Puget Sound Feeder Bluffs

Coastal erosion as a sediment source and its implications for shoreline management

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Cover Photo:

Eroding bluffs on the south side of Lily Point Marine Park, on Point Roberts in Whatcom County.

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Acknowledgements

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The importance of feeder bluffs to Puget Sound beaches was first recognized by Wolf Bauer in the early 1970s and he would be the first to point out that this work is long overdue. The work of Maury Schwartz and his students at Western Washington University provided critical context for understanding the role of these bluffs in Puget Sound drift cells.

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Executive Summary

Beaches make up about 1400 miles of Puget Sound's 2500-mile shoreline. They are an important component of the region's coastal environment and support a broad range of ecological functions, from spawning habitat for forage fish to the formation of estuaries and salt marshes. These beaches are complex geological systems that respond to changes in the availability of sediment and its transport along the coast. On Puget Sound, some of the sand and gravel on the beaches may come from streams and rivers, but much of it is derived from erosion of coastal bluffs. These bluffs are called *feeder bluffs*, for which we offer the following definition:

> *Feeder Bluff: An eroding coastal bluff that delivers a significant amount of sediment to the beach over an extended period of time and contributes to the local littoral sediment budget.*

The potential significance of feeder bluffs on Puget Sound has been recognized for decades, but their role in beaches and nearshore ecosystems has not been well understood and there has been no Puget Sound-wide mapping of their distribution. This project emerged from the need to understand these landforms better, to describe their location and extent, and to use this information to improve shoreline management in the region.

The Department of Ecology received funding for the Feeder Bluff project from EPA's National Estuary Program and the Marine and Nearshore Grants program at the Washington Department of Fish and Wildlife. This work had two major elements. The first was to complete the mapping and characterization of feeder bluffs for all of Puget Sound. The second was to provide guidance to help local planners, resource managers, and other groups to better understand the role of feeder bluffs on Puget Sound and to encourage improvements in policies and programs aimed at protecting both the bluffs and the beaches to which they deliver sediment. This report and a related website address this guidance element of the larger project.

Coastal Geologic Services of Bellingham led the mapping portion of this project. In 2012-2013, they reviewed and compiled previous mapping studies and then used a largely field-based approach to complete the mapping for the remainder of the region. The maps are available from the Department of Ecology and are included on Ecology's Coastal Atlas website. A report summarizing the methodology and the findings, *Feeder Bluff Mapping on Puget Sound*, is also available from the Department of Ecology (MacLennan and others 2013).

The mapping found that feeder bluffs account for a little more than 15% of the Puget Sound shoreline, but that their extent varies significantly from one county to another. In general, feeder bluffs are more prevalent in north and central Puget Sound where erosion rates are more rapid and beaches are often more extensive. The study focused on the distribution of existing feeder bluffs, but also recognized that the current extent is much reduced from historic levels due to the widespread construction of erosion control structures.

In this report, we investigate the geologic characteristics that influence the formation and evolution of Puget Sound beaches. This coastline is strongly influenced by the legacy of the last glaciation, which left a steep, bluff-dominated coast, a complex wave environment that leads to transport of sediment along the shoreline, and an abundance of coarse sand and gravel that erodes rapidly and builds beaches. The coast is divided into hundreds of relatively small littoral cells (also called drift cells), each with its own sources of beach sediment. In some locations these sources may includes rivers or streams, but the primary source of beach-size sediment in many areas is the erosion of the coastal bluffs themselves.

The fact that eroding bluffs are important sources of beach sediment has several ramifications for Puget Sound's coast:

- **Beaches and nearshore ecosystems**. Bluff erosion delivers sediment to beaches and is important for the long-term maintenance of beach ecosystems within the local littoral cell. The ongoing delivery of sediment to the beach system is a good example of an ecosystem process that supports a broad range of ecological functions.
- **Shoreline armoring**. Measures to prevent erosion of coastal bluffs, even if successful at protecting upland structures and property, diminish the supply of sediment to adjacent beaches. Concerns about the environmental impacts of shoreline armoring are not unique to Puget Sound and are not limited to their effect on sediment supply, but this is a particularly relevant management issue in this region where bluffs are common.
- **Sea-level rise**. Rising sea levels will be an increasing concern on all coasts during the coming decades. On a bluff-dominated coast such as Puget Sound, the ability of bluffs to erode naturally will allow beaches to migrate landward with less impact on beach character and coastal ecosystems and will also provide critical sediment that will benefit other beaches in the vicinity and allow them to adjust to the higher water levels.

Protecting feeder bluffs and their role in providing sediment to Puget Sound beaches is challenging since it requires balancing the need to maintain natural erosion with landowners' concerns about safety and the loss of shoreline property. There are a number of different approaches to managing and protecting these bluffs, ranging from improved development practices to the implementation of conservation strategies. The report looks at the following issues:

- **Building on are above feeder bluffs** poses two problems. First, these are often hazardous areas specifically because of the potential for erosion or landslides. Second, efforts to prevent erosion diminish the ability of the bluffs to continue to provide sediment to nearby beaches. Large setbacks can reduce risks and delay the need for protective measures. When structures do become threatened, emphasis should be placed on removing or relocating buildings and improvements rather than armoring the shoreline.

- **Shoreline Management Programs (SMPs)** provide numerous opportunities to better manage feeder bluffs. Local governments are required to establish policies that maintain ecological functions. Shoreline inventories can identify important bluffs and help prioritize sensitive shorelines. Environment designations can be used to target appropriate policies for important coastal bluffs. Setbacks can be established that reduce development in the most hazardous locations while also reducing the need to armor the shoreline in the long-term. Shoreline stabilization policies can include strict standards for new armoring on feeder bluffs and can encourage alternative approaches such as relocation of at-risk structures and mitigation of potential impacts on sediment supply.
- **Conservation and acquisition** may be the most effective ways of assuring permanent and effective protection of feeder bluffs, but can be expensive and may be best used for particularly high value shoreline areas. Several important feeder bluffs on Puget Sound have been acquired recently, protecting the long-term function of the bluffs, assuring that development is not built in hazardous locations, and providing additional environmental and recreational benefits.
- **Restoration of feeder bluffs** may be possible in some locations. Many historical feeder bluffs on Puget Sound have been armored and in many cases, concerns about property ownership and renewed erosion make restoration unlikely. Opportunities remain in some locations, however, for removal of shoreline armor and the restoration of natural sediment supplies. On some highly developed shorelines, artificial beach nourishment may have a place in restoring sediment to historically degraded beaches.

This project is intended to increase understanding of the role and distribution of feeder bluffs on Puget Sound. This should lead to improved policies for managing coastal bluffs and nearshore ecosystems, more generally. It may help funding agencies and local groups target key shorelines for protection and conservation efforts. The higher resolution maps should help refine earlier work by the Puget Sound Nearshore Ecosystem Restoration Project (PSNERP) that examined the degradation of sediment supply to different drift cells and may improve efforts by the Puget Sound Partnership (PSP) to monitor progress on the shoreline armoring vital sign.

There are also significant opportunities to improve our current knowledge. Mapping could be refined to better characterize the distribution of shoreline armoring and its relationship to historical feeder bluffs. Geological studies could help quantify erosion rates and sediment budgets, and to better characterize the sensitivity of beaches to changes in sediment. Ecological studies should look more carefully at how beach ecology relates to changes in the physical conditions of beaches. Together, these types of studies would help us better predict long-term trends in the condition of Puget Sound beaches and to consider scenarios of increased development, accelerated sea level rise, or changes in coastal management.

Acronyms

DNR	Washington Department of Natural Resources
ECY	Washington Department of Ecology
EPA	Environmental Protection Agency
GIS	Geographic Information System
PSNERP	Puget Sound Nearshore Ecosystem Restoration Project
PSP	Puget Sound Partnership
SMA	Shoreline Management Act
SMP	Shoreline Master Program
WAC	Washington Administrative Code
WDFW	Washington Department of Fish and Wildlife

Introduction

Puget Sound has almost 2500 miles of shoreline east of Cape Flattery and south of the Canadian border, roughly half of which consists of sand and gravel beaches and steep coastal bluffs. These beaches and bluffs are part of a dynamic geomorphic system, in which sediment derived from bluff erosion builds spits, forms back-barrier tidal wetlands, creates substrate for spawning forage fish, and maintains beaches in the face of storms, long-term erosion, and sea-level rise.

The term *feeder bluff* has been used for three decades on Puget Sound to describe eroding bluffs that deliver a significant volume of sediment to the beach. These beaches and bluffs are a key element in the Puget Sound nearshore ecosystem (Johannessen and MacLennan 2007), but they are also the focus of intense development pressure due to their proximity to the water and their scenic views. Property owners understandably seek to reduce erosion along their shorelines, but the construction of seawalls and bulkheads to stabilize coastal bluffs also prevents sediment from reaching the beach and the local littoral cell (or *drift* cell). Over time, armoring of these sediment sources may reduce the width of the high tide beach, change sediment size distributions, increase erosion on downdrift beaches, and adversely impact ecological functions.

One of the fundamental concepts of coastal geomorphology is that long-term patterns of shoreline change and beach erosion are often a function of the supply of sediment to the coast. In many cases, increased erosion has resulted from human modifications to sediment sources or to the transport of sediment along the shore (Komar 2000, Woodroffe 2002, Bird 2000). The most common sources of sediment to beaches are streams and rivers and the erosion of coastal bluffs, but the relative importance of each of these sources is a function of the geographic and geologic setting of the area.

Recognition of the importance of eroding bluffs as sediment sources on Puget Sound beaches dates at least to the early 1970s, when the Washington Shoreline Management Act (SMA) was passed and counties and cities began to develop the first generation of local Shoreline Master Programs (SMPs). These SMPs often included policies specifically discouraging the construction of bulkheads on feeder bluffs, but effective implementation was difficult due to the absence of technical understanding and in particular, of maps showing the distribution of actively eroding bluffs, combined with the inherent challenges of regulating the construction of erosion control measures.

Two terms occur frequently in this report and are briefly introduced here:

> **Feeder Bluff.** Geologists have long used the concept of *feeding* to describe the delivery of sediment to the beach, be it by eroding bluffs, streams and rivers, or by artificial means. The term *feeder bluff* has been used on Puget Sound since the 1970s to describe

eroding bluffs that provide sediment to beaches. The term is simple, descriptive, and familiar to many people working on the shores of the Washington and British Columbia.

Puget Sound. In this report we have adopted the broad definition of Puget Sound, which includes all inland marine waters of Washington, east of Cape Flattery and south of the Canadian border. This is consistent with the use of the term by the Puget Sound Nearshore Ecosystem Restoration Project (PSNERP) and by the Puget Sound Partnership (PSP). Historically, the term Puget Sound was narrower in geographic scope, originally referring to the waters south of the Tacoma Narrows and later expanded to include everything south Admiralty Inlet. The term *Salish Sea* has been widely adopted to describe the larger body of water, in both the U.S. and Canada that includes Puget Sound, the Strait of Juan de Fuca, and the Georgia Strait on the interior of Vancouver Island.

The objective of this report is to summarize what we know about the role of these bluffs on Puget Sound and is intended to provide background for recently completed maps of feeder bluffs and other coastal landforms (MacLennan and others 2013). This information is aimed at a wide range of coastal planners, resource managers, and others interested in the condition of Puget Sound's beaches. It is particularly relevant given recent work examining the role of geological and ecological processes in shaping nearshore ecosystems (Fresh and others 2011), the requirement that local governments update their shoreline rules under the 2003 Shoreline Guidelines, increased concern both regionally and nationally about the cumulative impacts of shoreline armoring (Shipman and others 2010), and the widespread recognition of potential changes that may accompany accelerated sea-level rise during the coming century (IPCC 2013).

This report reviews the geologic and geographic context of sediment sources on Puget Sound beaches and the influence of coastal bluff erosion on beach condition. It provides a brief overview of recent work to complete mapping of feeder bluffs throughout the region, although this process is described much more completely in another report, *Feeder Bluff Mapping on Puget Sound* (MacLennan and others 2013). We discuss the implication of this information for the long-term management of Puget Sound shorelines and summarize ways in which this information can be applied, with specific attention to the development of local Shoreline Master Programs and its use in restoration and conservation programs. Finally, the report outlines major data and knowledge gaps that still remain and should be high priorities for scientific work and funding over the coming decade.

The Geologic Setting of Puget Sound

Puget Sound's shoreline is a legacy of the region's glacial history. The Puget Lowland, the broad trough between the Cascade and Olympic Mountains, was shaped during the last ice age, between 20,000 and 15,000 years ago, when the Vashon Glaciation advanced to what is now the south end of Puget Sound (Easterbrook 1986, Booth 1994). The glacier and the meltwater flowing beneath it not only shaped the deep fjord-like troughs and the north-south fabric of the upland topography (Figure 1), but also deposited much of the sediment currently distributed across the landscape.

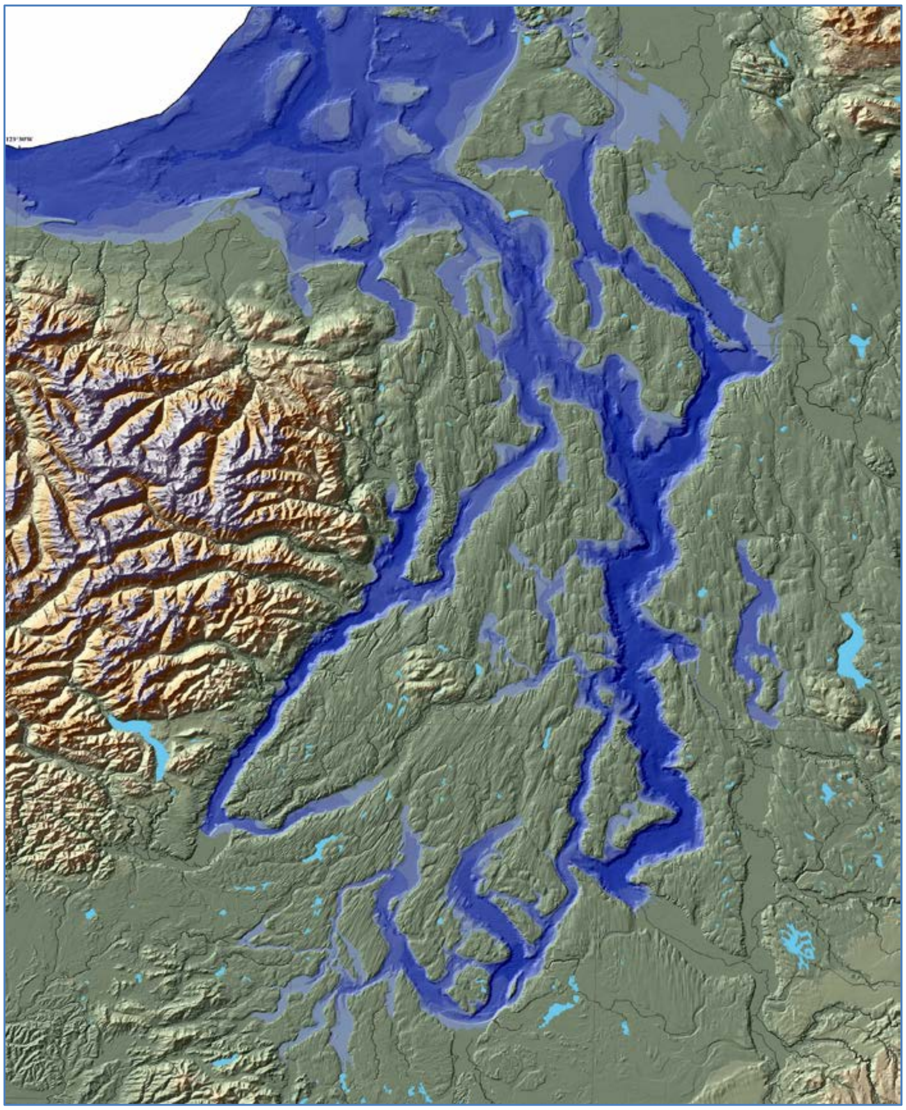

Figure 1. Shaded-relief map of Puget Sound showing complex, glacially-formed landscape. Digital elevation model from University of Washington. (http://www.ocean.washington.edu/data/pugetsound/psdem2005.html)

The current coastline is a result of marine waters gradually reoccupying the deep channels as global sea level rose following glaciation and consists of a variety of coastal landforms that reflect the action of modern geomorphic processes on the inherited terrain (Shipman 2008). In parts of Puget Sound, older bedrock occurs at the shoreline and leads to the characteristic rocky shorelines typified by the San Juan Islands. In other locations, modern rivers continue to build large deltas along the edge of Puget Sound, such as at the mouths of the Skagit and Nisqually Rivers. More than half of the region's shoreline consists of sand and gravel beaches, many of these backed by the steep bluffs (Johannessen and MacLennan 2007) that are the focus of this report.

As in other glacially influenced landscapes (for example, Great Britain, the Canadian Maritimes, and Alaska), Puget Sound beaches are complex, controlled by the inherited glacial topography and the abundance of coarse-grained sediment (Forbes and Syvitski 1995, Ballantyne 2002). Three major factors strongly influence the beaches of Puget Sound: the steep, bluff-dominated coastline, the irregular shaped shoreline and its influence on wave action and longshore sediment transport, and the highly variable, mixed sand and gravel beaches. Each of these is described below.

Steep, bluff-dominated coastline. The glaciers left a rolling landscape several hundred feet above modern sea level, dissected by deep troughs several hundred feet deep (Booth, 1994). These deep fjord-like troughs were inundated by marine waters as the continental ice sheets retreated and sea level rose during the Holocene. When post-glacial sea levels began to stabilize about 6000 years ago, waves and currents began to erode the already steep coastline to form our modern nearshore platform and widespread coastal bluffs (Figure 2). The platform is often narrow, dropping sharply offshore into deep water, in some places more than several hundred feet deep. The steep bluffs give rise to unstable slopes, complex hydrologic gradients, and frequent landsliding (Downing 1983, Shipman 2004, Johannessen and MacLennan 2007). The bluffs vary greatly in height, composition, and erosional mechanisms.

Figure 2. Steep, eroding bluffs on the west shore of Whidbey Island.

Complex shoreline and wave environment. The spread of marine waters into the Puget Lowland's glacially carved troughs and basins resulted in an intricate network of irregularly shaped water bodies (Figure 3). This creates a fetch-limited wave environment with high variability in the strength and orientation of wave action along the shore (Finlayson and Shipman 2003), leading to complex patterns of longshore sediment transport. This results in Puget Sound's shoreline being composed of hundreds of individual littoral cells (drift cells), each with its own sources of beach sediment and patterns of sediment transport and deposition (Keuler 1988, Schwartz and others 1989, Finlayson 2006, Johannessen and MacLennan 2007).

Puget Sound is largely isolated from the influence of the open ocean and wave action is generated primarily by local wind conditions. Beaches on sheltered coasts, such as Puget Sound's, present conditions substantially different than those of more exposed beaches elsewhere (Nordstrom 1992, National Research Council 2007). Longshore variability is often higher, geologic factors such as sediment sources and resistance to erosion strongly influence beach character, and the legacy of historical modifications may be more persistent (Nordstrom 1992, Shipman 2010).

Figure 3. Aerial view of Anderson Island in southern Puget Sound.
Image shows irregular coastline consisting of eroding bluffs and small spits and barrier beaches.

Mixed sand and gravel beaches. The geologic units that surround Puget Sound and that are exposed in its bluffs consist largely of Pleistocene sediment deposited by glaciers or rivers that flowed across the landscape prior to the last glaciation. These units typically contain large amounts of easily eroded sand and gravel which is transported to the coast by streams or delivered directly by bluff erosion (Keuler 1988, Johannessen and MacLennan 2007, Shipman 2010, Czuba and other 2011). The coarse sand and gravel tends to stay in the nearshore (fine-grained silt and clay is typically lost to deep water) and gives rise to the mixed beaches typical of the region.

The character of these sand and gravel beaches varies greatly alongshore, reflecting local variability in sediment sources and the subsequent sorting and resorting carried out by tides and wave action (Figure 4). The abundance of gravel has a strong influence over beach behavior, affecting wave interactions, transport characteristics, and beach hydrology (Finlayson 2006, Miller and Warrick 2012). The beach itself is typically a thin veneer of sediment, often less than a few feet thick (Keuler 1988), on top of an erosional platform cut into the older Pleistocene deposits.

Figure 4. Eroding bluffs at Fort Worden in Port Townsend.

The mixed sand and gravel beach reflects the complex composition of the glacial bluffs, from which the sediment was derived.

Littoral Cells and Sediment Budgets

Beaches on Puget Sound are strongly influenced by longshore sediment transport processes, due in large part to the effect of strongly oblique wave action on steep, swash-dominated beaches (Finlayson 2006, Curtiss and others 2009, Miller and others 2011). Most beaches exhibit a long-term net direction of sediment transport (net shore-drift), based on their orientation to predominant wave action (Schwartz and others 1989, Johannessen and Maclennan 2007). The direction of net transport has been mapped throughout Puget Sound based on geomorphic indicators such as spit configuration and beach geomorphology (Jacobsen 1981, Schwartz 1989). Rates of longshore sediment transport on Puget Sound beaches are much lower than on open-ocean coasts due to the lower wave energy. Nearshore sediment transport is typically dominated by wave-driven swash-zone processes, sometimes combined with wind-generated and tidal currents that distribute sands and gravels along the beach and winnow and transport fine sediments to deeper water. Wallace (1988) found large variability in annual net transport rates within the region due to local differences in fetch and resulting wave exposure.

Puget Sound's irregular coastline can be divided into more than 800 independent littoral cells, or drift cells, each with its own sources and sinks of sediment and an identifiable direction of net sediment transport (Finlayson and Shipman 2003, Johannessen and MacLennan 2007). Woodroffe (2002) distinguishes between sediment compartments and cells, suggesting that compartments are defined by major obstacles to longshore transport such as bedrock headlands (the Oregon coast, for example), whereas cells may have less distinct boundaries determined by local reversals in transport direction (Clayton 1980). Puget Sound is typical of the latter, where cells are often separated by zones of drift divergence or convergence. As a result, many cells on Puget Sound overlap, with a divergence zone providing sediment to two adjacent cells, or conversely, two cells contributing sediment to a single convergence zone (Figure 5).

Most beaches on Puget Sound lie within drift cells characterized by a net direction of sediment transport. Another category of beaches – pocket beaches – are typically relatively short segments of shoreline where beach material is contained between resistant promontories, beaches are oriented into the dominant wave field (swash-aligned) and there is no long-term net transport of sediment in one direction or the other. Pocket beaches are often associated with rocky coasts, but can also be found on artificial shorelines where historical fill and armor create headlands that can isolate individual beaches. Pocket beaches may derive sediment from upland or offshore sources.

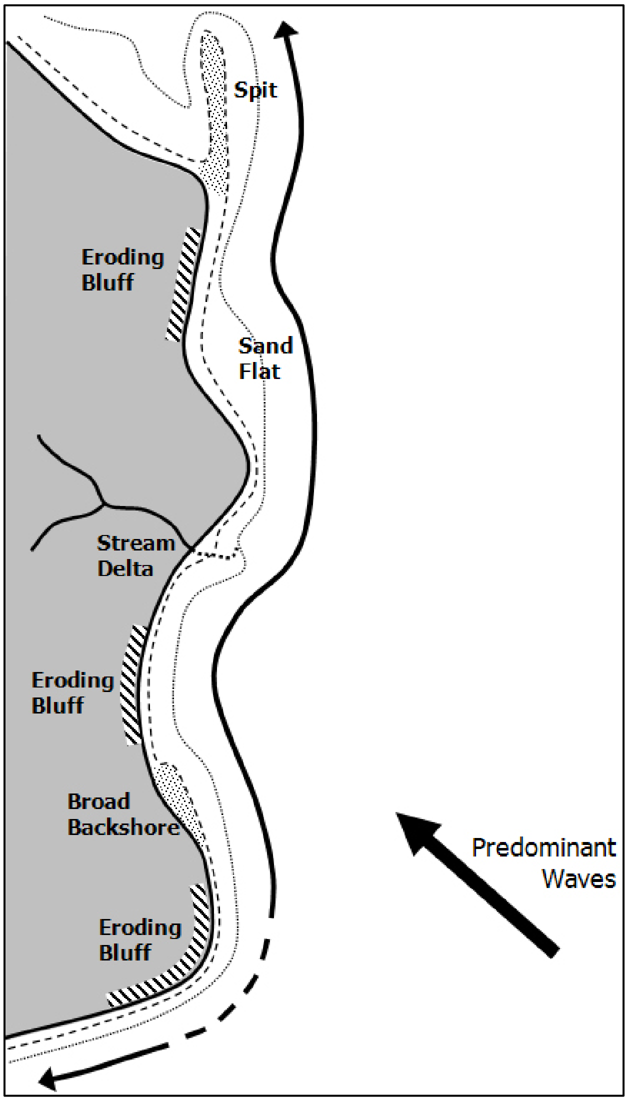

Figure 5. Diagram showing typical sediment transport on a Puget Sound shoreline.

Sediment from eroding bluffs is transported by wave action along the shoreline, where it accumulates in depositional landforms such as spits. The segment that extends from the dashed line at the bottom to spit at the top represents a littoral cell (or drift cell). The dashed line represents a divergence zone at a littoral cell boundary where net sediment transport may be in either direction. (From Finlayson and Shipman 2004).

Littoral cells are a valuable concept for evaluating shoreline change and other coastal behavior (Komar 1996). Connectivity within a cell means that events or modifications in one location may have a predictable impact elsewhere within the cell. At the same time, cells are largely independent of one another, so the effects of changes in sediment supply and transport are localized to a particular cell. In many ways, littoral cells can be used to evaluate sediment in a coastal environment much as watersheds are used to assess the flow of water and sediment in a riverine environment. Littoral cells have been employed as both analytical and management units (Davies 1974, Clayton 1980, Shih and Komar 1994, Bray and others 1995, Best 2003, Cooper and Pontee 2006) to address erosion and coastal change. Locally, cells have been the basis for studies of beach processes in Whatcom County (Bauer 1974, Johannessen and Chase 2003) and along the Strait of Juan de Fuca (Parks and others 2013). The Puget Sound Nearshore

Ecosystem Restoration Project (PSNERP) adopted drift cells as the process units used for its regional analysis of shorelines (Simenstad and others 2011).

Sediment Budgets

Every littoral cell has a sediment budget that accounts for the sources and sinks (losses) of beach sediment, as well as changes in the total amount of sediment in the cell over time. This informs thinking about how beaches change over time and how a shoreline may respond to changes in sediment supply or patterns of sediment transport (Komar 1996, Komar 2000). Depending on the setting, different parts of the budget may be more significant or better understood than others. Determining a precise budget is difficult because identifying, let alone quantifying, all of the sources and sinks of sediment within a cell is challenging. In addition, detecting changes in the volume of sediment stored within the cell is complicated when such changes occur over many years and are masked by other variability within the system (Clayton 1980).

Although beach erosion is typically associated with storms and waves, erosion patterns are often related to long-term deficits within a littoral cell (Komar 2000). One of the primary drivers of increased coastal erosion is the loss of natural supplies of sediment. Ultimately, erosion occurs where more sediment is lost to a particular segment of beach than gained.

The sediment budgets of littoral cells on Puget Sound are strongly influenced by the region's geologic framework:

- The steep coast means that bluffs consisting of poorly-consolidated Pleistocene sediments are located along the shoreline where they are readily eroded and can deposit directly onto the beach. The narrow beaches and steep offshore slopes may result in permanent loss of sediment to deep water and hinders onshore movement of beach-size material, particularly given the lower wave energy and lack of long-period waves that can transport sand shoreward.
- The complex, fetch-limited coastline leads to many, relatively small littoral cells, composed of highly diverse sediments depending on the local geology and landscape. The relative influence of bluff erosion and fluvial sources varies from one location to another. Sediment transport rates, along with erosion and deposition patterns, can vary greatly alongshore, complicating interpretations of beach change.
- The abundance and local variability of coarse sand and gravel in small coastal watersheds and in the bluffs themselves contribute both beach-size sediment and variability. Mixed sediment leads to complex beach behavior, differential transport rates, and partitioning of different substrate size classes both across the beach profile and along the shoreline.

A typical sediment box model that might be applied to Puget Sound beaches is shown in Figure 6. While numerous authors have discussed sediment budgets and their components (Ecology 1978-1980, Downing 1983, Keuler 1988, Galster and Schwartz, 1990, Johannessen and

MacLennan 2007, Warrick and others 2009), developing detailed budgets has been limited by the lack of quantitative information about erosion and transport rates and poor understanding of how different sediment sizes are transported within the Puget Sound nearshore.

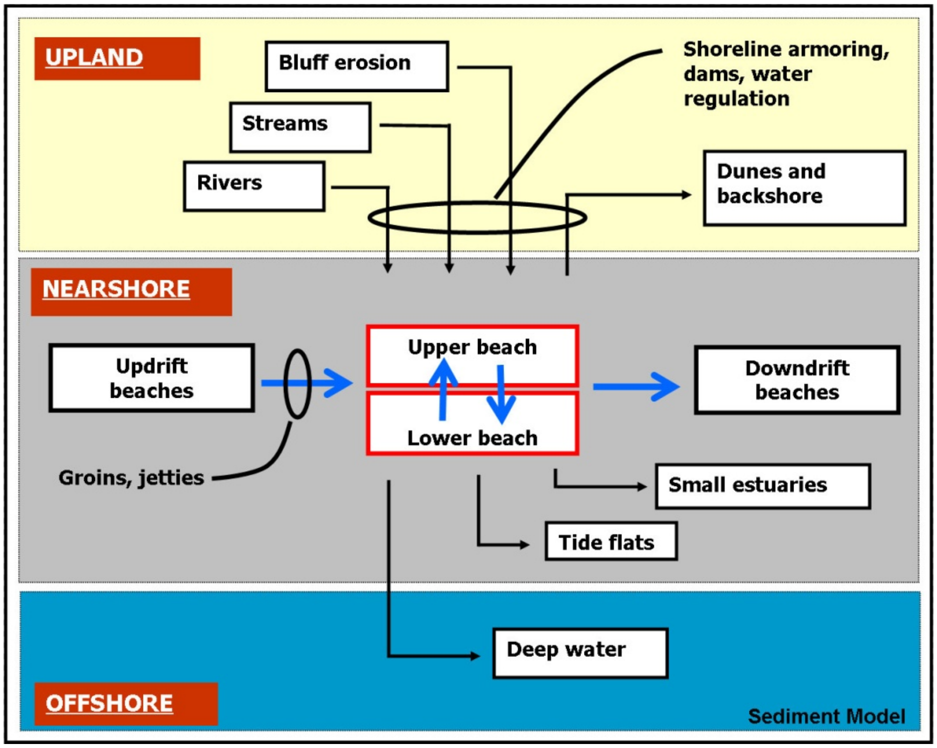

Figure 6. Conceptual model of sediment movement on a Puget Sound beach.

The top portion represents the land, the middle portion the beach and nearshore, and the bottom portion is the deep water of Puget Sound. The blue arrows show sediment transport on the beach itself. The ovals represent common ways in which human activities can disrupt sediment flows.

Sediment Sources

Globally, most beach sediment comes from rivers, streams, and erosion of the coast itself (Bird 2000), although sources vary significantly from one region to another depending on the geologic and oceanographic setting. On coasts with large waves and shallow slopes where waves can mobilize material at depth, erosion of offshore sand and gravel deposits can supply beaches with sediment (Bird 2000, Woodroffe 2002). Shoals and bars can supply beaches locally, but ultimately this material has been derived from a different source (Davis 1978). On Puget Sound, small waves and deep water close to shore diminishes the potential contribution of offshore sources – and also leads to more rapid and permanent loss of sediment into deep water.

Biogenic sources, such as coral and calcareous organisms, are an important source of sediment in some settings. Broken shell can form a significant component of the sediment on some Puget

Sound beaches, but on most beaches, a majority of the material found locally is inorganic, mineral sediment.

On many developed coasts, including the U.S Atlantic coast and in southern California, artificial beach nourishment has become a significant contribution to local sediment budgets. Beach nourishment has also been used in numerous locations on Puget Sound over the last several decades to address erosion, enhance recreational beaches, and as part of nearshore restoration actions (Shipman 2001, Clancy and others 2009, Johannessen and others 2014). In these applications, sand and gravel are typically brought by barge or truck from upland gravel pits and placed directly on the beach. In general, volumes are small and these projects do not represent a significant contribution to the overall sediment budget for littoral cells on Puget Sound.

Large Rivers

In many regions, rivers are a major source of beach sediment, but numerous factors influence the extent to which this material contributes to coastal sediment budgets (Bird 2000, Woodroffe 2002). The large rivers that drain mountain watersheds supply significant amounts of sediment to Puget Sound (Figure 7) (Downing 1983, Czuba and others 2011) but little of this is delivered in a manner where it can form and maintain beaches. Much of the volume of sediment is fine grained material carried in suspension and deposited in deep water. Much of the coarser material is deposited directly in the river deltas and the shape of the coastline makes it unlikely that river sediment moves onto adjacent beaches, except in limited situations.

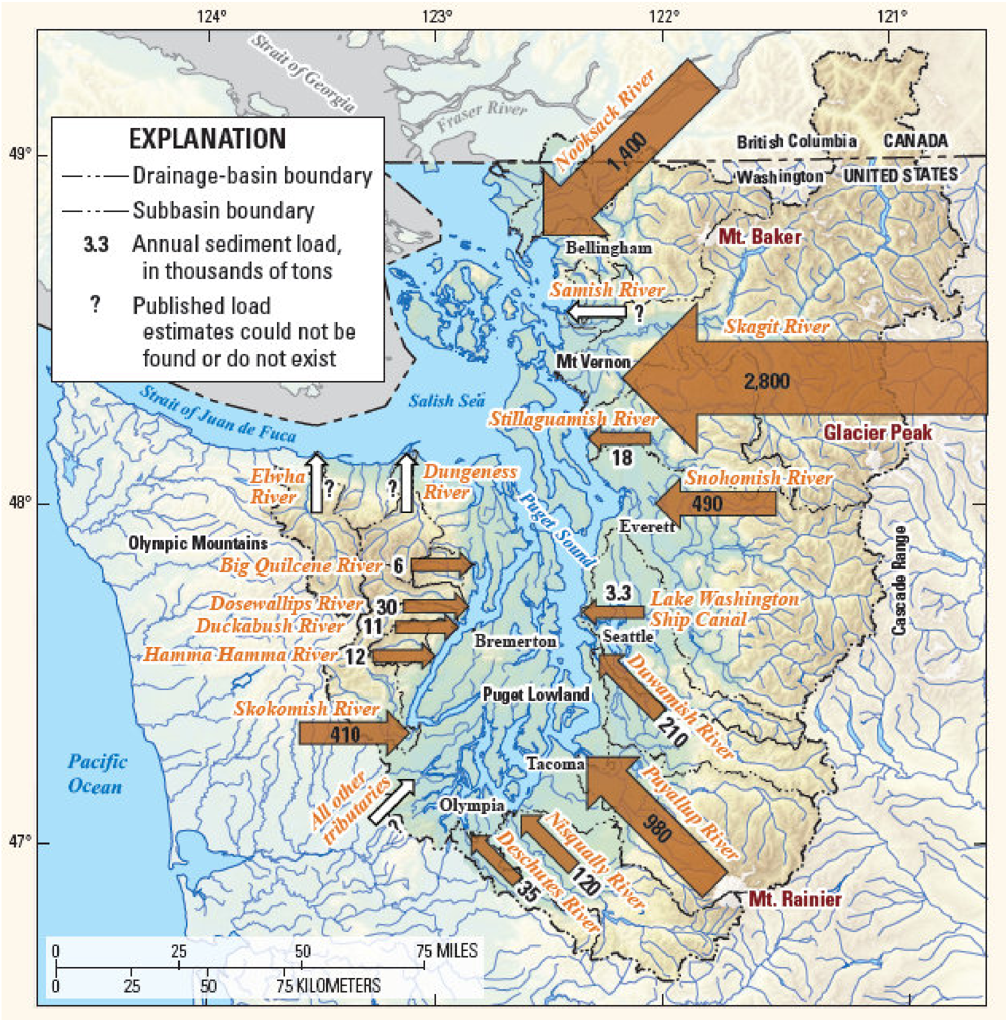

Figure 7. Map showing contributions of sediment from major rivers on Puget Sound.
(From Czuba and others 2011)

The Elwha and the Dungeness Rivers are examples of local rivers that contribute sediment to nearby beaches. These rivers empty onto the Strait of Juan de Fuca and deposit coarse sediment at the river mouths (Warrick and others 2009). These are both wave-dominated deltas and their shorelines consists of spits and barrier beaches (Figure 8). The configuration of their deltas allows wave action to move sediment along the coast to form beaches (Miller and others 2011). In these cases, river sediment appears to play a much larger role in beach condition and shoreline change than elsewhere on Puget Sound.

Figure 8. Aerial view of the Elwha River Delta.

Unlike most Puget Sound rivers, the Elwha empties directly onto an exposed coast where wave action can readily rework beach-size sediment and transport it along the coast.

These two rivers are the exception, since most of the large rivers entering Puget Sound empty onto deltas built into deep glacial troughs. The geometry of these troughs means that wave action in the swash zone and resulting sediment transport on nearby beaches is often towards the deltas, not away from them, suggesting that these adjacent beaches are not deriving their sediment from the river. Development on the fringes of many of the large river mouths has obscured transport patterns and historical landforms, but the Stillaguamish River in Port Susan (Figure 9) illustrates this relationship between a river mouth and adjacent beaches. Longshore transport on the beaches adjacent to the delta is towards the delta, consistent with predominant southerly wind action and evidenced by spits and other indicators of transport (Keuler 1988). Some of the sediment on these beaches may be derived from the river, but the river is not a likely source for sediment on beaches farther away.

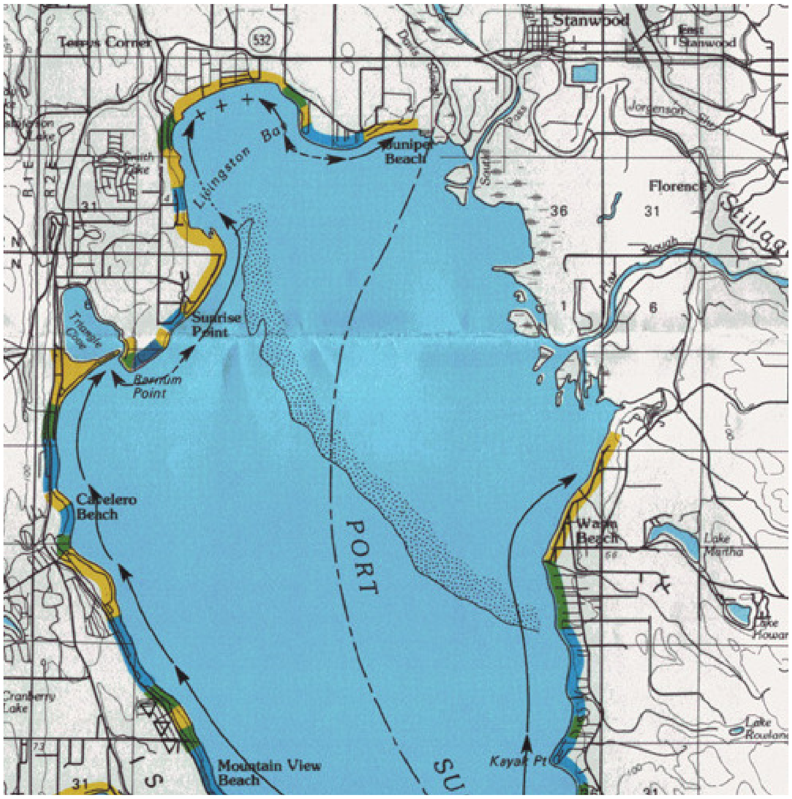

Figure 9. Map of Port Susan and Stillaguamish River Delta.

Arrows show wave-driven sediment transport on beaches is towards the river delta, even though the river delta itself has built southward into Port Susan. Map from Keuler, 1988.

Small Streams

Thousands of small streams empty into Puget Sound. Some deposit their sediment directly onto the beaches, where wave action can then move the material along the coast. Other streams deposit sediment in small estuaries where the potential contribution to nearby beaches is limited. Discharges and sediment loads of small streams are poorly known, although in some cases these may be significant, particularly when exacerbated by historical forestry or development practices. Quantifying sediment delivery is difficult due to the large number of systems, the flashy nature of their flows (affecting both discharge and sediment yield), and the challenges of instrumenting small streams.

The factors influencing sediment delivery from small stream mouths are similar to those affecting the larger river deltas. The configuration of stream mouth and the orientation of coastline to wave action may be important determinants of local contributions of sediment to nearby beaches or drift cells (Figure 10, Figure 11). Some cells receive many streams capable of delivering sediment, while other cells may have no streams or fluvial sediment sources at all.

Figure 10. Aerial photo of Stavis Bay.

This stream empties into a small estuary, which may trap much of sediment before it reaches the beach. Note that spits at the mouth indicate that sediment transport on the beach is towards the estuary.

Figure 11. Aerial photo of Piper's Creek in Carkeek Park, Seattle.

Stream empties directly onto the beach, forming a small intertidal delta.

Bluffs and Coastal Erosion

The erosion of the coast itself can be a significant source of beach sediment, particularly on steep coasts where erosion cuts into an elevated landscape (Bird 2000, Woodroffe 2002). This is common in glaciated regions where coastal bluffs are widespread and coarse-grained sediment is abundant (Ballantyne 2002). The role of bluff erosion as a contribution to local sediment budgets has been described in many locations, including Eastern Canada (Forbes and Syvitski 1995), the Great Lakes (Wood and Meadows 1997), and in Great Britain (Clayton 1989, Bray and others 1995). The role of bluff erosion as a sediment source on Puget Sound has been addressed in many documents, including Bauer (1974), Ecology (1978-1980), Terich (1987), Keuler 1988, Galster and Schwartz (1990), Macdonald and others (1994), Johannessen and MacLennan (2007), Shipman (2010), Johannessen (2010), and Parks and others (2013).

Bluffs vary significantly in the volume of sediment they deliver to the beach due to differences in erosion rates and sediment composition. In addition, their relative importance to the budget of the local littoral cell may depend on other characteristics such as the relative availability of other sediment sources and the volume of material transported along the shoreline. Some drift cells consist of long reaches of eroding bluffs with no streams, making the bluffs the only potential source of beach sediment (Keuler 1988). In other drift cells, eroding bluffs are scarce and stream-derived sediments may play a more significant role.

Three primary factors contribute to the volume of sediment delivered by an eroding bluff: the height of the bluff, the rate of erosion or retreat, and the composition of the bluff (Figure 12). The rate of erosion (retreat) of the bluff, combined with its height, determines the volume of sediment that arrives on the beach (Keuler, 1988). The composition of the bluff determines how much of that sediment remains in the beach system rather than being washed into deeper water. Quantifying the delivery of sediment to the littoral system from bluff erosion is difficult, as accurate long-term erosion rates are hard to measure and bluff composition is often challenging to characterize well (Bird 2000). The three primary factors are described in more detail below.

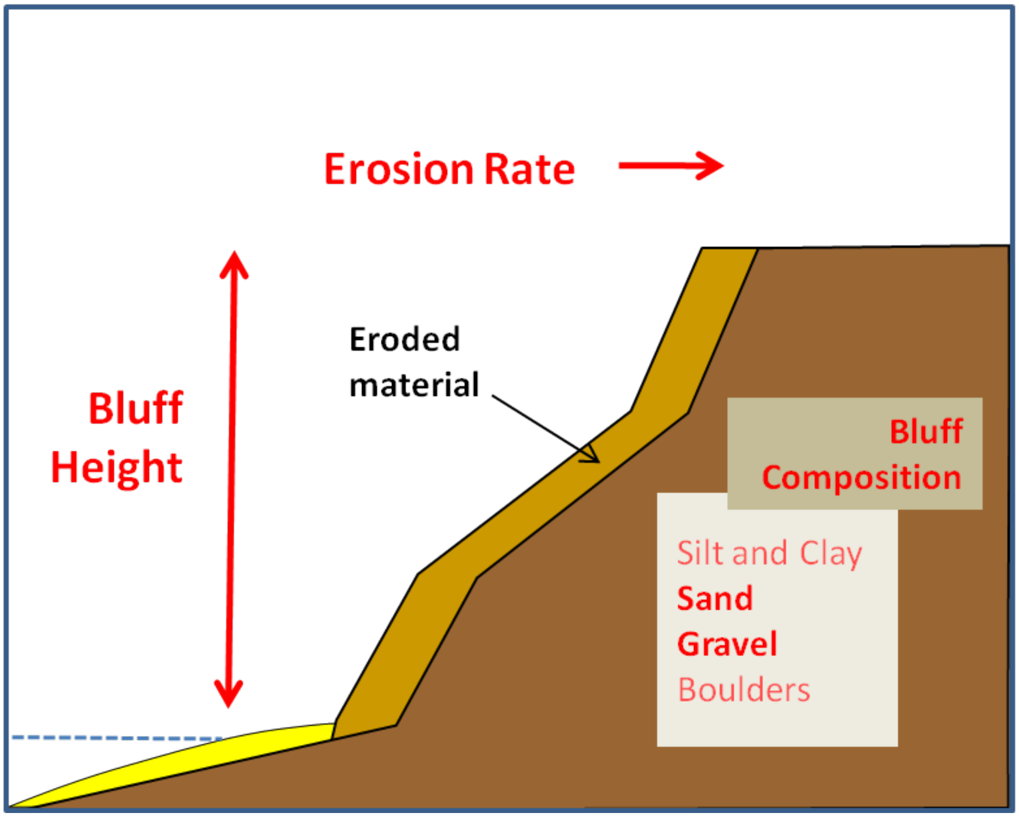

Figure 12. Factors influencing volume of sediment delivered by eroding bluffs.

Bluff height and erosion rates determine the overall volume of sediment eroded, but bluff composition is also important as only sand and gravel-size material contributes significantly to the forming beaches.

Bluff height. On Puget Sound, bluffs vary from small scarps only a few feet high to spectacular 300-foot cliffs (Shipman 2004). The height of the bluff simply reflects the elevation of the upland surface into which the shoreline has eroded. Bluff height is relatively easy to characterize, particularly with the advent of new topographic mapping tools such as LIDAR (Light Detection and Ranging), but effective height can still be complicated to evaluate on complex slopes where toe erosion may be occurring on different timescales than the retreat of the overall bluff. Examples include slopes with complex stratigraphy and those subject to infrequent deep-seated landslides.

Bluff retreat. Erosion rates of coastal bluffs are difficult to establish without precise measurements and long-term records. Erosion is an episodic process and several decades of data may be necessary to establish reliable rates (Keuler 1988, Hapke 2004, Johannessen and MacLennan 2007). In addition, determining accurate erosion rates on slopes dominated by infrequent, deep-seated landslides may be particularly problematic. Few erosion rates have been published on Puget Sound, although rates are known to vary significantly (Shipman 1995, Finlayson 2006). The most comprehensive survey of erosion rates was carried out in north central Puget Sound by Keuler (1988), who examined historical erosion at documented survey monuments.

The ability of waves to remove and transport sediment eroded from the bluff is a limiting factor on bluff erosion/retreat (Keuler 1988). In the same wave environment, a low bluff may erode faster than a high bluff, since less material must be carried away. Keuler (1988) noted a strong relationship between the volumetric rate of erosion and the local wave energy (indicated by fetch), suggesting that the controlling factor over erosion rates was not the ability of waves to erode the toe directly but the ability of the waves to remove sediment away from the beach where it was deposited.

In addition to wave energy and the resistance of the bluff itself to wave attack, the other important influence over bluff recession rates is the beach itself. When the volume of beaches is high – berms are wider and higher – wave action is dissipated on the beachface rather than on the toe of the bluff. Lee (2008) noted the strong dependence of erosion rates on the elevation of the beach. This relationship represents an important negative feedback on bluff erosion rates. Where bluff erosion is rapid and supports large beach volumes, downdrift erosion rates may be buffered. Conversely, controlling bluff erosion with seawalls may diminish sediment supply and lead to increased rates of downdrift erosion.

Bluff composition. The composition of an eroding bluff influences the availability of appropriately-sized sediment to the beaches. Sand and gravel are readily reworked by wave action and incorporated into the littoral system. Boulders and large cobbles will typically remain as a lag deposit on the beach if local waves are insufficiently powerful to transport the material. Fine-grained sediment (silt and clay) is generally winnowed from the beach material and redeposited in deep water offshore and removed from the beach system.

Puget Sound bluffs are typically cut into a locally variable stratigraphy of Pleistocene glacial and interglacial sediments. Glacial tills (e.g. Vashon Till) typically consist of variable amounts of silt, sand, and gravel. Although tills do provide sand and gravel, they are also highly resistant to erosion and often retreat slowly. Glacial outwash (e.g. Vashon Advance Outwash, Esperance Sand) is often composed entirely of sand and gravel and is a significant contributor of beach sediment, as are sandy interglacial fluvial units (e.g. Whidbey Formation). Beach composition on Puget Sound often reflects the composition of nearby eroding bluffs, although wave action and beach processes rapidly sort and resort this material. Characteristic sediment types such as peat (or artificial materials such as bricks or concrete from structures damaged by historical erosion) can often be traced along beaches downdrift from the bluffs where they originated.

Feeder Bluffs on Puget Sound

The term *feeder bluff* has been widely used on Puget Sound to describe bluffs that provide sediment to nearby beaches. Geologists have long referred to the delivery of sediment to the beach by erosion, or by artificial beach nourishment, as *feeding* the beach. The use of the term as a noun on Puget Sound is generally attributed to Wolf Bauer who popularized the concept in workshops and reports and led to its use in many local Shoreline Master Programs in the 1970s. The Coastal Zone Atlas of Washington (Ecology 1978-1980) discusses feeder bluffs and beach feeding on Puget Sound shores. Clayton (1980, 1989) also uses the term *feeder bluff* in describing the role of the Norfolk Bluffs in Great Britain in providing sediment to downdrift beaches.

We propose the following definition:

> Feeder Bluff: *An eroding coastal bluff that delivers a significant amount of sediment to the beach over an extended period of time and contributes to the local littoral sediment budget.*

This definition is simple and captures the underlying meaning of the term. It does not attempt to establish a quantitative threshold. Bluffs are inherently erosional landforms and most are likely to provide some sediment to the coastal environment. The significance of a given bluff as a sediment source will depend on the rate and volume of sediment it provides, the size distribution of the sediment, and the character of the local beaches or littoral cell to which it contributes.

Feeder Bluff Mapping

Several previous projects have mapped or evaluated bluffs in terms of their potential to deliver beach sediment on portions of Puget Sound. Bauer (1976) characterized littoral cells in Whatcom County and identified important feeder bluffs. The Coastal Zone Atlas of Washington (Ecology 1978-1980) mapped most of the Puget Sound shoreline, including the potential for beach feeding, but methods and criteria were poorly documented and there was inconsistency between counties. Keuler (1988) mapped shorelines in the Port Townsend 1:100,000 quadrangle and categorized bluffs in terms of erosion rates. This study also documents erosion rates in a number of locations and discusses the relationship of wave environment and erosion rates, noting that the volume of erosion is more closely related to wave energy than is the linear rate of shoreline retreat.

More recently, Herrera (2005) investigated beaches and sediment sources in Thurston County, with an emphasis on mapped landslides and the potential role of river sediment in influencing the local sediment budgets. Gerstel and others (2012) completed a study of sediment sources in Kitsap County based on detailed review of geologic mapping and remote sensing data that has subsequently been used by the county to prioritize restoration projects – in particular, opportunities to remove bulkheads in locations where sediment supply could be increased.

The Puget Sound Nearshore Ecosystem Restoration Project (PSNERP) used regional map data on bluffs and on shoreline armoring to estimate the integrity of sediment supply on a drift cell basis (Simenstad and others 2011, Schlenger and others 2011). The bluff data were coarse, based on 1:100,000 geologic mapping and an assumption that all bluffs contributed sediment equally. The armoring data was based on a compilation of many different local inventories which varied in both methods and quality. This allowed the first regional scale assessment of sediment supply, but this first-order approach might be improved with the incorporation of higher resolution data.

During the past decade, numerous local groups and jurisdictions have mapped feeder bluffs using a methodology developed by Coastal Geologic Services and summarized in Johannessen (2010). These studies have included Island County (Johannessen and Chase 2005), King County (Johannessen and others 2005), and numerous others. This approach employs detailed field mapping using standard criteria to categorize bluffs based on their potential to deliver sediment. The field approach also allowed identification of other landforms, such as barrier beaches (accretion shoreforms), and much improved resolution of armoring data. In addition, some of these studies also included a historical analysis, which estimated the delivery of sediment that would have occurred prior to the shoreline being armored or otherwise modified (Johannessen and others 2005, Johannessen 2010).

In 2012-2013, the Department of Ecology contracted with Coastal Geologic Services to complete a Puget Sound-wide map of feeder bluffs. This required compiling the existing mapping efforts and then applying similar methods and extensive additional field work to complete the dataset for the remaining areas. The result was a regionally consistent map of the coast, with an emphasis on bluffs and their potential sediment contributions. The GIS coverage is available from the Department of Ecology and the primary maps can be viewed on Ecology's Coastal Atlas.

The methods employed in this work and the results of the project are described in detail in an accompanying report (MacLennan and others 2013) and are not repeated here. The work applied field observations, a standardized set of criteria, existing geologic and topographic data, and aerial photography to identifying coastal landforms. The maps are consistent with previous feeder bluff mapping projects by the same team that identified three categories of eroding bluffs based on potential for delivering sediment. These include exceptional feeder bluffs, feeder bluffs, and transport zones – the latter indicate bluffs where rates of erosion are low and sediment contributions are minor. The maps also identified areas where talus from more resistant geology was believed to contribute bluff sediment.

Figure 13. Map of portions of Whidbey and Camano Islands.

Example of mapping from Maclennan and others (2013), showing a variety of bluff and shoreline types (see Figure 14). From Ecology's Coastal Atlas.

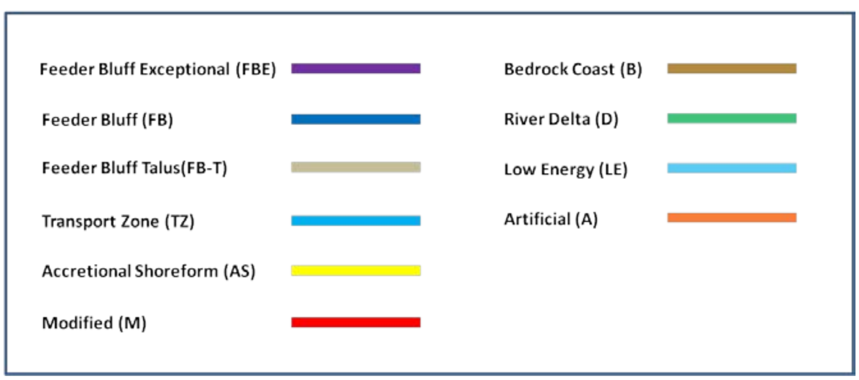

Figure 14. List of mapped landforms and bluff types.

Colors and labels correspond to those used in Figure 13 and 15.

The project (MacLennan and others 2013) also provided an opportunity to refine previous mapping of other landforms, including those not associated with beaches and bluffs, such as bedrock and deltaic shorelines. The emphasis was on the eroding bluffs, but the result is a Puget Sound-wide map of coastal landforms that is relatively consistent with the classification adopted by PSNERP (2008). An example of the maps is provided Figure 13.

The map data provide numerous insights into the geology of Puget Sound's coast (Figure 15). The distribution of beaches and bluffs, when compared to other types of coastline, varies significantly. San Juan County is characterized by extensive bedrock shores, while Snohomish and Skagit Counties are dominated by the large deltas of the Snohomish, Stillaguamish and Skagit Rivers. King and Pierce County have much larger shares of Modified and Artificial shoreline than other counties, reflecting the higher level of coastal development.

Feeder bluffs occur in all 12 Puget Sound counties, although their proportion varies significantly with the size of the county and the geology of its coast (Figure 15). Exceptional feeder bluffs are relatively rare and are more common in counties such as Jefferson, Clallam, and Island where bluffs are often high and where wave exposure contributes to higher erosion rates. In contrast, in more sheltered areas farther south in the region, feeder bluffs remain common, but few meet the criteria for the exceptional category. Transport zones, which reflect relatively stable bluffs with limited ability to deliver sediment, are more prevalent in sheltered portions of southern Puget Sound. Some of these relationships are further developed in MacLennan and others (2013).

Modified shores typically reflect areas where shoreline armoring (bulkheads, seawalls, and revetments) is present (but where the landscape was not sufficiently altered to be classified as Artificial). They are widespread in many areas, including many well removed from the major urban and industrial centers, reflecting the extensive amount of armoring that has occurred on rural and residential shorelines.

MacLennan and others (2013) note substantial differences in the distribution of bluffs and other landforms among individual drift cells and suggest that this may influence habitat structure. Some cells are composed largely of long reaches of feeder bluffs, while other cells have few, if any, significant feeder bluffs. This new mapping work provides a foundation from which to investigate the role of bluff-derived sediment supply in determining the characteristics of drift cells and beaches.

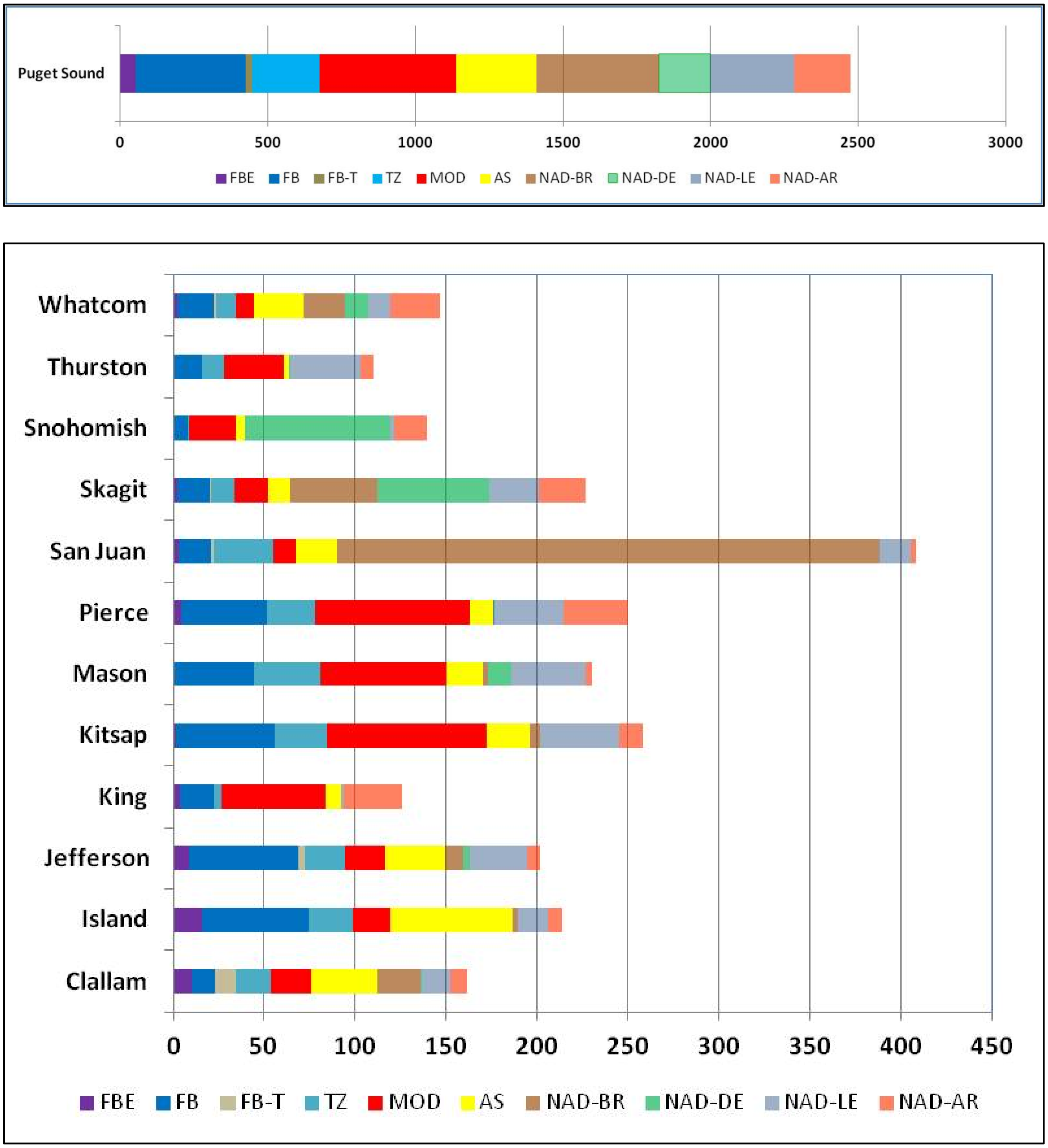

Figure 15. Chart showing extent of coastal landforms in Puget Sound counties.

Top portion shows Puget Sound totals, while lower portion shows breakdown by county. Distances are in miles. Solid colors to the left indicate bluffs and beaches. Muted colors to the right are other shorelines. For codes, see Figure 14. Data from MacLennan and others (2013).

Implications of Feeder Bluffs for Puget Sound Beaches

The fact that many beaches on Puget Sound are strongly influenced by the availability of bluff-derived sediment has significant implications for their development and management. It highlights the importance of geologic processes, including erosion, in maintaining nearshore ecosystems and assuring that the coast can be sustained in a relatively natural condition over decadal time frames while the area undergoes rapid population growth and changes in sea level that are likely to greatly exceed our past experience. These processes and linkages have been described in more detail in Johannessen and MacLennan (2007) and Fresh and others (2011).

Nearshore Processes and Ecosystems

Beaches are an important part of the Puget Sound nearshore environment, comprising at least half of all shorelines by length (MacLennan and others 2013). The geological processes shaping these beaches determine the distribution of sediment sizes, the intertidal morphology, and the disturbance regimes that in turn influence the type and character of nearshore habitats. Sediment delivery is an important ecosystem process within Puget Sound drift cells and impacts beaches at both small scales, such as providing sand to beaches, and at larger scales, such as maintaining spits that in turn shelter productive barrier estuaries (Figure 16) (Fresh and others 2011).

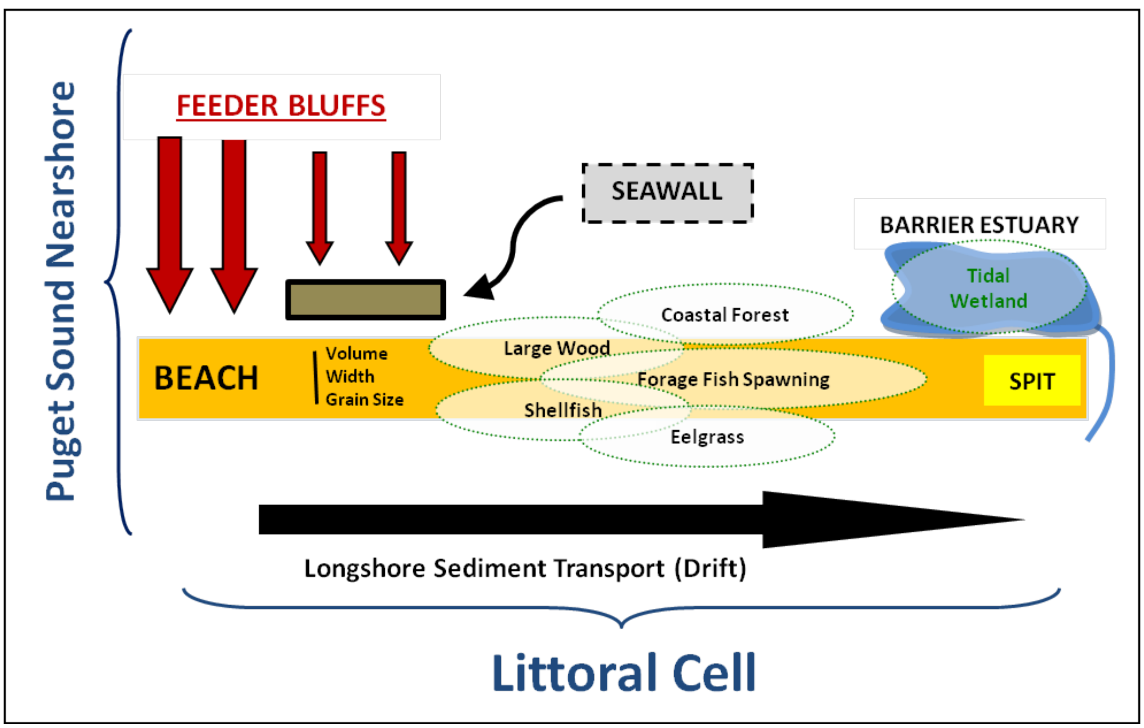

Figure 16. Conceptual model of a Puget Sound littoral cell (drift cell).

Sediment is delivered to the beach by feeder bluffs and is then transported by wave action along the shoreline. The beach itself supports a variety of habitats, ranging from substrate for forage fish spawning to coastal salt marsh behind spits. Seawalls reduce sediment supply and can lead to long-term changes on downdrift beaches.

Eroding bluffs support a wide range of ecological functions, including the recruitment of organic detritus and large wood (Tonnes 2008) and the provision of spawning substrate for sand lance and surf smelt (Penttila 2007). Ultimately, bluff erosion provides sediment to the larger nearshore system, potentially impacting shellfish habitat (Dethier 2006) and eelgrass beds farther offshore (Mumford 2007, Thom and Shreffler 1994, Williams and Thom 2001). Beaches are also important habitat forming features and spits and other barrier beaches are critical to maintaining Puget Sound's many small back-barrier tidal wetland systems (Johannessen and MacLennan 2007, Shipman 2008).

Shoreline Armoring

Concerns about the physical and biological impacts of shoreline armoring (the construction of seawalls and bulkheads) on beaches have increased in recent decades, both nationally and locally. Geological issues include changes in wave dynamics adjacent to structures and to beach hydrology, loss of the beach as the shoreline continues to erode against fixed structures (*passive erosion*), and most relevant to this project, the reduction or impoundment of natural sediment sources (National Research Council 1990, Kraus and McDougal 1996, Nordstrom 1992, Komar 2000, Griggs 2005). Beyond the issue of diminished sediment sources, shoreline armoring can affect ecosystems through the burial of upper beach habitats, reduction in beach wrack and the resulting effect on subsidy-based ecosystems (ecosystems that derive nutrients, detritus, and other organisms from elsewhere), and the increased isolation of terrestrial from marine ecosystems (Dugan and Hubbard 2006).

Armoring on sheltered coasts, such as Puget Sound, is complicated by the unique geology and ecology of estuarine beaches, the more urbanized nature of shoreline development, and often more complex land use and ownership patterns (Nordstrom 1992, National Research Council 2007). The impacts of armoring on Puget Sound shorelines have been reviewed by several authors (Macdonald and others 1994, Thom and others 1994, Williams and Thom 2001, Shipman and others 2010). In addition, there have been more detailed studies of biological responses to armoring and altered riparian connections (Rice 2006, Dethier 2010, Sobocinski and others 2010, Toft and others 2010, Heerhartz and others 2014) and geological responses to changes in supply and transport of sediment (Galster and Schwartz 1989, Parks and others 2013). Shoreline armoring was the focus of a national scientific workshop that was held on Puget Sound in 2009 (Shipman and others 2010).

The effects of shoreline armoring depend on the geomorphic and biological setting. In the case of coasts that depend on erosion as a source of beach material (Figure 17), stabilization diminishes the natural supply of sand and gravel to the local littoral cell (Komar 2000) and can lead to sediment deficits and increased erosion in downdrift areas (Kraus and McDougall 1996, Bird 2000, Woodroffe 2002, Johannessen and MacLennan 2007). This has been described in the Great Lakes (Wood 1988) and Great Britain (Clayton 1980, Bray and others 1995, McKenna and others 1992). Beach erosion on Ediz Hook in Port Angeles has been tied to the loss of sediment supply from both bluffs and from the Elwha River (Galster and Schwartz 1990). Downing (1983, p 54) noted that efforts to stabilize bluffs reduced sediment to down-drift beaches and "remedied one condition but aggravated another."

Feeder bluffs are inherently associated with retreating shorelines and although seawalls may help protect the toe of the bluff from erosion, they do not prevent the ongoing narrowing of the beach seaward of the structure. This is referred to as passive erosion and is in addition to the narrowing that is expected to accompany rising sea level. In addition to this loss of beach width and volume, loss of sediment supply may lead to changes in beach substrate – generally beaches will become coarser as finer sediment is preferentially winnowed away and not replaced (Macdonald and others 1994).

Figure 17. A timber pile bulkhead at the base of an eroding bluff in Snohomish County. Although continued failure on the upper slope may deliver small amounts of sediment over the top of the structure, this source of beach sediment has been effectively eliminated.

Predicting the impact of reduced bluff erosion on beaches will be complicated by natural variability in beach composition and morphology and by differing sensitivity of particular beaches to changes in sediment supply. The response of beaches may take years or decades, particularly at sites farther removed from the site of the armoring. Responses may take time to propagate through a system driven by relatively infrequent storm events and there may be a lag in response where significant sediment is already stored within the beach system. Feedbacks are possible, as the loss of sediment sources in one location is compensated for by increased beach and bluff erosion elsewhere (Macdonald and Witek 1994).

Shoreline armoring is a classic example of an environmental problem involving cumulative impacts. Individual structures may have a relatively small effect on the sediment budget of an entire drift cell and their effects may take years to materialize. At the same time, the aggregate impact of many small structures can become significant, particularly over longer time frames.

Sea-Level Rise

Rates of sea level rise are widely expected to increase during the coming century as a result of warming global temperatures, with estimates ranging from less than a foot to more than three feet by 2100 (Mote and others 2008, National Research Council 2012, IPCC 2013). Some of the variability in these estimates is attributable to local differences in vertical land movement and oceanographic factors, but the largest uncertainty stems from unknowns in carbon emissions, in the climate models themselves, and in their estimates of global sea level response (Mote and others 2008, National Research Council 2012). In the past 100 years, about 8" of sea-level rise has been recorded at the Seattle tide gauge – a rate comparable to the global increase during the same period.

Higher sea level is expected to drive more rapid erosion of coastal bluffs, as increasingly larger waves are more able to erode the beach and the reach the toe of the bluff (Figure 18). Increased erosion will likely motivate property owners to further armor the shoreline. At the same time, as sea level rises on armored shorelines, the beach will become narrower (*coastal squeeze*) and water levels at the seawall or revetment will increase, eventually requiring more robust structures (Titus 1986, Bray and Hooke 1997, Pethick and Crooks 2000).

The ability of beaches to accommodate rising sea levels depends in part on the availability of sediment to build higher beaches as water levels rise (Pethick and Crooks 2000). In a bluff-dominated system such as Puget Sound, bluff erosion will be an important source of sediment to maintain downdrift beaches and their associated ecosystems. One implication of this is that while rising sea levels will aggravate bluff erosion and lead to demand for more stabilization (Walkden and Hall 2011), the ongoing erosion of these bluffs is a key element in maintaining the long-term resilience of bluff-fed beach systems (Dawson and others 2009, Nichols and Cazenave 2010, Cooper and Pontee 2006).

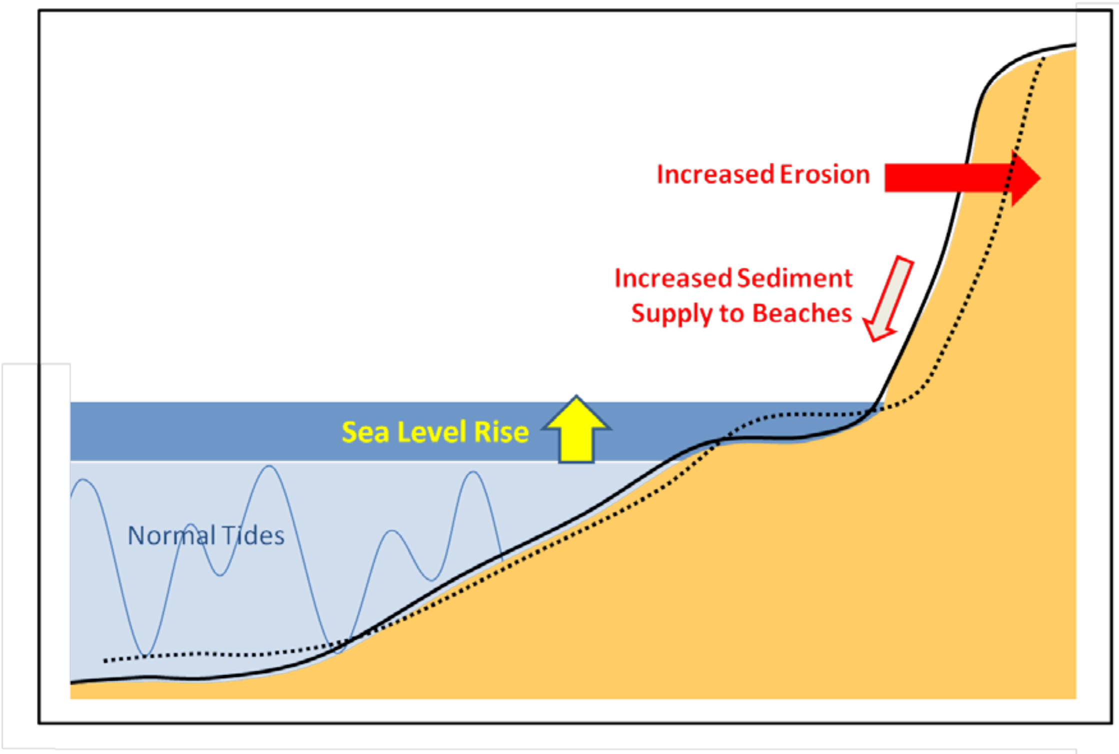

Figure 18. The response of coastal bluffs to rising sea level.

Coastal erosion enables the beach to translate upslope with little change in their character as water levels increase. The ability of the shore to retreat, along with the increased availability of sediment from continuing bluff erosion, allows the beach berm to build upward and landward.

Feeder Bluffs and Shoreline Planning

Knowledge of the location of feeder bluffs and their role in maintaining nearshore sediment budgets can benefit policies regarding development of coastal areas and protecting coastal resources. This information can be applied in a wide variety of ways, including the regulation of shoreline activities, the development of conservation and restoration programs, and simply as a tool for educating communities and property owners about their shorelines. The following section discusses a number of ways in which feeder bluff information might be applied on Puget Sound.

Building on Feeder Bluffs

Building on or above feeder bluffs requires developing safely while also protecting the natural functions provided by the eroding bluffs. Any bluff is a potentially hazardous location and feeder bluffs often have higher erosion rates and more serious slope stability issues than other shoreline areas. At the same time, any effort to slow erosion or otherwise stabilize the bluff impairs the bluff's important role as a source of beach sediment.

The simplest way to avoid both the hazard and to allow the natural erosion of the bluff is to avoid development in the first place. In reality, structures already exist or there are constraints on how a site can be developed (e.g. small lots, on-site septic requirements) that lead to structures being built closer to the edge than would otherwise be appropriate. The challenge becomes how to maintain the long-term function of the feeder bluff while also accommodating some level of development. Ultimately, the objective is to avoid development practices that will require erosion control measures that prevent sediment from reaching the beach.

Development on bluffs can be divided into two categories: 1) those activities that occur above and landward of the bluff crest and 2) those that occur on the face or at the toe of the bluff. Most development associated with feeder bluffs is built above (landward of) the bluff crest. In residential settings this may include homes and related structures such as decks, pools, gazebos, drain fields, as well as yards and gardens. In non-residential settings, this might include commercial structures, transportation facilities and public utilities, recreational facilities, and so forth. These may not directly impact feeder bluff function, but with time, are likely to be at risk from erosion or slope failures and will increase property owner's motivations to stabilize the bluff in the future (Figure 19).

Figure 19. Homes built along the bluff edge on North Beach in Port Townsend.
(Photo: Ecology 2006)

Two considerations guide appropriate development landward of feeder bluffs. The first is the rate of erosion and the mechanism of slope failure, since these will determine minimum setbacks. The second is the ability to remove or relocate at-risk structures in the future. A combination of large setbacks and rigorous standards for relocating structures may allow for development on these sites without jeopardizing the long-term health of the shoreline. At the same time, once development of any sort has occurred, resistance to removal or relocation can be expected.

In general, erosion rates are relatively slow on Puget Sound so reasonable setbacks can provide decades or more of safety (the greater threat on some sites is a large slope failure, not chronic erosion). In addition, large buffers (areas left in their natural condition) can reduce the risk of unintentionally exacerbating slope failures that result from removing vegetation and altering drainage. The presence of a natural, vegetated buffer along the edge of the bluff may also reduce the visual impact of small, non-threatening failures and increase a property owner's sense of security. Ultimately, buffers may reduce risks to development and preserve shoreline habitat, but do not prevent the long-term natural retreat of an eroding bluff or the eventual threat to structures that cannot be removed or relocated in the future.

Structures built on the face of the bluff, or at the base of the slope, are inherently vulnerable to ongoing erosion and slope failures. Maintaining them may require stabilization that reduces or eliminates natural erosion and sediment delivery. In general, such development will be more vulnerable to damage in the case of rapidly eroding bluffs and slopes with deep-seated instabilities.

Figure 20. Stair towers on eroding bluff on Marrowstone Island.
Impact on natural erosion and can be built in ways that limit vulnerability to small slope failures, but they can also increase pressure in the future to stabilize the bluff.

A realistic understanding of erosion rates and slope failure mechanisms may allow for certain types of structures, such as stairways or drainpipes, to be built without jeopardizing the long-term function of the feeder bluff (Figure 20). It may be possible to design and construct these so as to allow continued erosion and so that they can be easily relocated if damaged or threatened. More significant structures, such as houses or other buildings, roads, and recreational facilities, are more likely to require stabilization and are much more difficult to relocate or rebuild as erosion progresses.

Shoreline Master Programs

In Washington, shoreline activities are regulated by a number of local, state, and federal agencies, each charged with authority under different laws (Carman and others 2010). These include local counties and cities, the state Departments of Ecology and of Fish and Wildlife, and federal agencies such as the Corps of Engineers. The focus in the following material is on the

Shoreline Management Act, but some of this will also be relevant to other regulatory mechanisms.

Washington's Shoreline Management Act (SMA) requires cities and counties to prepare Shoreline Master Programs (SMPs) to address development and activities along their shorelines. Since 2003, jurisdictions have been updating their SMPs to meet new state Guidelines (Washington Administrative Code, Chapter 173-26). These Guidelines require communities to characterize their shorelines, designate shorelines for certain types of uses, and to develop appropriate and effective policies for protecting their shoreline (more information available from the Department of Ecology's website[1]). The following sections identify a number of places where information about feeder bluffs might contribute to the development of a Shoreline Master Program.

Ecological Functions and No Net Loss

The 2003 Shoreline Master Program Guidelines discuss the importance of assessing ecosystem-wide processes and requires local Shoreline Master Programs (SMPs) to assure "no net loss of ecological functions necessary to sustain natural resources and to plan for restoration of ecological functions where they have been impaired." WAC 173-26-201 (2) (c) (see Shoreline Handbook Chapter[2]). Sediment delivery is a critical geologic process that supports important ecological functions and local SMPs should identify the location of feeder bluffs and establish policies that protect naturally eroding bluffs and encourage the restoration of sediment sources where feasible.

This is challenging, as it requires protection of a process (coastal erosion) that upland property owners are highly motivated to prevent. The primary impediment to feeder bluff function is the construction of seawalls and related erosion control structures, setting up a conflict between the desire to prevent erosion of upland property and the requirement to maintain shoreline functions over time.

A mitigation sequencing approach offers one way to reduce the potential impacts of activities on feeder bluffs. The emphasis should be on ways to avoid development at sites where future erosion is likely and thereby reduce pressure to armor the shoreline, but this is often difficult due to existing development, site constraints, strong motivations to prevent erosion, and legal limitations on restricting the use of property.

Where avoiding these areas is not possible, there may be opportunities to minimize the impacts by reducing the size of erosion control measures or relocating at-risk structures. Concern about the environmental impacts of shoreline armoring has spurred interest in softer methods of

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[1] http://www.ecy.wa.gov/PROGRAMS/sea/sma/guidelines/index.html
[2] http://www.ecy.wa.gov/programs/sea/shorelines/smp/handbook/Chapter4.pdf

preventing erosion (Gianou 2014), but while these designs can be made ecologically friendlier through the addition of natural elements like large wood and vegetation, they generally do not address the long-term loss of sediment supply.

Offsetting sediment losses at specific sites is difficult. Artificial delivery of sediment to the beach has its own impacts, can be complicated to implement, and may be impractical on many sites. Off-site mitigation is difficult because restoring sediment delivery typically requires removing an erosion control structure and opportunities to do this are limited. Because the location where sediment delivery occurs is important, mitigation away from the site of the impact, even within the same drift cell, may be inadequate.

The SMP Guidelines leave local governments with considerable latitude in how they monitor ecological functions and assess the achievement of the no net loss requirement. A logical component of such a monitoring effort would be a mechanism for tracking the location, length, and character of projects that impact existing feeder bluffs. This might complement efforts of the Puget Sound Partnership and the Departments of Ecology and Fish and Wildlife to evaluate trends in the length of armoring, and, in particular, the length of armoring on feeder bluffs, over all of Puget Sound.

Inventory and Characterization

The Shoreline Master Program Guidelines require cities and counties to assess the distribution and character of ecosystem processes and functions within their jurisdiction (SMP Handbook Chapter[3]). The Guidelines encourage the use of existing information where possible and these new feeder bluffs maps can be an important element of a local shoreline inventory. Shoreline inventories typically include a variety of other coastal information that complements or adds value to the feeder bluff data, including other coastal landforms, drift cells and drift directions, unstable coastal slopes and landslides, and shoreline armoring. Inventories should also include restoration opportunities. These may be specific sites where derelict or unnecessary structures can be removed, locations where natural sources of sediment have been impacted, and places where restoration projects are being considered or have been completed.

Jurisdictions may often have access to better local data or may choose to obtain higher resolution, more up-to-date, or more locally relevant information. This would be particularly helpful where Puget Sound-wide information may be inadequate or incomplete, such as with new landslide maps or with inventories of shoreline armoring. At this time, many jurisdictions with Puget Sound shorelines have completed the preparatory work for their new SMPs so incorporation of this type information may occur in subsequent updates.

[3] http://www.ecy.wa.gov/programs/sea/shorelines/smp/handbook/Chapter7.pdf

Shoreline Environment Designations

The Shoreline Management Act and the 2003 Guidelines direct local jurisdictions to assign segments of shoreline to different environmental designations (see Shoreline Management Handbook[4]). These typically include Natural, Conservancy, Shoreline Residential, and Urban, but local governments are encouraged to consider other categories where appropriate. Policies, regulations, and development standards may differ among designations, reflecting different natural characteristics, historical land uses, and community goals for each segment of shoreline.

The designation of shoreline environments should be consistent with the local Inventory and Characterization. Designations provide an opportunity to identify shoreline reaches that are particularly vulnerable to long-term erosion and slope instability and to establish standards that foster safe development while also protecting the function of feeder bluffs. This might be particularly relevant in areas of known or emerging erosion problems, particularly where public facilities and road or utility corridors occur along the shoreline.

As much as possible, functioning feeder bluffs should be included within Natural or Conservancy designations, since these categories typically support more restrictive policies regarding setbacks and shoreline stabilization. In more developed designations where historical armoring is more extensive, policies might encourage relocation of threatened structures, restoration of feeder bluffs where possible, and offsetting the impacts of new stabilization where it cannot be avoided.

One approach to protect feeder bluffs in areas of existing or expected development might be to employ parallel designations (described on page 22 of Chapter13 of the SMP handbook[5]) – where the area above the bluff is designated to allow a range of activities but the face of the bluff and the shoreline is assigned a more restrictive designation. This allows for development, while also protecting the shoreline. In the long-term even well-placed structures may become threatened, but restrictions on stabilization will require design with relocation in mind.

Setbacks

Because stabilization and armoring impair feeder bluff function, policies generally try to discourage development practices that are likely to lead to demand for armoring in the future (Figure 21). This is best done by maintaining large setbacks for new development and by developing standards for the type of activities that can occur on or near the bluff itself, such as the construction of secondary structures, on-site sewage systems, stairways, trams, and other actions that may be vulnerable to future erosion. Wherever possible, these projects should be

[4] http://www.ecy.wa.gov/programs/sea/shorelines/smp/handbook/Chapter4.pdf
[5] http://www.ecy.wa.gov/programs/sea/shorelines/smp/handbook/Chapter4.pdf

designed so they can be readily relocated or removed if threatened by erosion and ideally should be sited so that they will not be at risk from erosion in the first place.

Figure 21. Air photo illustrating setbacks from the top of a bluff.

These homes south of Oak Harbor are built at the top of a feeder bluff. The homes on the left are located substantially back from the edge, but the new construction in the center is being built with a much smaller setback, underscoring the problems of managing bluff-top development (Photo: Ecology 2006)

Erosion rates are typically slow on Puget Sound, so a large setback can provide adequate protection for many decades or centuries. This becomes more complicated on sites that are subject to deeper landslides, where the effect of a single event may reach tens or even hundreds of feet inland, and these situations should be identified and evaluated carefully in a geotechnical analysis prior to development. In these cases, armoring of the toe is not likely to be an effective or sufficient strategy for stabilizing the slope.

Policies regarding setbacks and stabilization can be useful tools for educating property owners about potential risks to their property and encouraging safe building practices in locations where options for controlling erosion may be limited.

Shoreline Stabilization

The primary threat to the function of feeder bluffs is the construction of seawalls and revetments that prevent erosion, since they inherently cut off the natural supply of sediment to the local drift cell (Figure 22). This is not to diminish the potentially serious ramifications that erosion and landsliding can have on coastal development, but it underscores that there are tradeoffs associated with decisions to harden the shoreline. The impacts of armoring on feeder bluffs and beach ecosystems were described in the earlier section on Implications of Feeder Bluffs.

Figure 22. Rock bulkhead built to prevent erosion of bluff.

Although additional failures of this bluff are still possible, the supply of sediment to nearby beaches has been effectively eliminated.

The SMA Guidelines specifically address the issue of sediment impoundment as a result of shoreline hardening and how it may lead to changes in beach ecology and downdrift erosion patterns (WAC 173-26-231 (3) (ii)). Stabilization policies generally discourage armoring except where it is necessary to protect an existing structure from imminent harm and they encourage development that avoids the need for hard structures.

Rules adopted by local jurisdictions regarding stabilization of feeder bluffs may depend on the shoreline designation and whether the structure is new or a replacement of an older one. Policies might be tailored to the geologic conditions of a particular site, with stricter standards for exceptional feeder bluffs and more flexibility in dealing with shorelines where sediment supply is not as large a concern (transport zones or barrier beaches). At the same time, armoring has a wide range of impacts and while the impact of a new seawall on sediment supply in these other settings may be low, the structure may still cause major harm to riparian vegetation or to a spawning beach.

Restoration Plans

Development of Shoreline Master Programs under the new state guidelines requires the preparation of a restoration plan[6]. One reason for this was recognition that despite efforts to restrict new activities that impact ecological functions, there are likely to be continuing losses from existing development and that there will also be unpreventable impacts associated with new development. This is particularly relevant in the case of armoring on feeder bluffs, where the impacts of historic structures may worsen with time and where effective mitigation at an individual site may be impractical.

Typically, a restoration plan will identify both strategies for achieving restoration over a longer time frame and specific actions that might be implemented over a much shorter time frame. Strategic actions might include:

- Employ local inventories and characterizations, new feeder bluff information, and regional prioritization efforts such as the PSNERP Nearshore Strategies (Cereghino and others 2012) to identify where restoration is most likely to lead to improved functions at a reach or drift cell scale.
- Develop outreach programs for property owners that explain the role of feeder bluffs and solicit voluntary removal of shoreline armoring.
- Encourage shoreline education programs that teach about erosion and shoreline processes and that improve community awareness at the scale of drift cells.
- Design regulatory, tax-based, or other incentives that encourage property owners and other groups to carry out restoration projects in areas of coastal bluffs.
- Encourage collaborations with local land trusts, tribes, fisheries enhancement groups, parks authorities, and private developers. Often these other groups have already developed restoration objectives and may be able to leverage funds, outreach tools, and technical assistance.
- Investigate options for identifying and relocating at-risk development along feeder bluffs.
- Explore mitigation strategies that require landowners to compensate for incremental loss of sediment supply by subsidizing restoration of sediment sources in other locations.

Short-term Actions might include:

- Use the Shoreline Inventory to identify specific opportunities where restoration might be carried out. This might include removing old seawalls where it will not jeopardize

[6] http://www.ecy.wa.gov/programs/sea/shorelines/smp/toolbox/process/task4.1.html

upland development or within parks and other large parcels where redevelopment can accommodate the safe restoration of feeder bluffs.

- Work with property owners who are interested in restoring their shorelines and are comfortable living with natural erosion patterns. Provide assistance in working through permit issues involved in removal and relocation of structures.

Conservation and Acquisition

Besides regulatory restrictions on erosion control structures and bluff-top development, a number of other approaches may also help preserve feeder bluff functions over time. These include conservation easements and open space requirements, incentives for relocating vulnerable development, and acquisition of land along high-priority bluffs.

Preservation of feeder bluffs confers benefits beyond the long-term supply of beach sediment to nearby beaches. Because they are inherently hazardous due to the potential for erosion and landsliding, their protection can help prevent development that would otherwise be in harm's way. In addition, high bluffs are iconic Puget Sound landscapes, providing important aesthetic values and spectacular views. Bluffs often support valuable coastal forest, provide habitat for nesting birds and raptors, and might serve as refugia for native wildlife in otherwise urbanized areas (Thom and Shreffler 1994).

Exceptional feeder bluffs are relatively rare and should be high priority candidates for aggressive protection efforts, as they provide benefits to their entire drift cell, including increased resilience in the face of rising sea levels.

Acquisition of coastal habitat has traditionally focused on wetland systems, such as salt marshes and river deltas, but in the last several years efforts have been expanded to include a wider range of nearshore ecosystems, including beaches and bluffs. Acquisition is often initiated at the local level, through county parks departments, land trusts, and salmon restoration groups. Recent examples include Lily Point and Point Whitehorn in Whatcom County, Barnum Point on Camano Island, and Indian Point on Whidbey Island.

Figure 23. Eroding bluffs at Joemma Beach State Park in Pierce County.

There is a long history of public ownership of steep slopes and landslide-prone bluffs on Puget Sound and many of our best known state and local parks are on geologically hazardous sites. These sites can present challenges for park management, but low intensity recreation is generally a more appropriate use for these areas than residential development. Examples of Washington State Parks on large landslides (and feeder bluffs) include Camano Island, South Whidbey, and Kopachuck State Parks. In addition, Fort Worden, Fort Flagler, Joemma Beach (Figure 23), and Fort Ebey State Parks, along with many others, include feeder bluffs.

Restoration of Feeder Bluffs

Stabilization of eroding bluffs and development at their base has reduced natural sediment delivery to many of Puget Sound's littoral cells and beaches. The Puget Sound Nearshore Ecosystem Restoration Project (PSNERP) identified the loss of sediment inputs from coastal buffs as a major impairment of nearshore processes (Schlenger and others 2011). The areas of greatest impact are in central and southern Puget Sound, where urbanization and coastal transportation corridors have led to extensive armoring (Figure 24).

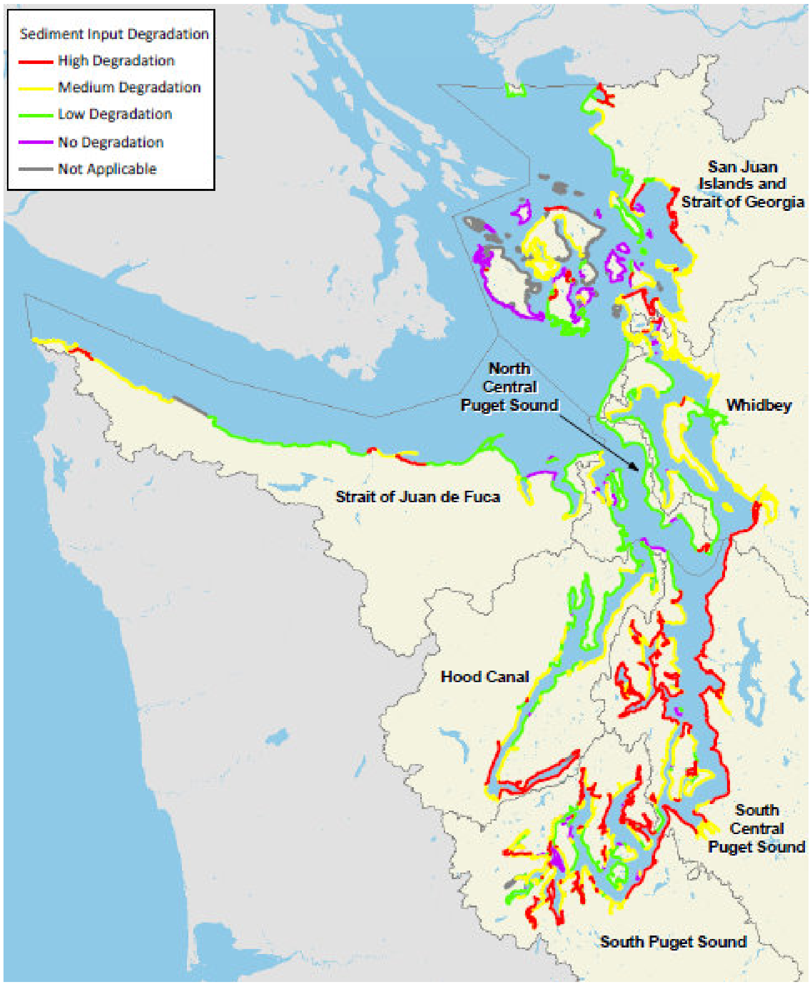

Figure 24. PSNERP map showing relative degradation of bluff-derived sediment sources.
In general, red indicates littoral cells where bluffs have been heavily modified and sediment supply has been diminished, while green and purple represent areas with lesser impacts. From the PSNERP Strategic Needs Assessment (Schlenger and others 2011).

Restoration of feeder bluffs and beaches impacted by lost sediment sources is a relatively new concept but is receiving increasing interest from both local restoration groups and state and federal funding organizations. Seawalls and revetments have been removed in recent years to restore habitat and shoreline functions, as well as to enhance recreational uses, although most of these have occurred on accretional shores (barrier beaches) or on historically filled (artificial) shorelines, not in areas of eroding bluffs.

Restoration of feeder bluffs implies the removal of erosion control structures that may have been in place for many decades and that may be important in protecting upland development from erosion or slope instability. Determining where this is feasible and where it brings the greatest value is critical to prioritizing restoration efforts. Kitsap County has recently completed a county-wide assessment of sediment supply and a prioritization of restoration opportunities

(Kitsap County Regional Shoreline Restoration Project, Gerstel and others 2012). Local studies such as this can take advantage of more detailed data and analyses that are tuned to the needs of the jurisdiction and other important stakeholders and can also include assessments of ownership and feasibility. This project has already led to a beach restoration project at Anna Smith Park in Tracyton (Figure 25).

Figure 25. Site of recent bulkhead removal in Tracyton.

Anna Smith Park, where Kitsap County removed a bulkhead on an eroding bluff, restoring natural shoreline functions.

The Estuarine and Salmon Restoration Program (ESRP) is seeking to support beach restoration projects, particularly those that restore historical sediment supplies. Their strategy builds on the work by PSNERP (Cereghino and others 2012). The new higher resolution feeder bluff maps developed in the current project should further contribute to prioritizing the locations of new projects and evaluating their effectiveness.

The PSNERP Management Measures Report (Clancy and others 2009) identified a number of techniques that can be applied to restoring beaches on Puget Sound and summarized both considerations and limitations in their application. Two of these techniques are particularly relevant to feeder bluffs. The first, bulkhead removal, has already been discussed. The second is beach nourishment. Nourishment does not restore feeder bluff function, but in some cases may be an appropriate means of restoring sediment to beaches in heavily impacted areas. It is often a valuable component of projects that remove old armor, as it can be used to rebuild historical beach profiles and to alleviate some of the rapid erosion that can accompany bulkhead removal. Both beach nourishment and bulkhead removal have been further described in the recently released Marine Shoreline Design Guidelines (Johannessen and others 2014).

Conclusions

Long term stewardship of beaches requires maintaining natural sources of sand and gravel. On Puget Sound, these sources are often eroding bluffs, although in many places this supply has been significantly diminished by past efforts to control shoreline erosion. Protecting remaining sources of sediment and preserving functioning beach systems benefits from knowledge of where these sources are located and their relevance to local sediment budgets.

We now have greatly improved information on the role and the distribution of feeder bluffs on Puget Sound. These new maps are regional in scope, yet have high spatial resolution. The maps identify several categories of eroding bluffs, allowing discrimination of those that are more important than others to local beaches. The material in this report, along with the accompanying maps, are intended to be both an educational tool and a guide to improving management practices on Puget Sound beaches.

This report builds a case that eroding bluffs on Puget Sound play an important role in maintaining beaches and nearshore ecosystem, that preventing erosion with the construction of seawalls and revetments is the greatest threat to this process, and that this will become a more serious problem if sea level rises significantly in the coming decades. This suggests several recommendations:

- High-value feeder bluffs should be prioritized for protection and restoration. While all bluffs may have ecological attributes, some bluffs are more important as sediment sources than others.

- Emphasis should be placed on relocating at-risk development rather than opting for conventional shoreline stabilization measures. This protects the function of the feeder bluff while also decreasing the future vulnerability of the development. Moving landward and relocating structures is consistent with the practice of managed retreat advocated by coastal experts concerned about the effects of sea-level rise and long-term coastal erosion. Doing this successfully will require public education and meaningful incentives.

- Conservation and acquisition are the most effective long-term strategies for protecting the most important bluffs. Regulations can require larger setbacks and stricter standards for stabilization, but may not be adequate to prevent long-term losses. Mitigation of impacts to natural sediment supply may have significant drawbacks.

While the basic role of eroding bluffs in maintaining Puget Sound beaches is understood, the details are not. Progress on a number of scientific questions would aid better management decisions in the future. Important topics needing work include:

- Systematic examination of beach sediment sources on Puget Sound including the role of streams and rivers, and the development of representative sediment budgets for different littoral cells.
- Studies of rates of coastal erosion and the factors that influence patterns of erosion. This would help in characterizing both potential risks to development in many areas and the role of bluffs in contributing to local sediment budgets.
- Investigation of the factors that influence the sensitivity of beaches to changes in sediment supply – in terms of both the nature and the rate of the response.
- Improved understanding of the relationship between the geological characteristics of beaches and the ecosystems that depend on them.

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