property damage from erosion and waves, bulkhead construction should be greatest where erosion rates are high and shoreline population density is increasing, the confluence of maximum erosion threat to newly developed properties. Thus, the location of shoreline armoring is likely to be disproportionately focused where it will most strongly reduce sediment supply/erosion, in effect maximizing the ecosystem impacts of future armoring. These factors result in a potential tradeoff between the short-term interests of private shoreline land owners and the long-term natural resource interests of the general public.

Restoration Programming and the Challenge of Beach Conservation

In Washington State, restoration programs typically use public bond revenue that is distributed through ‘capital budgets’ to fund projects that attempt to reverse ecosystem degradation. Historically, these sources of funds have been used to defray costs of building public health, transportation, education, and energy infrastructure. The 1998 listing of Puget Sound Chinook salmon under the Endangered Species Act and subsequent state and federal agency response has resulted in the development of a ‘salmon recovery economy,’ which today distributes tens of millions of dollars a year to Puget Sound organizations to restore habitat functions predicted to limit salmon populations. The current political leadership in Washington State has identified the Puget Sound as a threatened ecosystem of national importance that requires active management to prevent ecological decline (Puget Sound Partnership, 2008). Both federal and state budgets for Puget Sound ‘ecosystem restoration’ have increased substantially since 2006, and these investment levels have been largely sustained despite recent budget shortfalls.

Government restoration programs typically are responsible for project selection and contracting of funds, but not for implementation. A complex network of advocates, landowners, planners, technical experts, designers, contractors, contract managers, policy analysts, regulators, communication specialists, and stakeholders interact throughout development and implementation of a restoration authority to deliver on-the-ground projects. This ‘restoration system’ is more extensive, interdependent, and complex than is reflected in individual restoration authorities, and the structure and dynamics of the ‘restoration system’ strongly affects the outcomes of an individual restoration authority.

Some challenges faced by restoration programs working in beach ecosystems are common to all ecosystem restoration, but others are unique to beach ecosystems. Public benefit from ecosystem services is difficult to quantify, tracking the condition of an ecosystem is expensive, shoreline ecosystem degradation is frequently accepted as necessary for human well-being, and public dialog over shoreline land use is frequently stymied by conflicts over tradeoffs and ideological views of the relative importance of private property versus public trust rights. Public understanding of beach system dynamics and armoring impacts is limited.

On the other hand, restoration programs enjoy socio-political advantages not shared by regulatory programs. Although regulatory programs may reduce the profitability of some private enterprise, restoration programs generate economic activity that benefits local communities, and results in tangible outputs that can be seen by political leadership and their constituents. Restoration programs also may generate human capital through development of professional workgroups, opportunities for ecological learning, opportunities to increase the visibility of conservation issues, and an audience of influential policy makers interested in conservation and the outcome of public cash investments.

In this setting, more than a dozen individual state and federal restoration funding programs are selecting and implementing a small but increasing population of beach conservation actions. These include removal or modification of armoring, beach nourishment, removal or modification of overwater structures or fill, substrate modification, revegetation, and acquisition of development rights.

Contemporary Beach Restoration Practices

Projects focused on beach system restoration are less common in Puget Sound than those focused on deltaic tidal marsh, river floodplain, or tributary channel habitats. Few restoration programs explicitly solicit beach restoration actions, and few restoration workgroups are aggressively developing beach restoration projects. Proposal reviewers frequently lack resources with which to accurately evaluate the benefits of individual projects. Recent studies associated with Shoreline Management Plan updates are supporting assessment and strategy development for shoreline restoration (Diefenderfer and others, 2009). In 2007, the Estuary and Salmon Restoration Program received the heretofore unique legislative mandate to restore nearshore processes “including protection and restoration of beach sediments and removal of existing bulkheads” (ESHB 1216 Section 3155). In 2009, the Washington State Recreation and Conservation Office, which manages natural resource grant programs, added technical staff in 2010 to explicitly improve evaluation of nearshore projects, including those affecting beach systems. The nature of beach systems creates a particular set of logistical challenges to restoration:

8. Beach sediment supply is maintained by allowing erosion of property that is highly valued for residential development. The high value of shoreline properties makes conservation more difficult and expensive than in freshwater or upland settings.

9. Restoration or protection of sediment supply must be implemented at a scale relevant to the beach system being managed. Littoral cell length ranges over 4 orders of magnitude with a median length of approximately 3 km, where parcel density ranges from 6 to 21 parcels per km (PSNERP, 2009).

10. The thresholds of sediment supply necessary to conserve beach goods and services within a particular system are typically unknown.

A review of beach restoration awards and proposals to the Estuary and Salmon Restoration Program to date suggests three general classes of restoration actions related to the management of sediment supply and transport:

A. ***Protection of sediment supply***—projects that seek to prevent loss of sediment supply through property rights acquisition that allows for continued bluff erosion by preventing or removing shoreline development.

B. ***Restoration of sediment supply***—projects that seek to restore sediment inputs or transport within a beach system through removal of bulkheads or barriers to longshore sediment drift.

C. ***Beach nourishment***—projects that place mined and imported material on existing beaches to create lower gradient, higher elevation, or finer textured beaches.

No existing state regulatory authority can stop armoring of coastal shorelines for the purpose of protecting private property. Therefore, the protection of sediment supply is limited to acquisition of shoreline parcels, among the most expensive property in the Puget Sound region. Funding for protection of sediment supply through property rights acquisition, however, reduces the funds available for restoration of the 27 percent of shoreline already armored.

In order for beach conservation to be effective, it must over time restore or protect sufficient sediment supply to maintain ecosystem services, and allow the shoreline to respond to sea level change. Because of the need for willing land owners, voluntary project work within a typical littoral cell is incremental. To be successful over time, however, the scale of work must match the degree of sediment supply degradation. Future shoreline development may outpace restoration of sediment supply. In addition, stressors like water pollution may cause a decline in ecological services despite intact ecosystem structures.

Restoration Programming—Systems for Restoring Systems

The preceding analysis briefly defines the ecological risks of bluff armoring, the social context of beach restoration, and the tools and challenges typical of traditional restoration programs. The combination of limited restoration resources and widespread and ongoing degradation suggests that diffuse and opportunistic bulkhead removal by isolated restoration programs is unlikely to resolve the cumulative impacts of 1,070 km of armored shorelines, especially when the rate of armoring exceeds the rate of armoring removal.

In the opinion of this author, however, restoration programs provide a suite of tools and resources that are ultimately necessary for the restoration of beach ecosystems. Restoration programs manage substantial capital flows, define the terms and conditions for project implementation, implement and inform strategic planning, and develop regional restoration information networks (as discussed by Tichy and others, 1979; Plastrik and Taylor, 2006). Restoration programs are challenged to leverage limited resources and the "capital project tactic" into a strategic conservation response that achieves a long range goal of increased beach ecosystem functions. Under the scenario of extensive ongoing degradation of sediment supply, the program outputs likely to achieve long term program success are not the length of bulkhead removed, but rather the use of strategic prioritization to deliver pilot efforts that showcase exemplary beach management, and frame public debate on the management of sediment supply.

As described earlier, 'restoration systems' are local or regional social and economic networks driven by the funding from public restoration programs. Through project selection and funding, restoration programs are uniquely and collectively responsible for developing these 'restoration systems'. In addition to reaching physical objectives of ecosystem change, a highly functioning 'restoration system' could (1) study the ecological dynamics of beach systems (Bell and others, 1997), (2) create a forum for discussion of beach issues with property owners, (3) develop accurate parametric estimates of future restoration costs, and (4) create public events that increase awareness of the risks associated with sediment starvation. These effects can be obtained from a restoration program at a relatively small incremental cost, as they take advantage of existing activities. These 'secondary' benefits may be very important in developing the social and regulatory environment that would make program goals of broad-scale ecosystem restoration possible.

Personal observation and experience in Puget Sound restoration programs suggests six interrelated programmatic functions of a restoration system. Each system function is promoted at some rudimentary level within any given restoration program. An assessment of these six functions at the scale of a restoration system provides a useful framework for analysis of the strengths, weaknesses, opportunities, and threats that are considered as part of a program's strategic planning process (see Hill and Jones, 2008).

Function 1. **Strategic planning** includes activities that allow for the estimation of project benefits, resulting in comparison and prioritization of projects. Development can range from peer ranking of proposals to definition of a desired future landscape condition.

Function 2. **Capital distribution** includes mechanisms for the obligation and tracking of funds through contracts and agreements. Development can range from isolated solicitation and contracting procedures for each program to collaborative and administratively efficient funding systems that provide support through a restoration project's lifecycle.

Function 3. **Project development** includes those resources applied to bring a specific action from concept to execution, which can range from isolated and inexperienced project managers to strongly networked and interdisciplinary workgroups that use a body of well tested best- management practices.

Function 4. **Communications** maintain alignment of stakeholders around shared goals, and create consensus through the transfer of knowledge. Development can range from the isolated self-promotion of individuals or programs to collaborative national and regional messaging and outreach.

Function 5. **Stewardship** is that collection of mechanisms that prevent the loss of restoration gains and maintain the effectiveness of protection, from short term landowner agreements to conservation land use planning that engages communities and is supported by local governments.

Function 6. **Learning** is the development and application of knowledge to improve decision making. Development ranges from informal professional conversations to collaborative research among groups of projects and reference sites across landscapes.

Many authors have suggested that un-integrated project execution (a system focused on capital distribution and project development) without development of supporting systems (that is, strategic planning, learning, communications, and stewardship) increases the risk that ecosystem restoration will fail either through lack of technical efficacy or lack of public support (Walters and Holling, 1990; Ehrenfeld and Toth, 1997; Goetz and others, 2004; Van Cleve and others, 2004; Gelfenbaum and others, 2006; Reeve and others, 2006; Leschine and Petersen, 2007). However, the thorough integration of strategic planning, learning, communications, and stewardship into the process of project development and funding presents some substantial political and logistical challenges.

Strategic planning for Puget Sound beach restoration requires extensive regional assessment and conceptual modeling (Ehrenfeld and Toth, 1997; Diefenderfer and others, 2009) to direct assets among 812 shoreline segments. Complex private and public ownership of shorelines, the scale of beach impacts, and the scale of ecosystem processes being restored suggest an important role for learning, communications, or stewardship; weakness in these elements threatens program effectiveness. Under the pressures of performance and accountability systems, the short term conversion of capital into performance measures like 'acres restored' can become the focus of program activity to the exclusion of supporting the delivery of 'secondary' benefits like stewardship or learning that are more intangible.

Thus, there is a chronic tension between investing in the development of a more sophisticated restoration system and investing in on-the-ground implementation of projects that appear to show more direct progress toward meeting restoration objectives. This may be a false dichotomy resulting from the difficulty of quantifying social impacts in a system that has relied on measuring return on investment in acres.

Restoration Program Strategies for Development of Restoration Systems

When compared to the scale and rate of sediment supply degradation, restoration programs are resource limited. The analysis provided heretofore of what may be necessary for effective beach ecosystem restoration has only increased the scope of restoration program responsibility, threatening to draw resources away from on-the-ground restoration actions. By contrast, in the state of Washington, grant program performance is often evaluated by considering the percentage of funds that are 'passed through' instead of being 'consumed' for 'administrative' functions. This form of efficiency evaluation assumes that programmatic investments provide less value than project investments, and again may stem from the difficulty of quantifying the benefits of strategic planning, stewardship, learning, or communications. I foresee three potential advantages to integrating planning, learning, stewardship and communications with on-the-ground project development and funding:

1. 'On-the-ground' actions are what result in potential changes in ecosystem condition. By having 'on-the-ground' workgroups participating in planning, learning, stewardship and communications, we increase the likelihood that these efforts will be relevant to 'on-the-ground' work.

2. If learning, communications, and stewardship goals are described in advance, contract negotiations can be used to mobilize a flexible network of non-governmental actors that are often better positioned to achieve results than their governmental counterparts, and without incurring substantial 'administrative' costs.

3. There is a dynamism and energy to on-the-ground activities that can lend energy and imperative to enhance planning, learning, stewardship, and communications.

Restoration systems are created and operated by multiple independent actors and face the challenge of policy coordination common to all governmental efforts. Integration of “off-the-ground” functions increases the imperative of policy coordination. Although most restoration *programs* maintain coordination using a hierarchical chain of command, network and market mechanisms can provide alternative strategies to hierarchical mechanisms for coordination within a *restoration* system (Peters, 2006).

An example of a market mechanism is found in the competitive proposal process, in which a restoration program acts as a consumer, and indicates product preference through a request for proposals. Local organizations involved in project development act as producers, developing on-the-ground products that meet program desires. For this process to work well, the program must adequately describe the desired product and maintain that demand long enough to allow time for project development.

Network mechanisms, wherein individuals freely communicate, align goals, and voluntarily share resources, can provide a range of difficult-to-quantify benefits (Tichy and others, 1979). The structure of organizations can influence a resident individual’s ability to build network ties (Ibarra, 1993; Manev and Stevenson, 2001). In particular support for individuals to work across organizational boundaries can increase innovation by facilitating the transfer of novel information among organizations (Aldrich and Herker, 1977; Tushman, 1977). Restoration programs can support and shape these networks to enhance the sharing of resources or encourage the collaborative delivery of services within restoration systems (Plastrik and Taylor, 2006).

In conclusion, I have included a brief description of some programmatic opportunities being explored by the Estuary and Salmon Restoration Program to support the development and integration of complex restoration system function in Puget Sound.

1. **Strategic peer review:** A local technical network has been identified from the project development, regulatory, and agency communities. Participants are provided an opportunity to review and discuss regional restoration planning guidance, and then conduct a transparent peer review of project proposals. This reduces the cost of proposal review, while increasing network understanding of strategic planning, and increasing the likelihood of future project development aligned with strategic priorities. Competitive mechanisms further insure that projects are well aligned with criteria, and that the distribution of resources is less influenced by political agendas.

2. **Technical grant deliverables:** Grant contracts include specifications for deliverables at key stages of project development. These deliverables document design assumptions, as-built conditions, and monitoring strategies. They become part of a public record, accessible to other project developers, and supporting post-construction project evaluation. This delivery of project documentation provides the secondary function of incentivizing high quality work, because the quality of restoration planning will be memorialized through publically accessible documents.

3. **Project based learning supported by local technical networks**. The Estuary and Salmon Restoration Program is in the process of developing learning strategies including basic monitoring protocols and a prioritized list of project research questions. The protocols are driven by a set of hypotheses that are generated and prioritized through a community process designed to consider how monitoring and research can most directly improve restoration practice. Technical networks, including individuals likely to be involved in future project development, are used to check and guide work completed by local experts.

4. **Enhancement of spending plans and projects to increase learning**. Each annual spending plan is analyzed for the purpose of identifying opportunities to increase useful knowledge through monitoring and analysis of project actions and their outcomes. Although a base level of monitoring is used to verify project outputs (see 3 above), individual projects or smaller groups of projects are selected for the purpose of evaluating and testing uncertainties documented during strategic planning or project development. The contracts of these projects include provisions that support learning. The results of these ‘enhancements’ are used to adjust project selection and contracting, or to revise strategies.

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Summary of Discussions from Breakout Groups

Megan N. Dethier[1], Guy Gelfenbaum[2], and Charles A. Simenstad[3]

As outlined in the Introduction to these Proceedings, the overall objectives of the Workshop were (1) to summarize the 'state of the science' on the physical changes and ecological impacts of shoreline armoring, (2) to assess the levels of certainty of this knowledge, and (3) to identify information and data needs that will advance the understanding of the impacts of armoring on Puget Sound beaches. These objectives are addressed through synthesis of the information provided in the individual papers of these Proceedings along with summaries from small-group discussions in breakout groups, and by full group discussions prior to conclusion of the workshop. Workshop participants were divided into three groups, with each group composed of representatives from each of the major scientific disciplines related to understanding the biology and geology of beaches and the impacts of shoreline armoring. The following sections on Armoring Impacts, Research Needs, and Conclusions represent the outcomes from these breakout groups and the plenary group discussions during the Workshop.

Armoring Impacts

The underlying conceptual model used throughout the Workshop was that shoreline armoring can alter processes (for example, sediment or groundwater delivery to the beach), which can lead to changes in beach structure (such as beach width or sediment grain size), which in turn causes ecological impacts to natural beach functions. The levels of certainty about these connections vary widely; we often have the poorest documentation of how changes in structure actually affect ecological functions. One of the difficulties in understanding and predicting the ecological impacts of shoreline armoring is that physical (morphological and hydrodynamic) responses to armoring depend on the setting: types of sediment, beach morphology, position in a drift cell, and local wave and current regimes.

Many of the impacts of armoring were demonstrated in the presentations and were reinforced in discussions among scientists from different regions. In addition, as noted in the literature review by J.M. Coyle and M.N. Dethier in appendix C of this Proceedings, armoring impacts may occur via combinations of at least five direct and indirect mechanisms: (1) placement loss, (2) land-beach disconnection, (3) sediment impoundment, (4) passive erosion, and (5) active erosion. For each of these, the response time can vary widely. The workshop break-out sessions resulted in four conceptual models (figs. 1-4) that illustrate the diversity of processes that may be altered by armoring, and give some indication of how well each has been demonstrated through field studies. In addition, each of these conceptual models lists some of the constraints that may influence the importance or magnitude of a mechanism, as well as how feasible or useful armoring removal or other related management measures would be at a given location.

Placement Loss

Impacts associated with placement loss occur when armoring encroaches onto the beach (fig. 1). In the Workshop's group discussions, this was viewed as the most rapid and best demonstrated impact, but often the least widely recognized. Many impacts increase when bulkheads are located seaward of ordinary high water. Some of these impacts are direct, such as truncating the beach and thus reducing area for forage fish to spawn, invertebrates to live, and logs to accumulate. In addition, there are many indirect effects of placement loss that relate to the disconnection that armoring usually causes between terrestrial and marine processes (fig. 2). Bulkheads often change the land-sea transition zone from a complex, broad ecotone to a simple line. This land-beach disconnection can occur with armoring placed at any elevation on the shore, but is most severe with structures placed at lower elevations on the beach profile. A key issue, documented in some areas of Puget Sound, is the associated loss of natural backshore riparian vegetation landward of the armoring, such as the overhanging trees that characterize local unmodified shorelines (for example, see photographs in the paper by J.D.Toft and others in this Proceedings). Data from Puget Sound demonstrate that this combination of placement loss and loss of riparian vegetation may reduce the quantity and diversity of invertebrates, many of which are preyed on by juvenile salmon during their shoreline migration (see the paper by J.D. Toft and others in this Proceedings).

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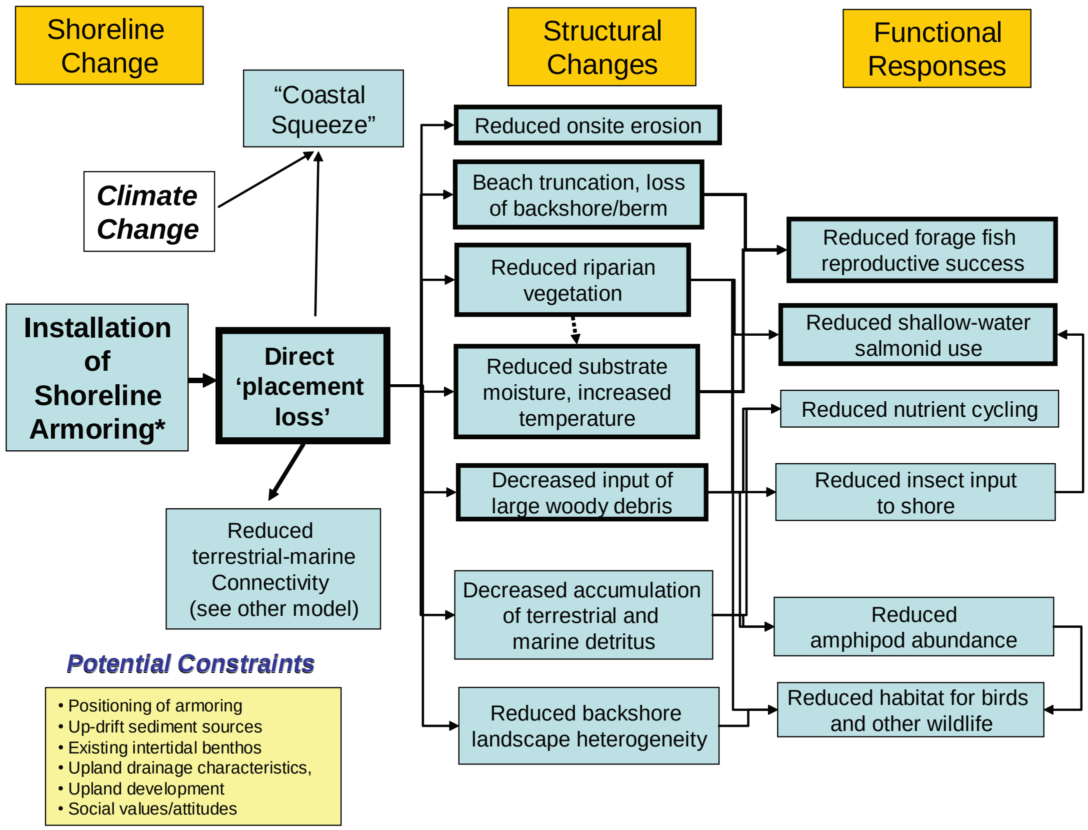

Figure 1. Conceptual model of the impacts associated with *placement loss*, which occurs when armoring encroaches onto the beach. The thicker black lines represent increased certainty in the response. Thinner black lines could represent less certainty in general or a lack of data for Puget Sound.

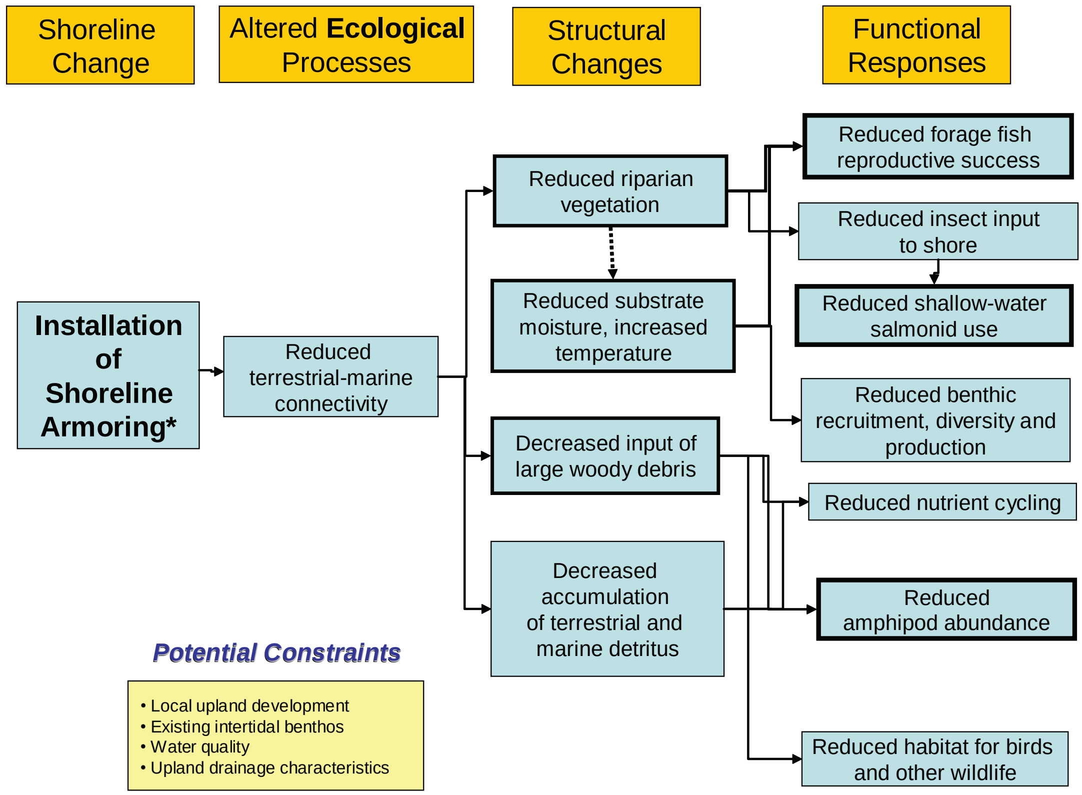

Figure 2. Conceptual model of *ecological processes* altered after installation of shoreline armoring. The thicker black lines represent increased certainty in the response. Thinner black lines could represent less certainty in general or a lack of data for Puget Sound.

Sediment Impoundment

Although sometimes difficult to quantify, another important impact of armoring involves changes to nearshore sediment processes (fig. 3), including sediment impoundment. Armoring often is constructed to prevent shoreline or bluff erosion; however, in doing so the structure reduces sediment supply from the bank or bluff onto the beach and into the shoreline drift cell. Even though most sediment on Puget Sound's beaches is believed to have originated from eroding bluffs, both historical and current rates of sediment supply are poorly quantified, in large part because of the difficulty of measuring such episodic and long-term processes. Participants agreed that not all armoring impounds sediment equally—a seawall that reduces sediment supply to the beach from an actively eroding bluff which supplied most of the sediment to a drift cell is more critical than one on a relatively stable, heavily wooded or low bluff that was only a minor source of sediment to that shoreline.

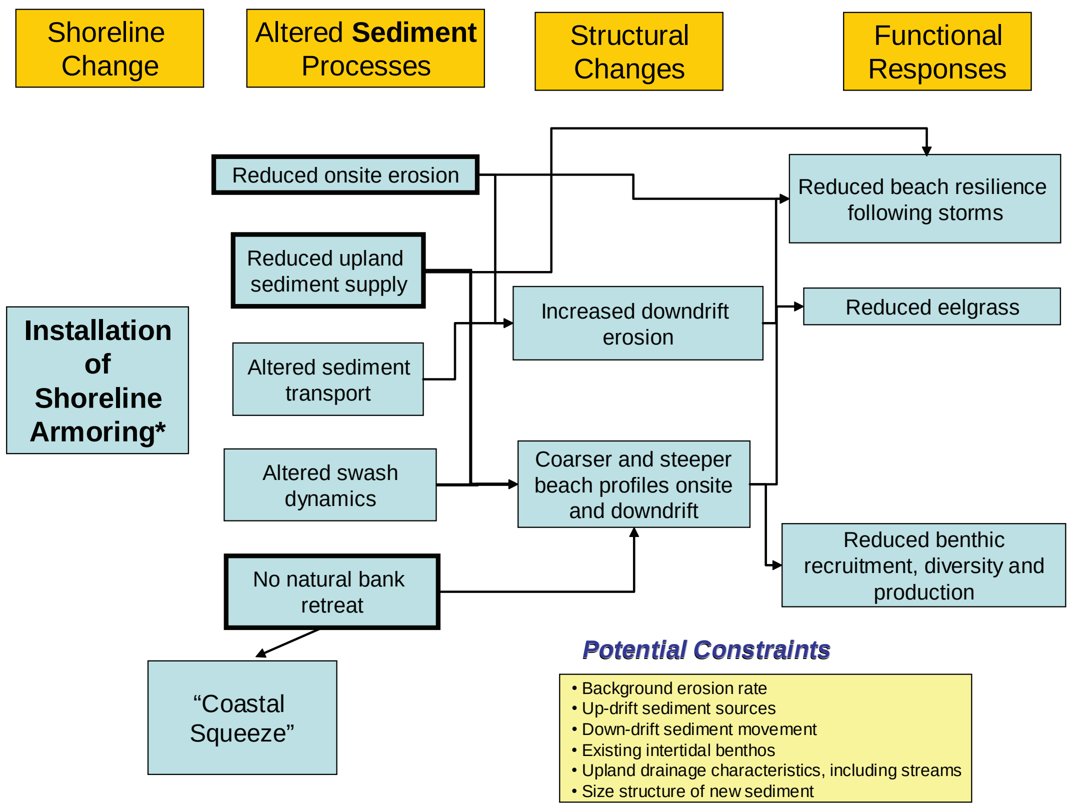

Figure 3. Conceptual model of *sediment processes* altered after installation of shoreline armoring. The thicker black lines represent increased certainty in the response. Thinner black lines could represent less certainty in general or a lack of data for Puget Sound.

Passive Erosion

Another inevitable effect of armoring on shoreline processes, regardless of its elevation, is that it halts the natural shoreline retreat or landward migration of the beach that accompanies sea level rise, land subsidence, or a sediment deficit. Passive erosion is the progressive loss of the beach that occurs when shoreline armoring is built on an already eroding shoreline. Armoring built on a coast that is eroding may provide protection to upland property or structures, but will not provide any protection to the beach seaward of the armoring. The loss of the beach that occurs as a result of passive erosion at modified shorelines is a change that may take years or decades to manifest depending on the background erosion rates, but is certain to occur and has been shown to be a major issue in other locations. Several scientists at the Workshop showed examples of the complete disappearance of beaches on eroding shorelines that contained armoring (see the paper by P. Ruggiero in this Proceedings for example).

Active Erosion

Alteration of hydrodynamic processes that may cause changes in beach geomorphology (fig. 4) were some of the most discussed but least agreed upon effects of shoreline armoring. In some areas, seawalls may increase wave reflection and scouring causing active erosion of beaches, especially when placed below ordinary high water. However, this effect remains an area of uncertainty, especially for the mixed sand and gravel beaches of Puget Sound. Armoring in other regions is believed to cause shorelines to become coarser and steeper. This effect has not been thoroughly investigated in Puget Sound but if it occurs, it could have significant ramifications to the ecology of local beaches. There are some data showing that modified beaches have lower moisture retention in the sediment (either from less shading or from coarser sediments), and this factor can affect forage fish embryos as well as other beach organisms (see the paper by C.A. Rice in this Proceedings).

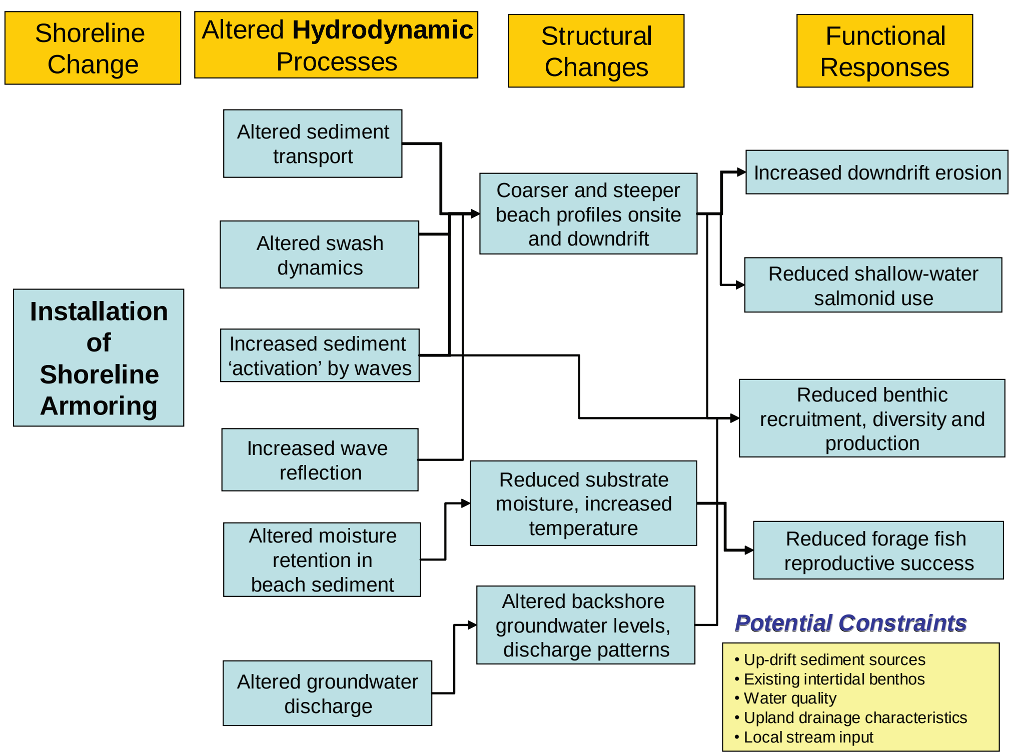

Figure 4. Conceptual model of *hydrodynamic processes* altered after installation of shoreline armoring. The thicker black lines represent increased certainty in the response. Thinner black lines could represent less certainty in general or a lack of data for Puget Sound.

Research Needs

There are local or short-term data sets that document some responses of armoring in Puget Sound, but long-term and cumulative data are lacking. This is particularly true for the hydrodynamic effects of shoreline armoring on beach geomorphology, and for what specific drift cell components produce the greatest effect. For example, it is uncertain whether there are thresholds, beyond which the cumulative loss of sediment supply leads to significantly altered beach structure and biological function. Many of the effects of shoreline armoring occur over variable temporal and spatial scales, depending on parameters such as wave energy or local sediment supply rate. Although it is certain that some changes, such as direct beach loss, will occur in the immediate vicinity of armoring, the alongshore extent of these impacts is uncertain.

Many of the data and knowledge gaps discussed during the Workshop and listed below can be informed with dedicated monitoring of beach restoration projects. For this reason, the Estuary and Salmon Restoration Program (ESRP), a Washington State funded effort, is encouraging learning opportunities by funding strategic monitoring of some nearshore restoration projects, including those involving the removal of armoring on beaches. Resolving other uncertainties, and particularly those related to hydrodynamic and geomorphic processes, may require dedicated monitoring and research funding to address the complicated, multi-disciplinary and often long-term processes involved.

Listed below are some of the high priority data and information gaps that exist regarding the impacts of shoreline armoring on sheltered coasts such as Puget Sound:

Geological-Oceanographic Uncertainties

- Does armoring on mixed sand and gravel beaches cause steeping and coarsening of the beach? What does this depend on (how/when/where)?
- What influences sediment composition on the Puget Sound low-tide terrace? How does sediment supply affect the elevation, width, and grain size of the low-tide terrace? Does armoring impact the low-tide terrace and, if so, how?
- What are patterns and rates of bluff erosion in Puget Sound? What local factors affect these rates (for example, rain versus toe erosion)? Can rates and factors be mapped and classified, for example, for each drift cell?
- How does coarse woody debris on beaches affect erosion rates and patterns of erosion?
- What are the patterns and rates of groundwater discharge through beaches locally and Sound-wide, and how are these affected by armoring?
- How do drift cell sediment budgets vary over time? What is the effect of shoreline armoring on drift cell sediment budgets?
- How will Puget Sound beaches with and without armoring respond to sea level rise? What is the anticipated degree of passive erosion that might occur?
- What are the average wave conditions (that is, the wave climate) for Puget Sound beaches? Is wave climate likely to change with climate change? Are simple wave fetch diagrams sufficient to model wave impacts on beaches?
- What are the relative contributions of sediment from streams compared to bluffs?
- What factors influence the effectiveness of ‘soft-shore’ and alternative erosion control techniques?

Biological Uncertainties

- What is the relationship of backshore vegetation to nearshore biota?
- What is the ecological significance of fragmentation of different nearshore ecosystems?
- To what extent do forage fish show beach fidelity for spawning? What is the overall condition of their populations? Is egg production and survival limiting? How might this change over time with sea level rise?
- What effects does armoring have on shorebirds and other seabirds, and how is this effect mediated?
- How does wrack contribute to the nearshore food web?
- What is the food web importance of talitrid amphipods (“beach hoppers”), which appears to be one of the primary biota impacted by shoreline armoring? Are they a major source of shorebird prey?
- What effects, if any, does armoring have on eelgrass, and how is this effect mediated?
- Does shoreline armoring have a significant cumulative effect on juvenile salmonids migrating along the shoreline? Does the spatial distribution of armoring affect this response?

Conclusions

Any gathering of scientists to discuss the ‘state of the science’ of an important issue will inevitably result in a list of questions that need further research, as above. However, Workshop participants, who came from a wide variety of backgrounds and disciplines, agreed that although there exist significant uncertainties that currently limit our understanding, there is enough known to make some general statements about the impacts of armoring. The breakout groups were not tasked to develop specific recommendations to policy makers, but the following conclusions were clear outcomes of discussions:

- While armoring alters the shoreline in different ways in different ecosystems around the world, almost every study has demonstrated impacts to some beach feature or function that society regards as valuable. These range from loss of space for recreation on the beach, to decreasing the numbers of foraging shorebirds, to erosion on adjacent properties. The benefits accrued by erosion control structures must be weighed against their negative impacts to public resources and to shoreline ecosystems.
- All armoring is not likely to be equally harmful in terms of loss of sediment to the shoreline, because natural sediment supply to the beaches varies so widely. Specific coastal assessments can suggest geomorphic factors or locations (for example, position within a drift cell) that are most valuable for protecting sediment supply.
- Armoring built lower on the shore (that is, lower elevation than extreme higher high water) has increasingly negative impacts, regardless of mechanism. As sea level rises, even structures that were originally built high on the beach may encroach farther into the intertidal.
- Armoring of individual properties is often treated as a benign activity, but the cumulative result of armoring multiple properties may have significant long-term impacts on beaches and drift cells.
- As sea level rises, passive erosion in areas with armored shorelines will result in the progressive loss of beaches around Puget Sound. This will reduce both the recreational benefits and the ecological functions provided by the beaches.

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Appendix A. Conference Attendees

Attendees	Affiliation
Brenda Bachman	U.S. Army Crops of Engineers
Bob Barnard	Washington Department of Fish and Wildlife
Peter Namtvedt Best	City of Bainbridge Island
Randy Carman	Washington Department of Fish and Wildlife
Paul Cereghino	Washington Department of Fish and Wildlife (WDFW); National Oceanic and Atmospheric Administration (NOAA)
Jill Coyle	University of Washington
Carolyn Currin	National Oceanic and Atmosheric Administration, North Carolina (NOAA, NC)
Megan Dethier	University of Washington, Friday Harbor (UW)
Rick Dinicola	U.S. Geological Survey (USGS)
Jenifer Dugan	University of California, Santa Barbara (UCSB)
Guy Gelfenbaum	U.S. Geological Survey (USGS)
Gary Griggs	University of California, Santa Cruz (UCSC)
Bernard Hargrave	U.S. Army Crops of Engineers
David Hubbard	University of California, Santa Barbara (UCSB)
Debbie Hyde	Pierce County
Nancy Jackson	New Jersey Institute of Technology (NJIT)
Jim Johannessen	Coastal Geologic Services, Inc. (CGS)
Paul Komar	Oregon State University (OSU)
Kirk Krueger	Washington Department of Fish and Wildlife
Tom Leschine	University of Washington
Lynda Lyshall	Puget Sound Partnership
David Michalsen	U.S. Army Crops of Engineers
Tom Mumford	Washington State Department of Natural Resources
Doug Myers	People for Puget Sound
Karl Nordstrom	Rutgers
Jim O'Connell	Hawaii Sea Grant
Phil Osborne	Golder Associates
Tim Quinn	Washington Department of Fish and Wildlife
Casey Rice	National Oceanic and Atmospheric Administration (NOAA)
Susan Roberts	National Research Council (NRC)
Mary Ruckelshaus	National Oceanic and Atmospheric Administration (NOAA)
Peter Ruggiero	Oregon State University (OSU)
Hugh Shipman	Washington State Department of Ecology
Si (Charles) Simenstad	University of Washington
Curtis Tanner	Washington Department of Fish and Wildlife
Kathy Taylor	Washington State Department of Ecology
Tom Terich	Western Washington University
Jason Toft	University of Washington
Marijke van Heeswijk	U.S. Geological Survey (USGS)

Appendix B. Puget Sound Shoreline Field Trip: Kitsap County and Bainbridge Island

Hugh Shipman[1]

Shoreline Armoring on Puget Sound: State of the Science Workshop

May 13, 2009

Field Trip Itinerary

11:45	Depart Alderbrook on Hood Canal by bus
1:00-2:00	Field Stop #1: Suquamish Tribal Center and Agate Pass
2:20-3:00	Field Stop #2: Fay Bainbridge State Park
3:30-4:30	Field Stop #3: Pritchard Park
5:00-7:00	Dinner on Bainbridge Island
7:00	Depart Bainbridge by bus
8:00	Return to Alderbrook

NOTE: This field trip guide reflects the final field trip itinerary. The original planned field trip included a different site on Bainbridge Island, a boat tour, and a visit to the Bremerton waterfront. Last minute mechanical problems, combined with stormy weather, required a shift to a different field site and cancellation of the boat trip.

Overview

From Alderbrook, we will travel by bus along south shore of Hood Canal and east towards Bremerton. From there, we will drive northwards through Silverdale and Poulsbo, to our first stop near Suquamish on Agate Pass.

We will make three stops on our bus trip. Each site illustrates a relatively different shoreline and highlights unique issues. Our first stop features eroding bluffs, a small stream mouth, and a recent soft shoreline project. Our second stop will be along a more exposed depositional beach on the main basin of Puget Sound, where we will see a typical Puget Sound mixed sand and gravel beach, along with a nearby example of a heavily developed spit. Our final bus stop will be a Superfund project on the southern shore of Eagle Harbor, where cleanup and redevelopment efforts have resulted in a restored beach.

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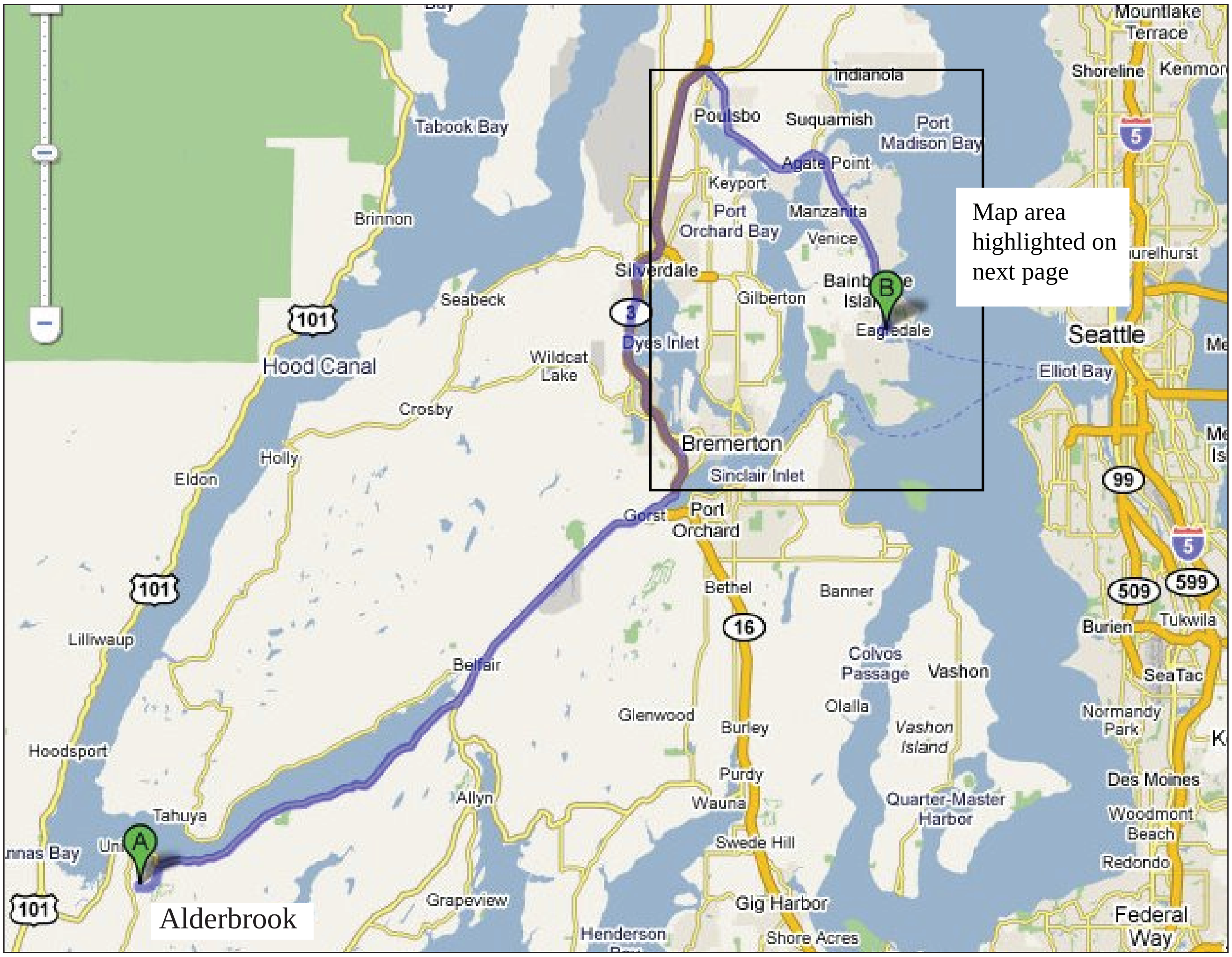
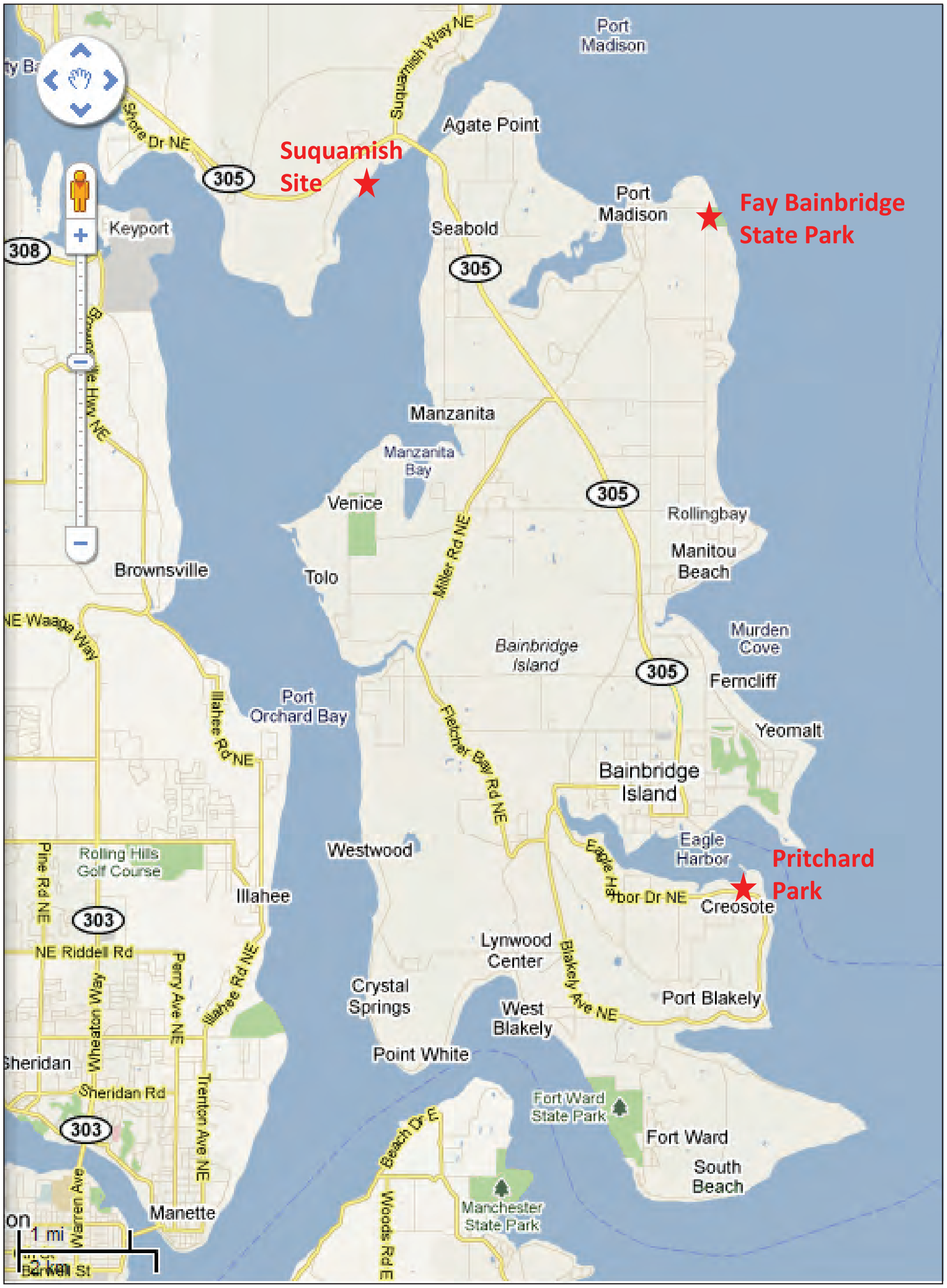
Field Trip Map



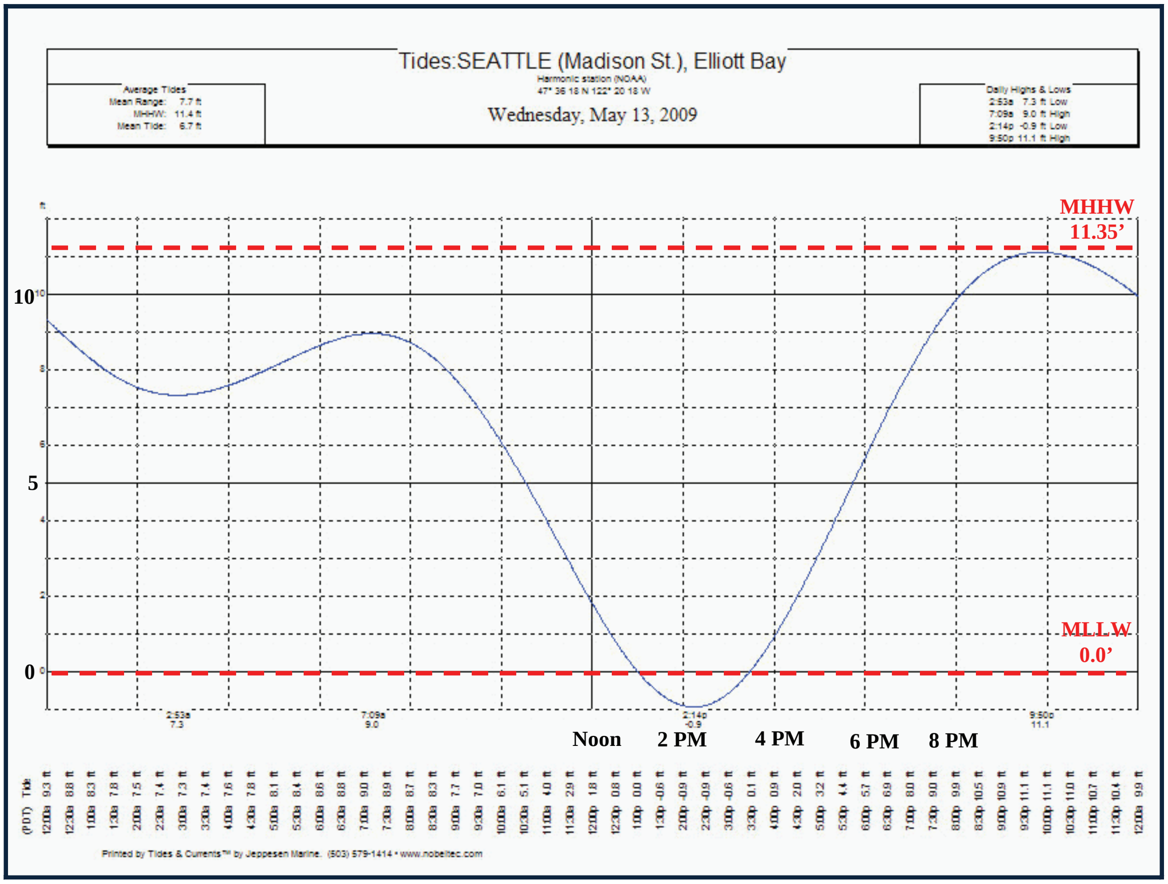
Source: Google, 2009

Map of Bainbridge Island and Vicinity



Source: Google, 2009

Tides During May 13 Field Trip



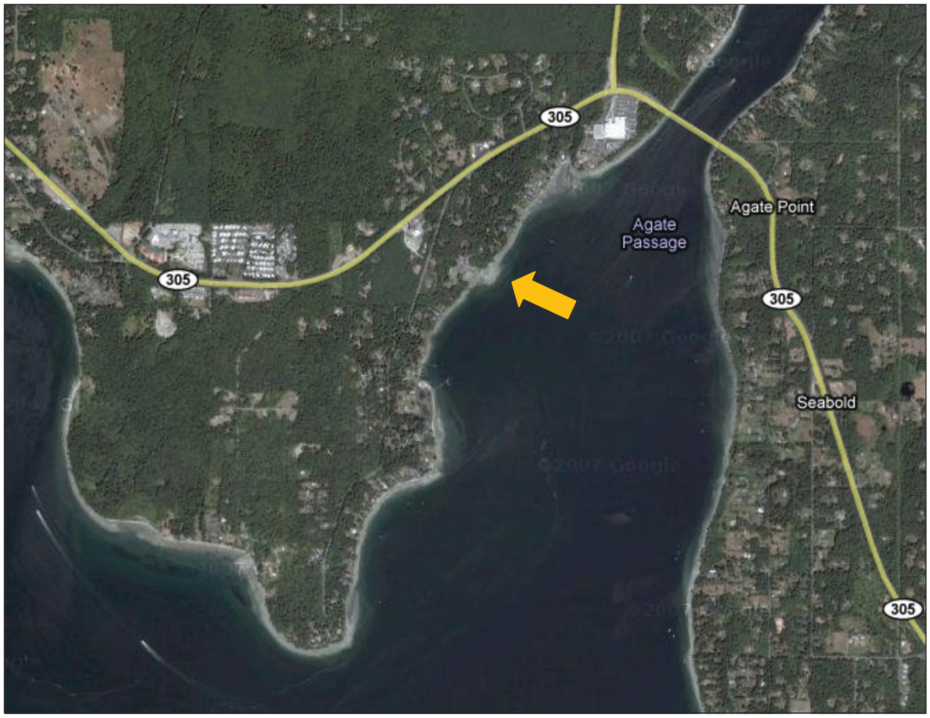
Tides, shown here for Seattle, are fairly similar in timing and height throughout the area of our field trip. The tides during the field trip will be lowest around 2PM (1 ft below MLLW) and will be rising throughout the boat trip.

Puget Sound experiences mixed semidiurnal tides. Mean Higher High Water in Seattle and vicinity is 11.35 ft above MLLW (0 ft). The lowest tides tend to occur during the daytime in late May and June (and at nighttime during December and January). Extreme low tide is approximately -4 ft; extreme high tide is between 14 and 15 ft.

During severe weather, tides may be routinely elevated 2 ft above predicted levels, but the Sound does not experience the extreme storm surges of the sort familiar to those on the east coast. During El Nino events (for example 1983, 1998, 2006) sea level on the west coast, including in Puget Sound, can be elevated an additional 6-8 in., which greatly increases the likelihood of extreme high water events.

Field Trip Stops

1. Suquamish Tribal Center — South of Agate Pass



This site is located on northern shore of Port Orchard, just south of Agate Pass. Exposure is primarily from the south across Port Orchard, with a fetch of 2-3 miles

Source: Google, 2009

The low, relatively steep bluffs in each direction are composed of glacial till, which often forms steep slopes with limited vegetation. We will see evidence of erosion, although the long-term rate of bluff retreat would be low. A small stream enters the Sound at this site. The developed portion of the site is built partially on artificial fill in the low areas surrounding the historic stream mouth.

The beach at this site is dominated by the intertidal delta of the small creek (see oblique aerial photo). Stream mouth deltas such as this are common on Puget Sound. Little is known about their relative importance, compared to the eroding bluffs, in delivering sediment to the littoral system, although it likely varies significantly between sites.

Longshore transport on this shoreline is from south to north, driven by the predominance of southerly storms and the greater southerly fetch. The volumes of transport may be relatively low on this shoreline due to the modest wave exposure and the limited availability of sediment.

Concerns about the eroding bank in front of the large building led to the recent stabilization project. This project is typical of others on Puget Sound where there is tension between the need to protect upland structures using standard accepted engineering techniques and the desire to protect shoreline processes and ecologic functions. As is often the case, the result is some interesting compromises. The project employs a deep pile wall, a reconfigured soil bank with plantings, and the structural incorporation of large wood on the beach.

Photo: Department of Ecology

Oblique aerial photograph of Suquamish site. Note bluffs in each direction, variability in bank vegetation, and the distinct intertidal delta fan at the stream mouth.

View northeast, looking across the stream delta at a mid-tide. The bluff is developed in glacial drift which often forms steep, bare cliffs.

Bank stabilization project in front of building, showing vertical pile wall, recently planted and regraded slope (covered with mesh), and large anchored logs.

2. Fay Bainbridge State Park, Bainbridge Island

Point Monroe, and Fay Bainbridge State Park, immediately to the south (yellow arrow) are located at the northern end of a 3-mile littoral cell (red arrow) along the eastern shore of the island.

Fay Bainbridge State Park is located immediately south of Point Monroe, along a spit that begins farther south, follows the coastline north, and then forms a hook at Point Monroe itself, enclosing a small tidal lagoon.

Longshore transport is to the north as a result of southerly storms and an extensive fetch (10–15 mi). Sediment is supplied by bluff erosion within a littoral cell that begins 2–3 mi to the south.

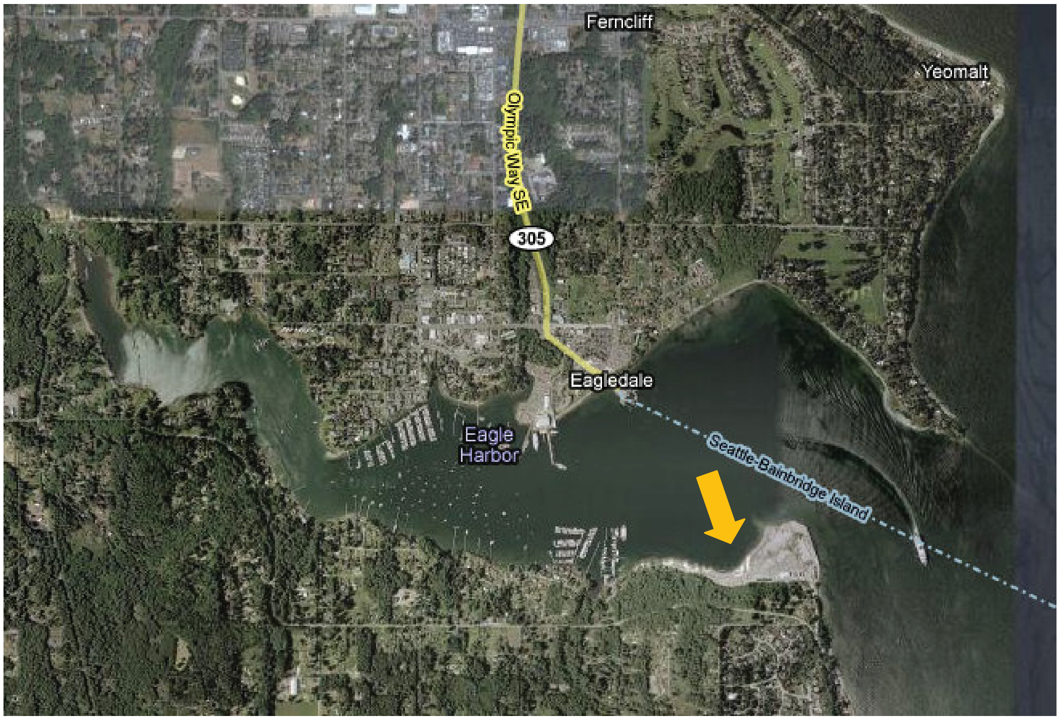
View north from the State Park showing homes along the Point Monroe spit. Note that many seawalls extend well below the waterline at the time of this picture (approx. Mean Higher High Water).

View north of the beach from south of Fay Bainbridge Park. Illustrates typical berm with drift wood, gravelly foreshore, and broad sandy low tide terrace.

Point Monroe itself is developed with waterfront homes, many of which are heavily armored to protect against erosion and storm damage. The spit experienced serious damage in December, 1990, following a pair of unusual northerly windstorms (most major storms and wave action on the Sound come from the south). Many seawalls were destroyed and in some cases homes themselves were damaged when walls collapsed or when backfill was eroded out from under the walls during the height of the storm.

Point Monroe is a recurved spit that actually begins 1-2 kms south (left) of these images. The broad backshore at the park and where the homes are to the south historically contained an extensive wetland system that drained north towards the lagoon. This photo illustrates the extent of residential development on the spit itself, with homes located on both exposed beach and on the lagoon. Note the extensive use of seawalls to protect homes.

3. Pritchard Park, Bainbridge Island



Source: Google, 2009

Pritchard Park is located on the southeastern shore of Eagle Harbor, on the east side of Bainbridge Island. The island's commercial center of Winslow lies on the north side of the harbor.

The western portion of Pritchard Park lies inside the harbor and is sheltered from typical southerly storm waves, although boat wakes may be an issue in this heavily used harbor.

Source: U.S. Coast Survey
T-Sheet # 1303a (1872)

Historically, a small spit called Bill Point marked the southeastern entrance to Eagle Harbor. Sediment was supplied by eroding bluffs south of the point and transported northward by southerly wave action. The shoreline west of the spit would likely have been a combination of salt marsh and a narrow, low-energy beach along the base of the bluffs.

Aerial photo of site when creosote treatment facility was still in operation.
(Source: Eric Nelson, U.S. Army Corps of Engineers)

Throughout much of the 20th century, a creosote plant operated at this location. The facility closed in the 1980s and was taken over by EPA as a Superfund site. Remediation began in the late 1990s, with construction of a steel sheet pile containment wall and treatment of contaminated soils.

Under the guidance of the Corps of Engineers, historic fill, overwater structures, and debris were removed from the western portion of the site, a large sediment cap was placed to isolate contaminants, and a broad sandy gravel beach was created. This beach has become a popular recreational site for local residents.

On the eastern edge of the site, facing Puget Sound, there are plans to remove a failing timber bulkhead and to relocate a roadway with the objective of allowing natural erosion of the steep bluff to occur, restoring an historic source of beach sediment to the point.

Aerial view of Pritchard Park site taken in July, 2009. Sheet pile wall and soil remediation facilities are located on the point in the foreground. The created beach can be seen behind point.

NOTE: Pritchard Park was substituted for Bainbridge Waterfront Park as a result of last-minute changes to the workshop field trip. An earlier version of this field trip description includes the Waterfront Park site.

Initial excavation of historic fill and debris on western portion of the site (Source: Eric Nelson, U.S. Army Corps of Engineers.)

Photo of the same area as above, taken in 2005, following capping and beach creation.

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).

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A key process to understanding the effects of armoring on Puget Sound beaches is the local importance of net shore-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).

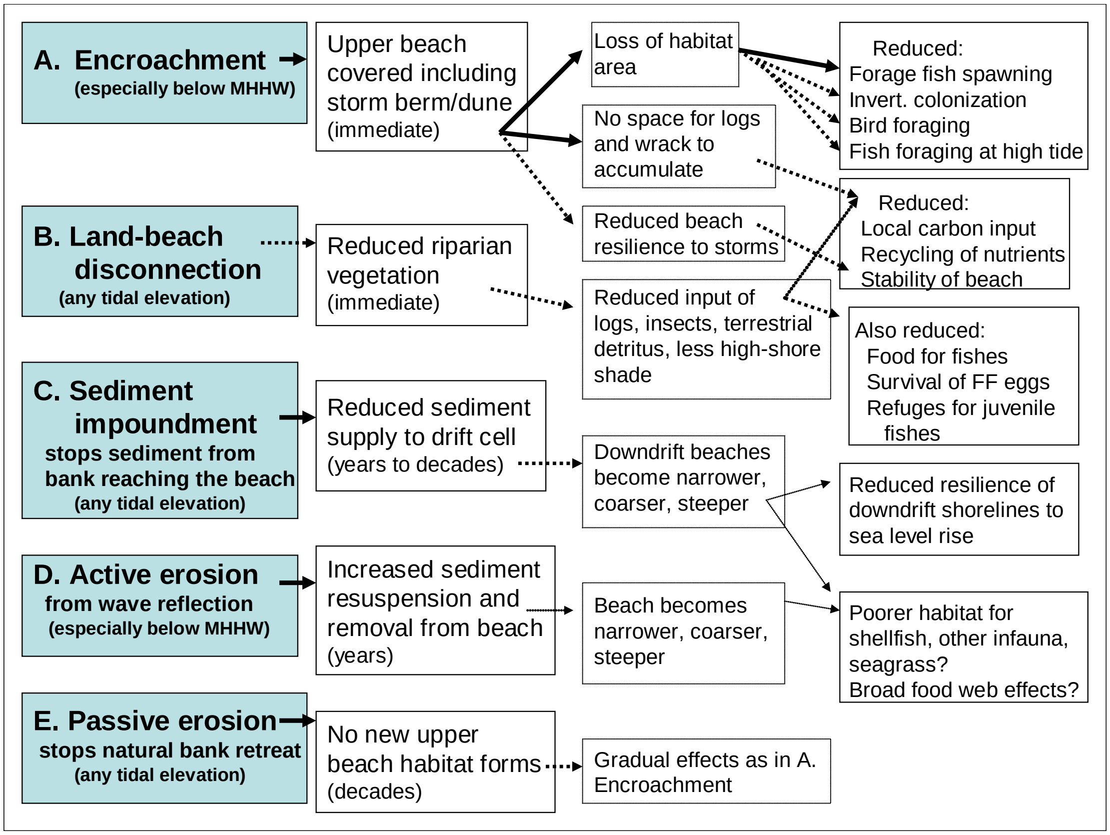

Figure 1. Five mechanisms by which armoring could alter shoreline processes and functions, and their ultimate impacts on nearshore biota. MHHW = mean higher high water. Linkages that are more certain (for Puget Sound) are shown with more solid arrows.

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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