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

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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.

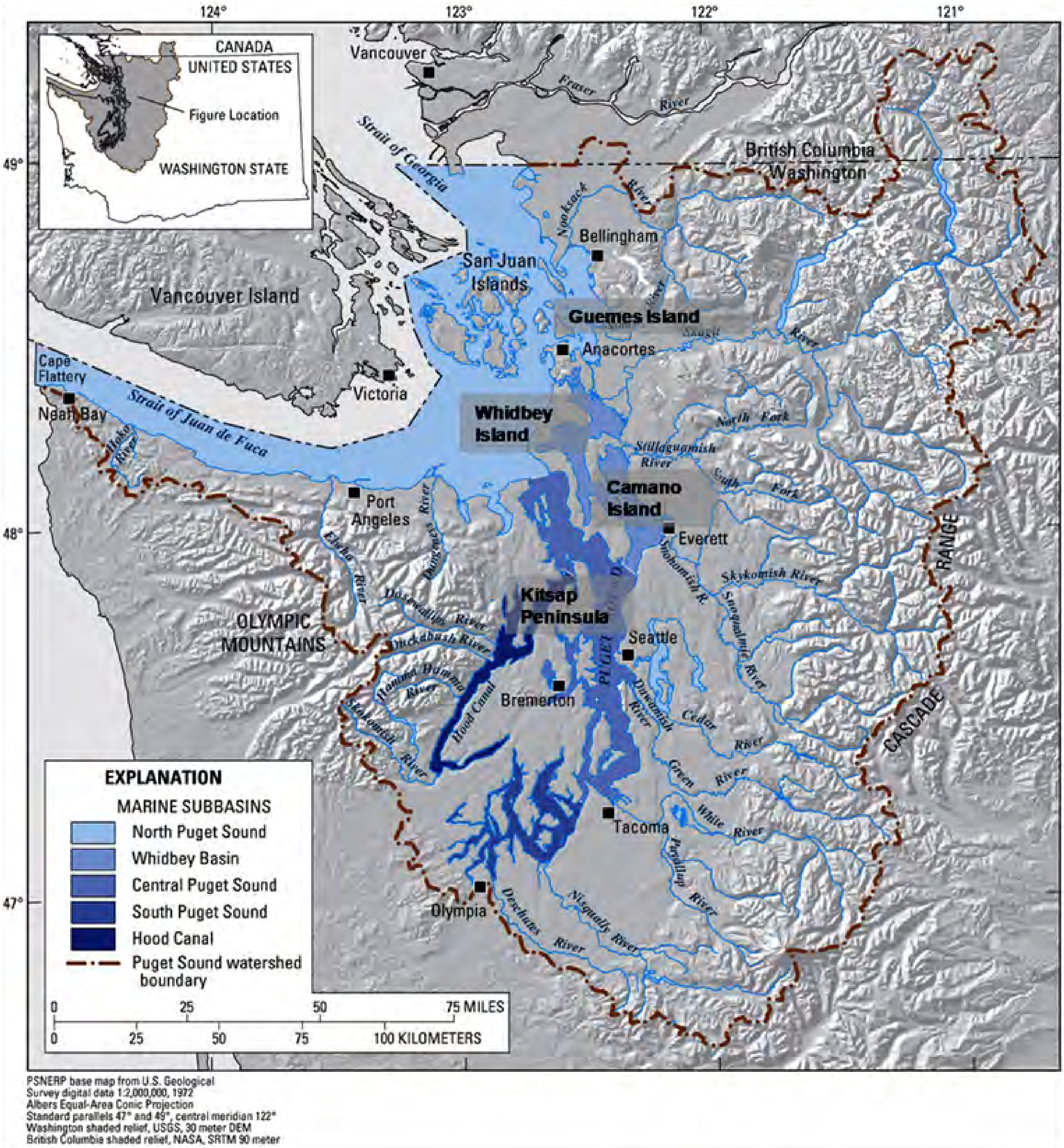

Figure 1. The Puget Sound basin, showing major rivers, oceanographic subbasins, and selected locations referred to in this paper.

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).

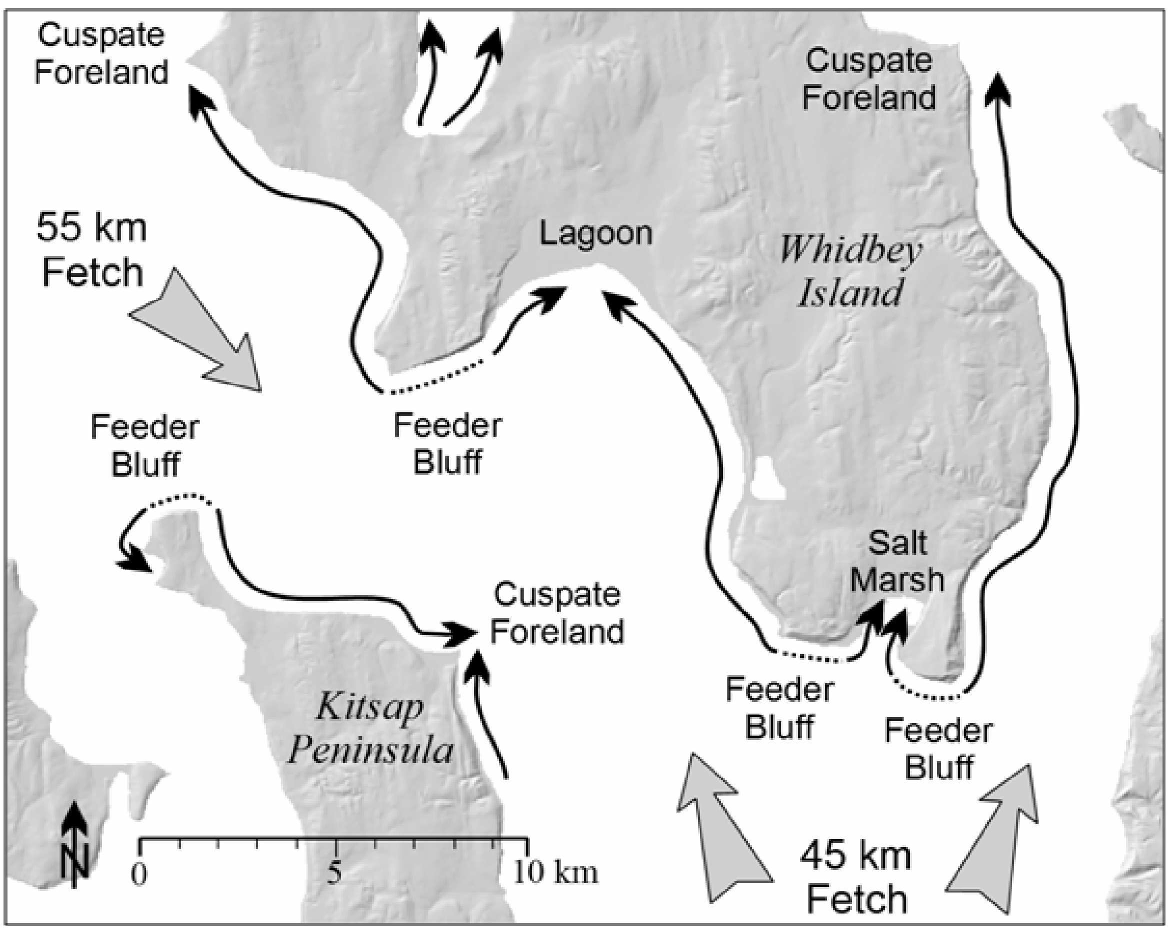

Figure 2. The complex pattern of longshore sediment transport (black arrows) and littoral cells in north central Puget Sound (from Finlayson and Shipman, 2003). Net transport patterns reflect the combination of maximum fetch (large arrows) and the predominance of southerly storm waves.

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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