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A Geomorphic Classification of Puget Sound Nearshore Landforms

Prepared in support of the Puget Sound Nearshore Partnership

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Acknowledgments

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Front cover: Gravel spits on the south end of Indian Island on Oak Bay. Photo by Hugh Shipman.

Back cover: Left, aerial view of Wiley Slough on the Skagit River delta. Photo courtesy Washington State Department of Ecology. Right, north side of Deception Pass, Fidalgo Island. Photo by Hugh Shipman.

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Executive Summary

The shoreline of Puget Sound includes more than 3,000 kilometers of beaches and bluffs, estuaries and lagoons, river deltas and rocky coastlines. Each of these shoreline types is shaped by different geomorphic processes and each gives rise to a different suite of nearshore ecosystems and ecological functions. Within each of these coastal settings, the environmental stressors and the resource management challenges will be different.

Strategic regional approaches to environmental protection and restoration will only be successful to the extent that they accurately incorporate this fundamental variability in the geomorphic landscape.

The Puget Sound Nearshore Ecosystem Restoration Project (PSNERP) has adopted a process-based approach to restoring and preserving nearshore ecosystems, recognizing that (1) the need for ecological restoration most often results where natural processes have been disrupted and (2) efforts to restore ecosystems without addressing impairments to these underlying processes are unlikely to succeed. Spatially explicit approaches to restoration will require understanding which processes operate at a particular place and what the context of that place is within a complex geologic landscape. Regulation of shoreline activities also benefits from the consideration of geomorphic context. Washington's new shoreline guidelines (WAC 173-26) require cities and counties to update their local Shoreline Master Programs over the next several years with a goal of achieving no-net-loss of ecological functions. Accurately characterizing the ecological functions associated with a particular site or shoreline reach will be important in developing meaningful regulations. Doing this will benefit from developing assessment methods and management approaches appropriate to specific coastal environments.

This report proposes a conceptual classification of Puget Sound nearshore landforms that is hierarchical, that reflects the primary role of geomorphic processes in shaping the landscape and that is relevant to the unique setting of Puget Sound. The report outlines a systematic framework that describes the geomorphic variability of the Puget Sound shoreline and that can guide strategies for assessing, managing or restoring nearshore environments. This framework is based on the concept that ecosystems are shaped by physical processes and are uniquely associated with particular coastal landforms. The report identifies the factors that influence the primary shoreline types observed on Puget Sound and discusses the close relationship between geomorphic processes and landforms and how this influences ecosystems.

The character and distribution of nearshore landforms on Puget Sound is a function of the complex shape and geology of the coastline, along with the subsequent erosion and deposition of sediment by waves, tides and rivers. The region's topography (and bathymetry) and geology are largely the result of major glaciation about 15,000 years ago, which formed much of the current landscape and deposited much of the sediment now found along the shoreline. The considerable lateral variability we observe on Puget Sound's shoreline is due to the irregular shape of this glacial landscape and the diversity of sediment types left by the glaciers. After the ice retreated, the shoreline continued to change as waves and streams eroded and redistributed sediment, forming valleys, deltas and beaches. Coastal landforms continue to evolve today under the influence of modern processes: bluffs retreat, spits shift, lagoons fill in and deltas grow.

Regional scale variability in landforms along Puget Sound's shoreline reflects broad variation in geology and oceanography, climate and precipitation, wave action, tidal range currents and local sea-level history. Bedrock is more prevalent in northern parts of the region, thus the rocky San Juan Islands. The largest river systems in Puget Sound basin drain the Cascades and, therefore, most of the big river deltas lie along the Sound's eastern shore. Widespread features such as spits occur throughout the Puget Lowland but their size, their character and their abundance differ between northern and southern Sound because of regional differences in tides, wave exposure and topography.

Most Puget Sound shorelines can be broadly categorized into one of the following four *geomorphic systems.*

- *Rocky coasts*. These are best typified by the San Juan islands, where bedrock is prevalent along the water's edge and shorelines lack abundant mobile sediment. Sediment tends to be limited to isolated pocket beaches that exhibit little longshore sediment transport. Some rocky shorelines plunge steeply into deep water and lack a broad nearshore zone. Where rocks are less resistant to erosion and wave action is more significant, rocky shorelines may be fronted by erosional platforms and extensive intertidal ecosystems.
- *Beaches.* Beaches dominate much of Puget Sound's shoreline. They are characterized by the active transport of sediment by wave action. They can be divided into those associated with coastal bluffs, where the coastline has retreated landward, and those associated with barrier beaches, where sediment has been deposited seaward of the original coastline. Barriers are numerous and include spits, tombolos, cuspate forelands and a variety of other forms. Most Puget Sound beaches (other than the pocket beaches along rocky coasts) exhibit net longshore transport of sediment and the development of discrete littoral drift cells, within which sources and sinks for sediment and a direction of net transport can be defined.
- *Embayments.* This term describes protected estuaries and lagoons within which there is too little wave action to form beaches. The term *pocket estuary* has been widely

used on Puget Sound to describe these features. Most of these small embayments are tidally influenced, but they also include isolated lagoons and wetlands. *Estuaries* are those with a significant input of freshwater – for example, from a surface stream, whereas *lagoons* have limited freshwater input. A large number of the estuaries and lagoons on Puget Sound are formed and enclosed by barrier beaches, emphasizing an important geomorphological relationship between the wave-dominated beach environments and these small protected estuarine environments.

- *Large river deltas.* This category is reserved for the deltas of the large rivers that drain the Cascade and Olympic mountains. These deltas, built of fluvial sediment deposited at the coastline, are often broad and low-lying, and represent the marine extension of alluvial floodplains. Many have been heavily modified for agricultural and urban uses. Deltas can be distinguished based on the relative influence of waves, tides and river processes in their formation. Deltas are associated with streams of all sizes, but smaller ones are generally subsumed within the other systems – for example, stream deltas can occur within the upper reach of a small estuary or directly on an exposed beach.

These four major *systems* form the foundation of this shoreline classification and reflect the fundamental role of waves (beaches), tides (estuaries and lagoons), and rivers (deltas). Shorelines within each of these systems can be further divided into individual *landforms*, which generally reflect patterns of erosion and deposition of coastal sediment (e.g., bluffs, barrier estuaries, wave-dominated deltas). Landforms can in turn be viewed as assemblages of *components*, relatively homogenous features of similar tidal elevation or of substrate that often correspond to specific habitats (e.g., low-tide terrace, bluff face, backshore/berm, sand flat). This framework is hierarchical, reflecting the fact that some geomorphic processes influence a broader suite of landforms than others. The hierarchy emphasizes relationships among landforms formed by similar processes and highlights the fact that landforms of different scales are nested.

This framework is relatively comprehensive in that it explains much of the variability observed in the Puget Sound shoreline. It is also fairly simple, allowing different groups to adapt or expand the framework to better suit their particular objectives. Groups focused on salmon recovery may develop more detail regarding small estuaries and river deltas. Planners dealing with shoreline development may need to develop more resolution on coastal bluffs and among different barrier beach environments. Not all coastal variation can be explained by this typology. Small, yet important, features such as stream mouths and tidal channels are not captured well. Variability within types – for example, the large number of barrier beach configurations – is discussed, but not addressed systematically. Some environments, such as the tidally dominated heads of some larger inlets (for example, South Sound inlets and Discovery Bay, which share attributes of both deltas and embayments), may require additional consideration.

The classification is built around landforms at different scales, but the underlying emphasis remains on natural processes. Geologic and geomorphic processes form and maintain coastal landforms. At the same time, these landforms form a physical template that controls the spatial pattern, intensity and character of more localized geomorphic and ecological processes. Geomorphic processes inform two important aspects of coastal behavior:

- The relationship among landforms in space is typically a function of the flow of water or the transport of sediment from one place to another. The stability of a barrier beach is tied to the supply of sediment delivered by an eroding coastal bluff. The development of tidal channels on the front of a delta is a function of sediment supply, but also of the tidal hydrology of upstream areas.
- The behavior of landforms over time and the character of associated ecosystems is a function of long- and short-term temporal change. Geomorphic processes have characteristic rates that determine how rapidly landforms evolve, how quickly they respond to altered conditions and how much variation they exhibit over short periods of time.

This shoreline classification is a tool that can inform efforts to grapple with Puget Sound's complex coastline. One example of where this geomorphic typology might be applied is in the ongoing efforts by local governments and salmon enhancement groups to describe and characterize nearshore conditions. Perhaps the first step should be to identify the primary geomorphic environments along the shoreline of interest. Assessment methodologies will be different in some environments than in others. Evaluation of the effects of human structures (e.g., docks and piers) or of restoration measures (e.g., dike removal) should reflect the appropriate geomorphic setting (a bulkhead within a small estuary is different than a bulkhead at the foot of an exposed bluff). Another application of the classification might be the evaluation of historical shoreline change and its significance for proposed restoration actions. While direct measurement of shoreline change can be difficult, understanding the geomorphic processes acting on a particular landform allows inferences about the possible rate and character of past and future changes. Large deltas can be expected to follow different trajectories than pocket beaches on rocky coasts because the underlying processes driving change are different.

This paper emphasizes the relationship between landforms, nearshore geomorphic processes and, by inference, ecosystem processes and functions, but many other aspects of the natural and built landscape are also inherently linked to the geomorphology of the shoreline. Development history and resulting land-use patterns, natural hazards, vulnerability to sea level rise and water-quality problems are often correlated with geomorphic type, suggesting that the classification may be a helpful way of looking at a broader range of environmental issues on Puget Sound.

Introduction

Puget Sound contains more than 3,000 kilometers of diverse shoreline, including rocky coasts, sand and gravel beaches, coastal bluffs, small estuaries and lagoons, and river deltas. Each of these environments is (1) characterized by different geomorphic and ecological processes, (2) associated with different natural resources and ecosystems and (3) subject to a distinctive suite of environmental problems and potential solutions. As a consequence, any spatially explicit strategy for managing or restoring shorelines can benefit by considering the variability within the geomorphic landscape.

Two ongoing efforts in Washington underscore the need for such a strategy. The Puget Sound Nearshore Ecosystem Restoration Project (PSNERP) has emphasized the importance of process-based restoration, recognizing that (1) ecological restoration is most often needed where fundamental natural processes have been disrupted and (2) efforts to restore the structure of ecosystems without addressing these disrupted processes will likely be unsuccessful (Simenstad et al. 2006). PSNERP is charged with characterizing historical and current conditions, developing conceptual models and selecting site-appropriate portfolios of restoration actions. In addition, recent Washington state guidelines for developing local Shoreline Master Programs (WAC Chapter 173-26, adopted in 2003) stress the need to protect and restore ecological functions. These guidelines require jurisdictions to inventory and characterize shoreline conditions and to develop policies and regulations for protecting and restoring ecological processes specific to different environments.

The report proposes a *conceptual classification* of Puget Sound nearshore landforms that should inform and improve shoreline management and restoration planning. This classification, or *typology*,[1] forms a conceptual framework that is hierarchical, reflects the primary role of geomorphic processes in shaping the landscape and is relevant and appropriate for the unique setting of Puget Sound. Although many classification systems have been proposed for coastal systems, few address the variety and the character of the landforms found in our region.

I have chosen the terms conceptual classification and *typology* deliberately, emphasizing explanation and synthesis rather than rule-based discrimination and the delineation of units that can be mapped. The objective is to develop a context for describing widely varying shoreline environments, not to draw maps of the Puget Sound shoreline. This typology is intended to guide those charged with mapping and classifying shorelines, but specific approaches to map classifications will depend greatly on their geographic scope and the questions being addressed.

The geographic scope of this paper is the nearshore zone of Puget Sound, including all inland waters of Washington state eastward from the mouth the Strait of Juan de Fuca and south from the Canadian border (Figure 1). We have adopted the broad definition of *nearshore* used by PSNERP, which extends from the head of tide and the upper edge of coastal bluffs seaward to the offshore limit of the photic zone.

In this report, existing approaches to coastal classification—including work specific to Puget Sound—are reviewed first. The major factors that have influenced the development of the modern shoreline are summarized from the perspective of both the long-term evolution of the shoreline and the major regional controls over landscape formation. This leads to the description of a hierarchical *typology* of coastal landforms that can be related back to geomorphic processes. The resulting framework is then used to organize a detailed description of the geomorphic variation observed on Puget Sound's shoreline. The report concludes with a discussion of how this geomorphic typology might apply to specific coastal management problems. The appendices provide (1) a glossary of key terminology and (2) identify resources that might assist in identification and geomorphic mapping of shorelines.

1. Various italicized terms throughout this paper are defined in the glossary (Appendix A).

Previous Work

Coastal Classifications

Geomorphic variation in coastal environments has been described and classified in numerous ways, reflecting the inherent complexity of shorelines and the diversity of applications in which such classifications are applied. The choice of a classification depends on its intended purpose (Cooper and MacLoughlin 1998, Montgomery and Buffington 1998) and a single system is unlikely to address all possible concerns, which may range from improved scientific understanding of shoreline changes over time to management needs for oil-spill response or restoration planning.

Simple shoreline classifications have eluded coastal scientists (Snead 1982, Pethick 1984, Fairbridge 2004, Finkl 2004), in part because the definition and delineation of *landforms* depends greatly on the scale of the analysis (landforms are the fundamental geomorphic unit, defined by their shape and the processes that form them). Landforms, at any scale, are themselves typically combinations of smaller landforms. The topology of landforms varies with the type of feature and the scale of analysis. Beaches and rocky shorelines are continuous, linear features while estuaries and deltas tend to be discrete and more polygonal. Most shorelines are linear at regional scales, but become more complex at local scales (Fricker and Forbes 1988). The overlapping influence of oceanography, geology and ecology, and the need to incorporate terrestrial and marine science, makes coastal classification highly interdisciplinary, raising conceptual difficulties and confusing terminology (Cooper and MacLoughlin 1988).

Coastlines have been classified on regional and global scales (Shephard 1973, Snead 1982, Finkl 2004), often with emphasis on regional controls such as plate tectonic setting (Inman and Nordstrom 1971) or patterns of relative sea-level change (Johnson 1919). Many classifications limit themselves to particular geomorphic environments, such as sea cliffs (Emery and Kuhn 1982), deltas (Wright and Coleman 1973, Wright 1985), estuaries (Day 1981, Alongi 1998) and barrier beaches (Hayes 1979, Wright and Short 1984).

Geomorphological classifications may emphasize the shape of landforms (morphology) or the processes that form them (genesis), although these are inherently linked (Davies 1977). Shoreline classifications often focus specifically on the geomorphic processes shaping the landforms. Deltas and estuaries have been broadly classified based on the relative influence of wave (beaches), tide (estuaries) and riverine (deltas) processes (Wright 1985, Carter and Woodroffe 1994). Coastal landforms are often distinguished as either erosional or depositional, but this depends on both the temporal and spatial scales of analysis. For example, a barrier beach forms through long-term deposition of sediment, yet many barriers are actively eroding and retreating. Similarly, a river delta is fundamentally a depositional environment, yet portions of a delta may erode over time.

Puget Sound Studies

Although the basic principles of the aforementioned broad classifications apply in Puget Sound, most were designed either to describe much larger areas of coastline or to address a narrower range of geomorphic environments. Puget Sound's glacial origin resulted in a wide variety of coastal landforms, many of which are not well described in a coastal literature dominated by sandy ocean beaches, large estuaries and deltas, and exposed rocky coastlines.

Puget Sound shorelines have been classified in various different ways. As with classifications carried out elsewhere, these efforts have had specific purposes, have focused on small geographical areas and often have been restricted to narrow geomorphic settings. Studies have tended to be focused on beach and bluff landforms, coastal wetlands or nearshore biological communities. They have ranged from simple categorization of shorelines to detailed inventories of coastal habitats and have included both sound-wide and highly local efforts.

Downing (1983) broadly divided the Puget Sound coastline into depositional landforms (deltas, tidal flats, dunes and a variety of barrier beaches) and erosional landforms (sea cliffs, platforms and cobble-armored beaches). Terich (1987) proposed a simple suite of six coastal types to guide property owners in evaluating coastal sites, including (1) high bluffs, (2) low bluffs, (3) developed shorelines with seawalls, (4) deltas and tidal flats, (5) rocky shores and (6) beaches with wide backshores. This classification was adapted for an assessment of Bainbridge Island shorelines (Best 2003, Williams et al. 2004). Philabaum and Schwartz (1974) and Bauer (1974) characterized coastal landforms and processes in Whatcom County, focusing primarily on shoreline bluffs and beaches.

Several process-oriented studies of Puget Sound beaches have relevance to classification. Keuler (1988) mapped beach processes in the Port Townsend area, characterizing coastal bluff erosion and depositional landforms. Schwartz et al. (1989) describes studies of longshore transport throughout Puget Sound, distinguishing beaches from shorelines where wave-induced sediment transport is less significant (e.g., rocky shores and river deltas). The Coastal Zone Atlas (Washington Department of Ecology 1978-80) mapped numerous shoreline characteristics, including aspects of sediment transport, coastal geomorphology and substrate. More recently, detailed shoreline characterizations have classified eroding bluffs, historical sediment supplies and accretional shorelines in King County (Johannessen et al. 2005).

Investigations of specific categories of geomorphic features have also been carried out, including Bauer's (1975) inventory of accretion beaches (spits and barrier beaches) and Kunze's (1984) survey of high-quality coastal wetlands, which were categorized by their geomorphic context (e.g., coastal spits, coastal lagoons, tidal rivers). Recently, Collins and Sheikh (2005) identified and characterized over 800 tidal wetlands throughout the region, assigning each to one of 18 geomorphic settings. Todd et al. (2007) have identified and characterized historical changes within deltas, small estuaries and lagoons along Hood Canal and eastern Strait of Juan de Fuca shorelines.

Dethier (1990) developed a nearshore marine and estuarine habitat classification based on the National Wetland Inventory (Cowardin et al. 1979), addressing limitations in that scheme's applicability to estuarine and marine systems by incorporating consideration of wave and tidal energy and salinity. Dethier's system strongly emphasizes substrate characteristics, energy levels and salinity regimes that influence biological communities at a local scale. The Washington Shore Zone Inventory (Berry et al. 2001) incorporates the habitat classification of Dethier (1990) and the geomorphic classification of Howes (1994) to map Washington's entire marine shoreline, dividing it into relatively homogenous segments hundreds or thousands of meters in length. It emphasizes substrate and intertidal morphology rather than geomorphic processes and larger coastal landforms.

Beamer et al. (2003, 2005) describe a geomorphic classification of shoreline habitats in the Whidbey Basin that uses geologic and topographic information. Donoghue (2005) outlines a methodology to classify coastal landforms that combines the Shore Zone Inventory (Berry et al. 2001) with other data sets. Both of these approaches use Geographic Information Systems (GIS) to apply prescribed rules to available shoreline data in order to systematically classify and map shorelines.

The goal of this report is to develop a geomorphic framework that describes a majority of the landforms observed in Puget Sound. One objective of this framework is to relate these landforms to geomorphic processes relevant to coastal management and restoration. A second objective is to provide an organizational scheme that is sufficiently flexible to apply to a wide variety of coastal environmental issues as well as to different parts of the region. This classification builds on previous coastal classifications, including work done on Puget Sound, but is more descriptive, synthesizing knowledge of coastal geomorphic systems, explaining the sources of variability influencing shoreline differentiation and emphasizing the context of individual landforms within the larger coastal environment.

Geomorphic Setting

Evolution of the Puget Sound Landscape

Coastal landforms are a function of the inherited (antecedent) topography and geology of the shoreline, the long-term pattern of relative sea-level change and the ongoing redistribution of sediment by physical processes. In areas heavily impacted by past glaciations, the complex topography and the distribution of different sediment types across the landscape strongly influence the coastal landscape (Kelley 1987, Ballantyne 2002).

The Puget Lowland, between the Cascade and Olympic mountains (Figure 1), is the result of broad movements of the earth's crust related to the subduction of the Juan de Fuca Plate beneath the western edge of North America over many millions of years. These tectonic processes have established the broad-scale topography of the region and the distribution of older geologic units (bedrock), and they influence the pattern of historical and modern sea-level change.

The modern landscape of the Puget Lowland is largely a legacy of the Vashon glaciation (15,000-20,000 BP), the most recent of the glaciations that have shaped this region. Ice advanced across Puget Sound, depositing large volumes of glacial sediment and subsequently shaping these sediments to create the current topographic and bathymetric terrain. The glacier left a distinct north–south grain to the region's hills and valleys, which are generally superimposed on a broad outwash plain about 100 meters in elevation (Booth 1994). Meltwater flowing southward beneath the ice is believed to have scoured the major troughs that define Puget Sound today (Burns 1985, Booth 1994). Most of the sediment exposed on the edges of river valleys and along the coastal bluffs is glacially derived.

The glacial landscape was subsequently modified during the Holocene (since the glaciers retreated) by fluvial erosion and deposition, coastal processes and hillslope mass-wasting along the steeper slopes bounding streams and the coastline. The major rivers, which flow from the Cascades and Olympics, carried sediment into their lower reaches, building alluvial valleys and deltas (Collins et al. 2003). The growth of many of these large river deltas has been influenced by eruptions and mudflows associated with the Cascade volcanoes. Lesser streams drain hundreds of small watersheds located entirely within the Lowland and often within a few kilometers of the coastline; they cut into the erodible glacial sediments, forming small valleys and ravines, and redeposit material in narrow floodplains and at the marine shoreline.

The evolution of the shoreline since glaciation has been strongly influenced by changes in relative sea level, the pattern of which has been complicated in the Puget Sound basin (Shipman 1990). Relative sea level during the last 15,000 years has been a function of global (eustatic) sea-level changes and localized emergence and submergence tied to isostatic rebound (ice removal) and tectonics (regional tilting and localized seismic events). Because glacial rebound and tectonic warping have not been uniform across this region, the northern and southern parts of Puget Sound have different sea-level histories. During the late Holocene (the last 5,000 years), sea level may have remained relatively constant in northern Puget Sound, whereas in southern Puget Sound, submergence has occurred.

Coastal processes, such as longshore sediment transport and delta formation, have operated since the ice retreated, but the modern shoreline has largely formed since global sea level began to approach its current position 5,000–6,000 years ago. Stream and river mouths built deltas and estuaries where they reach the sea. Erosion of the coastline and sediment transport by waves and currents resulted in the redistribution of sediment to form erosional shorelines (bluffs and an erosional nearshore platform) and depositional shorelines (spits and barrier beaches). Most large rivers have continued to expand their deltas seaward during the last several thousand years. As these deltas have grown, they have extended into areas previously dominated by wave-driven coastal processes. The Skagit delta, for example, has engulfed rocky islands and shorelines previously characterized by eroding bluffs and barrier beaches.

Regional Variability

The distribution and character of coastal landforms in the Puget Sound basin arises from a combination of factors, some of which vary over short distances but many of which are more regional in nature. Factors that vary locally include shoreline orientation to waves, local heterogeneity in geology and proximity to stream mouths. Factors that vary regionally include both the geology and the topography of the inherited landscape and differences in major process controls, such as tidal range, climate and sea-level history. These broad-scale factors, described in the following text, provide a basis for describing differences in the distribution and types of landforms found in different parts of the Puget Lowland.

- **Physiography.** The southern and central Puget Lowland tends to be characterized by a wide, elevated outwash surface (Booth 1994), a more deeply dissected landscape, and a more linear glacial fabric than the northern Puget Lowland, where a less uniform glacial fabric results in broad depressions in the post-glacial landscape that form wide bays rather than narrow troughs. East–west differences also occur in the Puget Lowland, with the west side dropping steeply from the Olympic Mountains toward Hood Canal whereas the east side is marked by a broad rolling terrain drained by large several large river systems

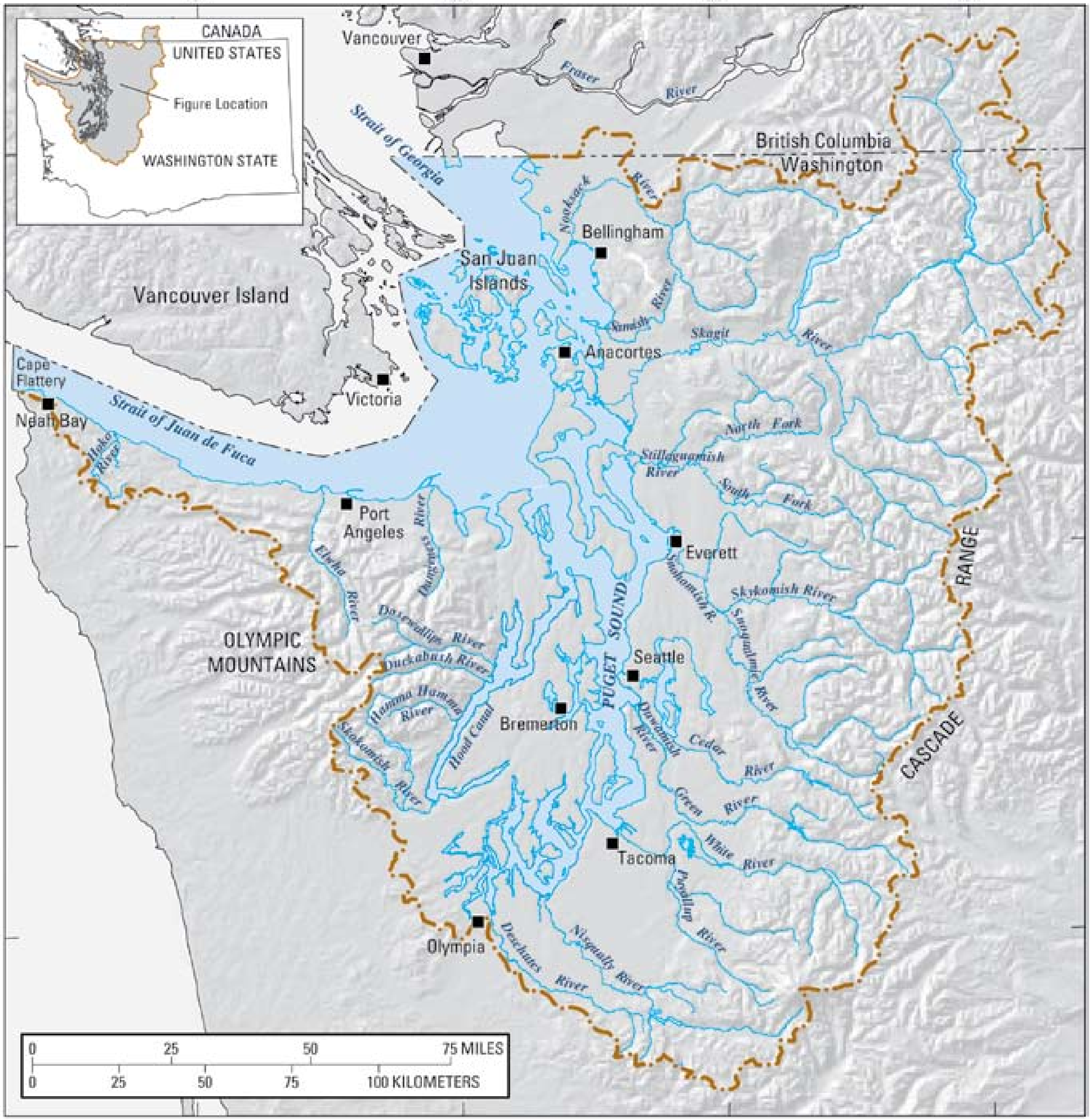


Figure 1. Puget Sound and its contributing watershed

(Figure 1). One consequence of these large-scale topographic differences is that the size and steepness of coastal watersheds differ significantly across the region. The largest drainages are those originating in the Cascades and therefore the largest rivers and deltas are located on the eastern side of the Sound. In contrast, the peninsulas (e.g., Kitsap, Key, Quimper) and islands (e.g., Hartstene, Whidbey, Marrowstone) contain smaller drainages with correspondingly lower discharges and minor sediment yields.

- **Geology.** The distribution of underlying geologic materials is not uniform across the region, reflecting both heterogeneity in bedrock exposures and variability in the glacial deposits. The widespread exposure of bedrock in a band extending through the San Juan Islands and the Chuckanut areas of the northern Lowland leads to significant difference in the distribution of coastal landforms. Regional differences in the composition (grain size, for example) of the more recent glacial and interglacial sediments may also influence shoreline evolution, but these differences are more difficult to characterize, in part due to the high degree of local variability.
- **Sea-level history.** Sea level has influences at two time scales. Early Holocene sea level impacted numerous landscape-forming processes, but in particular, it controlled the development of coastal stream valleys. In southern Puget Sound, where sea levels were considerably lower than today, streams eroded their valleys well below modern sea level, and these valleys have been subsequently drowned by rising sea level to form small, narrow inlets and embayments. In contrast, in the northern Puget Lowland, sea levels were similar to, or even higher, than the modern shoreline. Therefore, drowned stream valleys and their related landforms are rare or absent.

  Modern sea-level change also varies regionally, with the southern part of Puget Sound experiencing more rapid rates of rise than the northern (Shipman 1990, Verdonck 2006). This may contribute to differences in the evolution and the current form of beaches, deltas and estuaries (Beale 1990, Finlayson 2006). In addition, instantaneous changes in relative sea level associated with earthquakes have affected Puget Sound shorelines locally (Bucknam et al. 1992, Sherrod et al. 2004).
- **Tidal range.** Tidal range generally increases with distance from the Pacific Ocean, approximately doubling between the Strait of Juan de Fuca and the bays of the south Sound (Mojfeld 2002, Finlayson 2006). Tide range is a significant factor in controlling the formation and behavior of estuaries, and may influence long-term erosion rates (Rosen 1977).
- **Climate.** Climate affects precipitation, which in turn influences stream and river discharges, the stability of coastal bluffs and, ultimately, the delivery of sediment to the coast. Precipitation varies significantly within the Lowland, ranging from over 50 inches per year in southwestern Puget Sound to less than 24 inches per year in the rain shadow northeast of the Olympic mountains; this variation considerably affects the fluvial (riverine) discharge and possibly the sediment yield of coastal watersheds.
- **Wave exposure.** Wave exposure is related to climate (storminess, wind climate) and to physiography (shoreline orientation, fetch). The irregular shape of the Sound, combined with the relatively small size of the water bodies, results in a fetch-limited environment (Finlayson and Shipman 2003) and significant local variability in wave energy and orientation. This influences beach formation and barrier development, which in turn affects the formation of many coastal wetlands. In addition, broad regional differences occur in wind patterns and in the shape and size of marine basins, which affects wave energy and its impact on erosion and sediment transport rates.

The influence of these factors in shaping landforms in different regions of the Puget Lowland is described in Table 1. The selection of regional divisions is adapted from the oceanographic basins originally proposed by Ebbesmeyer et al. (1984). These divisions reflect bathymetry and circulation patterns (Burns 1985), not shoreline geomorphology, but they capture important regional characteristics of tidal range, wave environment, sea-level history, climate and geology. As a result, we might expect them to drive systematic differences in distribution and character of coastal landforms across the Puget Lowland.

Table 1. Geomorphic characteristics of Puget Sound oceanographic basins. Basin definitions adapted from Ebbesmeyer et al. (1984), Burns (1985), and Redman et al. (2005). Within any particular region, extensive local variability will still occur.

Region	**Description**	**Geomorphic Characteristics**
Northern Straits	Northern Whatcom County shoreline and bays, including Georgia Strait	Glacial sediment Limited sea-level rise Moderate tidal range Considerable wave exposure
San Juan Islands	Islands and the mainland south of Bellingham	Extensive bedrock shoreline Limited sea-level rise Moderate tidal range.
Strait of Juan de Fuca	Cape Flattery east to Rosario Strait and Admiralty Inlet	Bedrock on western Strait, glacial sediments to the east Relatively stable sea level with possible emergence at western end Moderate tidal range Considerable wave exposure.
Whidbey Basin	Deception Pass to Possession Sound, including Skagit Bay and Port Susan	Glacial sediment, with limited bedrock at northern end Moderate sea-level rise Moderate tidal range Strongly influenced by Skagit River
Main Basin	Admiralty Inlet south to Tacoma Narrows	Glacial sediment Moderate sea-level rise Moderate tidal range
Kitsap bays and inlets	Bays and channels on east side of Kitsap Peninsula	Glacial sediment Modest sea-level rise Moderate tidal range Limited wave action
South Sound	Puget Sound south of the Tacoma Narrows	Glacial sediment Considerable sea-level rise High tidal range
Hood Canal	South of Foulweather Bluff	Glacial sediments with some bedrock Modest sea-level rise Moderate tidal range

Geomorphic Typology

Coastal landforms can be divided into several major categories or systems (Downing 1983, Terich 1987, Bird 2000, Woodroffe 2003), reflecting fundamental differences in the availability and sources of sediment and the relative influence of waves, tides, and river energy in distributing it. Based on the factors previously discussed, we propose a typology that recognizes four major geomorphic systems within Puget Sound: rocky coasts, beaches, protected embayments, and large river deltas. Each of these broad shoreline types can be further divided into discrete landforms, typically associated with local patterns of sediment erosion and deposition. Most of Puget Sound's shoreline can be placed within the conceptual framework outlined in Figure 2 and Table 2.

This hierarchical framework consists of four broad geomorphic systems, with each system divided into characteristic landforms and those, in turn, comprised of components. In general, these represent increasingly smaller spatial units, although their scales range greatly.

- Regions (10–100 km). Regions are relatively large areas characterized by broad similarity in controlling factors such as geology, climate, tidal range, or sea level history, but predominantly defined by their oceanographic setting. Each region consists of a different distribution of geomorphic systems or landforms. Regional controls extend beyond sediment and geomorphology and also influence ecosystems in a variety of ways more related to circulation, salinity, and temperature. These regions are conceptually similar to the litho-topo provinces proposed by Montgomery (1999) to describe regional influences on fluvial geomorphology in high-relief watersheds, but also incorporate wave environment and sea level, factors not considered in the riverine environment.
- Geomorphic Systems (1–10 km). These broad categories of coastline reflect the relative influence of wave, tidal, or fluvial processes in controlling the transport and distribution of sediment and the resulting evolution of landforms. These systems include beaches, small embayments, and river deltas. A fourth system, rocky coastlines, is characterized primarily by the limited availability of mobile sediment and the lack of major depositional landforms.

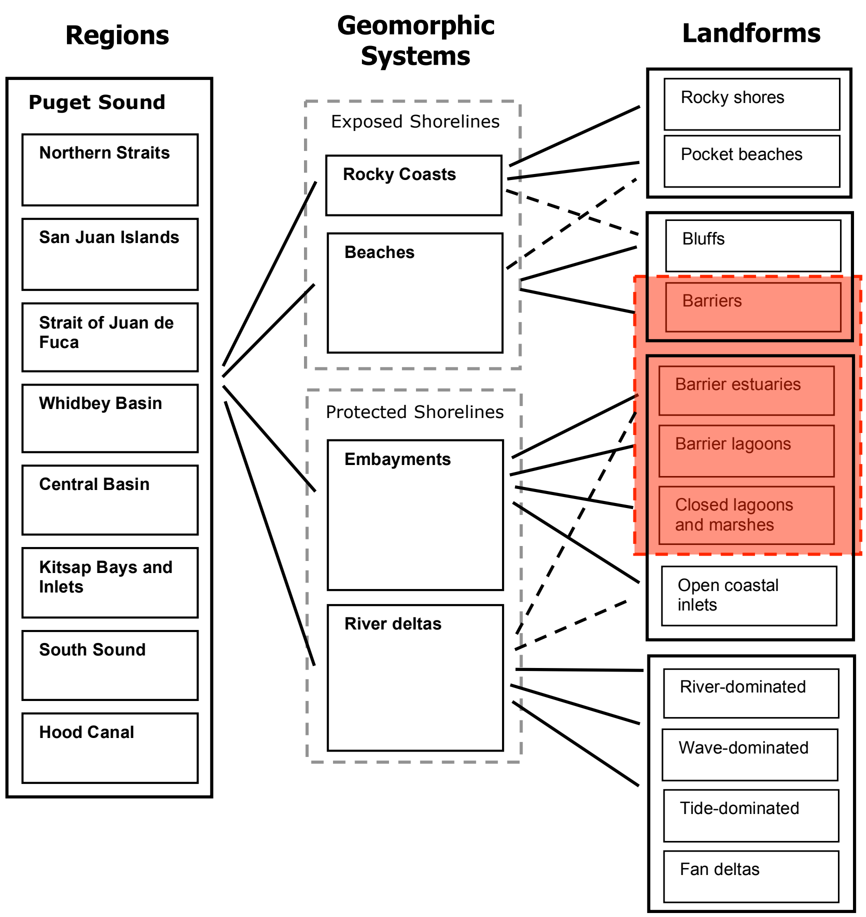


Figure 2. Geomorphic framework of Puget Sound shorelines. In practice, divisions may be indistinct. Dashed lines between geomorphic systems and landforms indicate some landforms may reflect elements of more than one geomorphic system. The dashed box (red) under landforms highlights the common association of barrier beaches with small estuaries and lagoons.

Table 2. Puget Sound geomorphic units, including geomorphic systems, landforms and components. Landforms do not necessarily include all identified components.

Systems	Landforms	Components
Rocky coast Resistant bedrock with limited upland erosion	**Plunging** Rocky shores with minimal erosion/ deposition and no erosional bench or platform	**Cliff/slope**
	Platform Wave-eroded platform/ramp, but no beach	**Cliff** **Ramp/platform**
	Pocket Beaches Isolated beaches contained by rocky headlands	**Cliff** **Backshore** **Beach face** **Low tide terrace**
Beaches Shorelines consisting of loose sediment and influenced by wave action	**Bluffs** Formed by landward retreat of the shoreline	**Bluff face** **Berm** **Beach face** **Low tide terrace**
	Barriers Formed where sediment accumulates seaward of earlier shoreline	**Berm** **Beach face** **Low tide terrace**
Embayments Protected from wave action by small size and sheltered configuration	**Open coastal Inlets** Small inlets protected from wave action by their small size or shape, but not extensively enclosed by a barrier beach	**Stream delta** **Tide flats** **Salt marsh** **Channels**
	Barrier estuaries Tidal inlet largely isolated by a barrier beach and with a considerable input of freshwater from a stream or upland drainage	**Stream delta** **Tide flats** **Salt marsh** **Channels** **Tidal delta**
	Barrier lagoons Tidal inlet largely isolated by a barrier beach and with no significant input of freshwater	**Tide flats** **Salt marsh** **Channels** **Tidal delta**
	Closed lagoons and marshes Back-barrier wetlands with no surface connection to the Sound	**Salt marsh** **Pond or lake**
R**iver deltas** Long-term deposition of fluvial sediment at river mouths	**River-dominated deltas** Extensive alluvial valleys with multiple distributaries and significant upstream tidal influence **Wave-dominated deltas** Deltas heavily influenced by wave action, typically with barrier beaches defining their shoreline **Tide-dominated deltas** Deltas at heads of bays where tidal influence is much more significant than fluvial factors, typically with wedge-shaped estuary **Fan deltas** Steep, often coarse-grained deltas with limited upstream tidal influence	**Alluvial floodplain** **Salt marsh** **Tide flats** **Subtidal flats** **Distributary channels** **Tidal channels**

The delineation of systems reflects the dominant influence of a particular geomorphic process and where multiple processes affect a segment of shoreline, there may be overlap or ambiguity among systems.

- Landforms (100–1000 m). Each geomorphic system consists of different landforms, generally reflecting different long-term patterns of sediment accumulation or deposition. Landforms are often highly complex features, their configuration determined by the local shape of the coastline, the availability of sediment, and local variability in wave, tide, and stream-related processes. Landforms extend across the nearshore, including subtidal, intertidal, and supra-tidal components. Landforms can often be divided into numerous sub-types (for example, barrier beaches may be classified as tombolos, spits, cuspate forelands, and so forth; estuaries may be divided according to their geomorphic setting or the relative influence of marine or freshwater conditions.
- Components (10–100 m). Landforms are comprised of a characteristic suite of components, which describe relatively homogeneous geomorphic features typically characterized by a particular substrate and elevation range. Components correspond to geomorphological units that might be mapped in the field. In linear systems such as beaches, a component may be narrow but extend for many kilometers (low-tide terrace, backshore berm), whereas on expansive, low-gradient landforms such as deltas, components can extend for 100s of meters or kilometers in all directions (delta plain, tide flats). Components often can be related directly to biological elements (salt marsh in a high tide flat, eelgrass on a low-tide terrace, coastal forest on a bluff-face).

A hierarchical typology helps illustrate relationships among landforms created by multiple processes operating over a range of temporal and spatial scales (Montgomery and Buffington 1998, Klijn and Udo de Haes 1994). It provides flexibility in addressing a complex system where different shoreline environments vary in scale and in shape and where some landscape units nest within others. This framework shows the way in which distinctly different landforms may be closely related (barriers and bluffs) while physically similar features may form in rather different geomorphic settings (low-tide terraces and delta tidal flats).

Developing a single framework to address the entire range of coastal landforms also presents limitations. Because different landscape features have very different shapes, sizes, and relationships with one another it is not possible to maintain consistency across the entire hierarchy (Albert 1995). Beaches and rocky shorelines are inherently long, continuous features, whereas deltas and estuaries are usually discrete, isolated features (Figure 3).

In general, geomorphic systems, landforms, and components reflect increasingly smaller landscape units, but the spatial scale of these levels may differ from one geomorphic system to another. A large low-gradient landform such as a river delta may consist of extensive, relatively uniform components thousands of meters across, larger than an entire barrier estuary. This typology does not capture small, but geologically and ecologically significant, features such as stream mouths. The location of stream mouths is a function of the shape and distribution of terrestrial drainage basins and they can occur in any of the major geomorphic systems. Stream mouths might be categorized as components, but unlike many other components that are relatively simple, homogenous units, stream mouths are in themselves highly complex geomorphic features that are difficult to describe in terms of elevation or substrate.

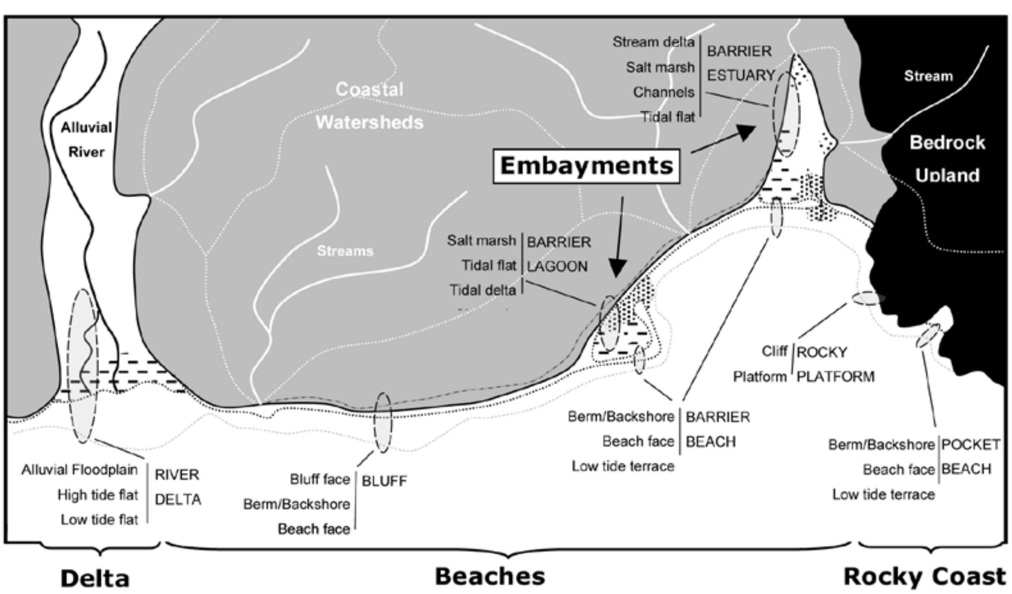


Figure 3. Coastal landforms typical to Puget Sound. The illustration demonstrates the hierarchical relationship among geomorphic systems (delta, beaches, rocky coast, and embayments), landforms (e.g. barrier beach, bluff, rocky platform) and components (e.g., beach face, channels, low tide terrace).

Relationship Between Landform and Process

The relationship among landforms and geomorphic processes is fundamental to geomorphology (Davies 1973, Cowell and Thom 1994, Stallins 2006). The coastal systems and landforms outlined in the preceding section evolve over centuries as a result of long-term geomorphic processes such as delta growth (fluvial sedimentation, channel migration), bluff retreat (mass-wasting, beach erosion), and barrier formation (sediment deposition, barrier migration) (Carter and Woodroffe 1994). These geomorphic processes redistribute sediment on the landscape, eroding some places, transporting sediment, and depositing sediment to form new features at various scales (for example: ripples, bars, marshes, deltas). As these landforms evolve, they further influence the manner in which water (or gravity or wind) interacts with the shoreline, resulting in further landform change (Cowell and Thom 1994). As a spit grows across the mouth of an estuary, it modifies the wave environment and changes sediment transport and tidal flows, which in turn alter the pattern of erosion and deposition both within the estuary and along the spit itself.

Landforms allow us to infer the geomorphic processes influencing a particular shoreline segment or feature. Whereas landforms can be identified, categorized, and with appropriate criteria, mapped, processes are much more difficult to observe or to assign boundaries. Besides being the result of geomorphic processes, landforms also form a physical template that controls the spatial pattern, intensity, and character of more localized geomorphic (Table 3), hydrodynamic, and ecological processes. Often, these local processes are the same ones that, when taken together, result in the long term maintenance and evolution of landforms. Overbank deposition of fine sediment into a delta marsh during a flood has immediate influences on surface elevation, substrate size, and vegetation, yet over time, the cumulative effect of many such events lead to growth of the delta, the shifting of distributaries, and the evolution of tidal channels (Hood 2004).

The association of landforms and processes informs two important aspects of coastal behavior. The first of these is how landforms are related to each other in space. Landforms are not isolated features, but are linked by geomorphic processes usually involving the flow of water and the transport of sediment (Klijn and Udo de Haes 1994). A barrier beach may be related to a long reach of coastal bluffs through longshore sediment transport (Finlayson and Shipman 2003) and its pattern of erosion may be determined by changes to the sediment supply provided by the erosion of those bluffs (Galster and Schwartz 1990). In a delta environment, channel development on a tidal flat may be influenced by changes to upslope tidal hydrology (Hood 2004).

The second aspect of coastal behavior that is informed by geomorphic processes is how landforms change over time. Landforms are not static, but change as sediment is added, removed, or redistributed. These changes are governed by the time scales of the associated geomorphic processes. Processes operating over long time scales (centuries) determine how landforms evolve or shift position over time. Processes acting at medium time scales (years to decades) may influence the response of a landform to a change in sediment supply or climatic shift. They may also be relevant to understanding patterns of historic shoreline change or for projecting the future trajectory of a landform in response to sea level change. Short-term variability in processes, typically driven by discrete events (storms and floods), has obvious influence on human activities, but is also important ecologically as it establishes the frequency of small disturbances that in turn may govern the composition of biological communities (Montgomery 1999).

Table 3. Major geomorphic and hydrologic landscape-forming processes associated with particular landforms. Processes listed under geomorphic systems generally apply to all landforms within that system.

Geomorphic Systems	Nearshore Landforms and Geomorphic Processes
Rocky Wave action Tidal exchange/hydrology Mass-wasting	**Rocky shorelines** Erosion (limited) **Pocket beaches** Sediment transport
Beaches Wave action Tidal exchange/hydrology Longshore sediment transport Cross-shore sediment transport	**Bluffs** Mass-wasting (landslides and erosion) Shoreline retreat Sediment delivery Freshwater input -- groundwater seepage -- stream flows **Barrier beaches** Accretion and erosion Overwash and breaching Barrier migration Aeolian sediment transport
Embayments Tidal exchange/hydrology Tidal channel formation Inlet formation and migration Marsh accretion	**Estuaries** Sedimentation (fluvial) -- stream delta formation Sedimentation (marine) -- tidal delta formation Freshwater inflow Estuarine mixing **Lagoons** Sedimentation (marine)
River Deltas Fluvial sedimentation -- delta growth Freshwater input Tidal exchange/hydrology Channel formation Channel migration/avulsion Marsh accretion	**River-dominated deltas** Overbank deposition Natural levee formation **Wave-dominated deltas** Barrier formation Longshore sediment transport

Description of Puget Sound Landforms

The typology of shoreline landforms outlined in the previous sections provides a convenient framework for the more detailed discussion of Puget Sound's shoreline that follows. In this chapter, which is organized around the four geomorphic systems (Rocky Coasts, Beaches, River Deltas, and Embayments), we describe and illustrate characteristic landforms and their settings, the role of major geomorphic processes, and their constituent components.

Rocky Shores

Rocky shores occur where resistant bedrock occurs at the coastline. Erosion rates are slow or negligible, limiting the formation of shore platforms and reducing the availability of mobile sediment. Rocky shorelines are often irregular in shape, as erosion has not smoothed out promontories and deposition has been insufficient to fill in indentations. The distribution of rocky shores in the Puget Lowland reflects the location of older, more resistant Tertiary geologic units, with the most extensive areas being in the San Juan Islands and the western Strait of Juan de Fuca.

Geomorphic variability along rocky shores is determined largely by antecedent topography, geologic composition, wave exposure, and shoreline orientation (Woodroffe 2002, Bird 2000, Hampton and Griggs 2004, Trenhaile 2002). Bedrock shorelines change slowly over time due to the resistance of the bedrock units to erosion and fact that the limited amount of mobile sediment reduces the dynamic response of the shoreline to wave action and tidal currents. Some rocky shores are influenced by the delivery of sediment from nearby streams and rivers or eroding bluffs, which can lead to the accumulation of gravel or cobble on the shore platform, the formation of isolated pocket beaches, or the juxtaposition of rocky uplands, ledges, and reefs within otherwise fine-grained depositional environments (for example, the scattered rocky knobs found within the Skagit River delta near La Conner).

Numerous classification systems have application to rocky shorelines (Washington Department of Natural Resources 2001, Howes 1994), often based on wave exposure, the morphology of the platform or ramp, or the presence and size of sediment on the platform. For the purposes of this report, however, we divide rocky shorelines into those that lack a significant intertidal platform, those on which erosion has created a platform or ramp, and those where sediment has accumulated to form a pocket beach between rocky headlands.

- **Plunging shorelines**. These are rocky shorelines that have undergone negligible erosion and retreat and therefore lack a distinct nearshore platform (Woodroffe 2002). This may be due to the resistance of the bedrock or to the lack of significant wave action, but in either case, the intertidal gradient reflects the shape of the inherited bedrock surface, which may range from near-vertical to gradual (Figure 4a).
- **Platform and ramp**. Where erosion of a rocky shoreline has occurred, a narrow ramp or platform can form, creating a more gradually sloping intertidal zone (Trenhaile 2002). This surface may be marked by boulders or cobble, but typically lacks significant volumes of sediment (Figure 4b). Where the platform is wide, sand or gravel is abundant, and the orientation of the shoreline to the local wave environment is favorable, beaches can form on the platform and the shoreline begins to resemble a resistant coastal bluff.
- **Pocket beaches and barriers**. Where coarse sediment is available along rocky shores, either due to erosion of the shoreline or delivery by a local stream, it tends to be compartmentalized between rocky headlands and promontories, leading to the formation of isolated pocket beaches (Figure 4c). These pocket beaches may form directly in front of a rocky bank or cliff, or they may form barriers, partially or completely isolating a back-barrier lagoon or wetland. Pocket beaches are generally oriented perpendicular to the major direction of wave approach (swash-aligned). Although sediment may be moved in a longshore direction within pocket beaches, the net transport is generally zero.

Beaches

Beaches occur along shorelines with 1) an abundant supply of sand or gravel and 2) sufficient wave action to rework this material (Bird 2000, Woodroffe 2002). The first condition is commonly met on Puget Sound, where much of the coastal landscape is constructed of readily erodible glacial and fluvial sediments that are transported to the coastline by streams and landslides. The second condition is also met in much of the Sound, except in small, sheltered embayments or where broad intertidal flats (usually associated with larger river deltas) dissipate wave energy before it reaches the shoreline.

The reworking of sediment by wave action, across the range of the tide, divides beaches into a characteristic suite of cross-shore elements, including a broad, gently sloping low-tide terrace, a steeper beach face or foreshore, and a backshore berm (Figure 5). Puget Sound beaches typically exhibit a distinct two-part profile with an abrupt transition between the fine-grained low-tide terrace and the steeper, coarser-grained foreshore (Downing 1983, Finlayson 2006). Despite these similarities, beaches display considerable variability in overall morphology (platform width, beach profile, and backshore character) and in texture (sediment size and distribution) (Finlayson 2006, Dethier 1990). These differences are related to longshore heterogeneity in wave exposure and orientation (Finlayson 2006, Finlayson and Shipman 2003), bluff and platform geology, local sediment availability and longshore drift (Schwartz 1989, Keuler 1988), beach hydrology, and the presence of secondary features such as rocky outcrops, stream mouths, and tidal inlets. Variation may also reflect beach history (erosion or accretion) and biological factors.

The dominant geomorphic process associated with beaches is sediment movement by wave action, which can include erosion, transport, and deposition of material (Downing 1983, Woodroffe 2002) Sediment movement perpendicular to the shoreline is cross-shore transport and gives rise to the characteristic beach profile. Movement parallel to the shoreline is longshore transport and redistributes coastal sediment, often over many kilometers, and is significant in shaping and forming other coastal environments, such as back-barrier estuaries and lagoons. Other geomorphic processes, such as sediment delivery by landslides and streams, sediment transport by tidal currents, erosion and redeposition by seepage of groundwater on the beach face, may be locally significant.

Most beaches on Puget Sound lie within littoral cells (or drift cells) within which there is a net long-term transport of sediment along the shoreline (Figure 7). Beaches with no net transport are often pocket beaches (Figure 4c) and are most commonly associated with rocky coastlines, although they are also common on developed shorelines where originally continuous beaches have been segmented by landfill or coastal structures. Drift cells are semi-independent coastal compartments, each containing it's own sources and sinks of sediment.

Beaches can generally be assigned to two fundamental geomorphic settings. The first is where the coastline has eroded landward, into existing upland terrain, forming a coastal bluff. The second is where beach sediment has accumulated seaward of the original coastline, forming a barrier beach. The spatial pattern of bluffs and barriers along Puget Sound's shoreline is complex (Figures 6 and 7), reflecting the irregular shape of the coastline and accompanying local changes in wave energy and orientation, differences in the abundance and texture of sediment sources, and the redistribution of coastal sediment over time by longshore transport (Finlayson and Shipman 2003).

Figure 4. Rocky coastlines. Photos courtesy of the Washington State Department of Ecology (WDOE).

a. Plunging rocky shoreline on James Island. Rocky shoreline drops directly into deeper water with little break in slope. A very small pocket beach is located in the center of the image.

b. Rocky platform at Davidson Head, San Juan Island. Wide, rocky intertidal bench, with limited mobile sediment.

c. Pair of adjoined pocket beaches on southern Lopez Island Beach sand and gravel is contained between rocky headlands and the beaches are aligned with incident waves.

Figure 5. Typical beach profile at Cama Beach on Camano Island, showing low-tide terrace (with eelgrass meadow), beach face (or foreshore) and a backshore berm (with logs and vegetation). The beach in the foreground is a barrier beach while the background is a coastal bluff (forested).

Coastal bluffs. Coastal bluffs are widespread on Puget Sound, reflecting the extensive reach of marine waters into an elevated landscape consisting of erodible glacial sediments (Shipman 2004). The term coastal bluff is broad and we use it here to describe any shoreline where the upland rises directly landward of the beach. This includes both high, steep cliffs, as well as more gentle slopes that intersect the shoreline with little historic erosion (shoreline cliffs that consist of resistant bedrock and that lack a significant beach are discussed under rocky shorelines) (Figure 8). Coastal bluffs form as an eroding shoreline advances into upland areas, and consequently, they are inherently associated with an erosional platform that underlies the beach and a low-tide terrace.

The most distinctive features of a bluff are its height and its shape. The height of a bluff is a simple function of the elevation of the terrain into which the shoreline has eroded. The shape (morphology) of the bluff depends on its geologic composition, surface and groundwater hydrology, the nature of mass-wasting processes, and the relative rate of erosion at the bluff toe (Keuler 1988). The geologic composition of bluffs also influences two important processes. The resistance of the toe of the bluff to marine (usually wave-induced) erosion is an important control on the rate of shoreline retreat. The overall composition of the bluff dictates the size and abundance of sediment delivered to the beach and the littoral system as erosion proceeds.

Barrier beaches. Barrier beaches are a complex class of depositional coastal landforms, formed over time from the transport and deposition of sand and gravel seaward of the original coastline. They consist of a relatively continuous ridge of sand and gravel rising a small distance above high tide. Barriers often form across embayments in the coastline, at distinct bends in the shoreline, or where sediment transported alongshore converges from two directions. Barrier beaches may be referred to simply as barriers or as depositional or constructional landforms. The terms accretion beach and accretion shoreform are widely used in the Puget Sound region to describe barriers.

Puget Lowland barriers range from a few tens of meters to several kilometers in length. Barriers are most commonly categorized by their shape. The configuration of a barrier beach is a complex function of sediment supply, orientation to waves, original coastline shape, nearshore bathymetry, and the influence of streams and tidal inlets. A remarkable variety of barrier types has been identified and a rich, often inconsistent nomenclature has developed around them. Barrier beaches found on Puget Sound include spits, recurved spits, stream-mouth spits, bay barriers, bay-mouth

Figure 6. Photo illustrating the juxtaposition of bluffs and barriers along a short stretch of beach (this example is from the eastern shore of Discovery Bay). Note steep bluffs in both foreground and background, with a looped barrier in the middle. The barrier encloses a closed lagoon and salt marsh, a type of coastal embayment. Longshore sediment transport (net) is towards the distance.

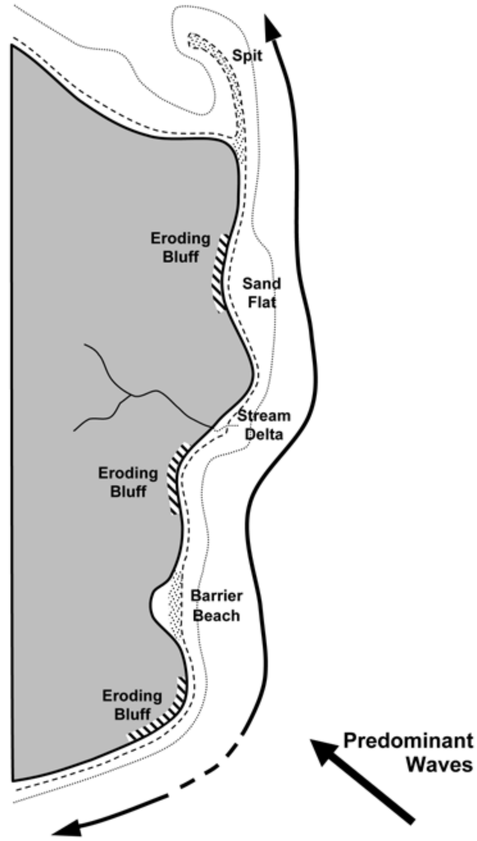


Figure 7. Schematic of a typical littoral cell on Puget Sound, extending from the eroding bluff at the bottom to the spit at the top. The cell consists primarily of eroding coastal bluffs. The bluffs are interrupted by a stream mouth and a short segment of barrier beach. The arrows denote the direction of net longshore transport or drift. The dashed line denotes a reach of shoreline (eroding bluff) where its orientation allows sediment to be moved in either direction, and which is therefore shared by two cells.

barriers, bay-head barriers, looped spits or barriers, tombolos, and cuspate forelands (Figure 9). Barriers may occur alone or in complex combinations, making simple classification difficult.

Barriers are relatively dynamic landforms, subject to changes in form or position due to changes in sea level, fluctuations in sediment supply, or shifts in associated stream mouths or tidal inlets. Barriers often evolve in systematic ways over time in response to accumulation of sediment, rising sea level, or erosion of adjacent shorelines. Changes in barrier configuration typically involve erosion in some places and accretion in others, so the simple characterization of barriers as accretional or depositional landforms can be misleading. These terms reflect the geomorphic origin (genesis) of these features, but may not reflect modern coastal processes. Many barrier shorelines are eroding: cuspate forelands may experience erosion on one limb while the other limb accretes. Spits and other barriers may experience beachface erosion on their seaward side and accretion on the backside of the barrier as the entire feature migrates landward.

Barrier beaches exert major influence over the formation and character of coastal embayments, such as lagoons and estuaries (see following section). Barriers often build across the mouths of coastal embayments, reducing wave energy and modifying tidal exchange within the embayment. Barriers that form at stream mouths influence the shape of small estuaries and control the position of the stream outlet. Where barriers form seaward of the original coastline, they can create protected embayments on their landward sides that may evolve into lagoons and salt marshes. The result is that although barriers and embayments are subject to very different geomorphological and ecological processes, they are tightly associated and each can influence the form and development of the other.

Figure 8. Coastal bluffs. Photos courtesy of the WDOE.

a. High bluff near Warm Springs in Snohomish County.

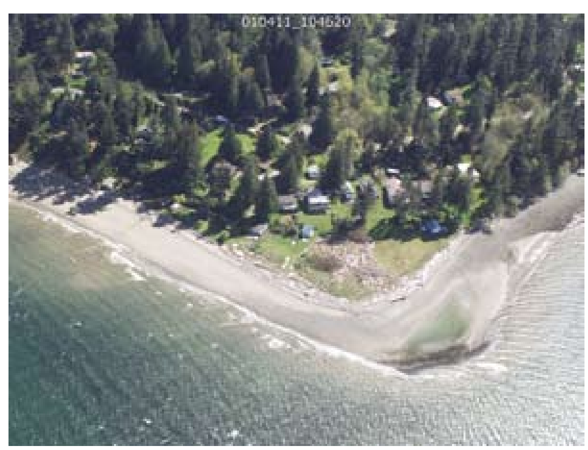
b. Low, forested bluff in southern Puget Sound.

c. High, gravel bluff near base of Dungeness Spit on Strait of Juan de Fuca.

Figure 9. Barrier beaches. Other examples are illustrated in Figure 11 of the following section on embayments. Photos courtesy of the WDOE.

a. Point No Point, Kitsap County. Cuspate foreland located at a sharp bend in the coastline. Back-barrier wetland system has been significantly drained and modified.

b. Spit at Indianola formed across the mouth of Miller Bay. Spit has been heavily developed and a channel has been dredged along its back side.



c. Small barrier on the eastern shore of Holmes Harbor on Whidbey Island. This small cuspate foreland encloses a small marsh and lagoon.

Small Embayments: Estuaries and Lagoons

Puget Sound contains many hundreds of small, protected embayments and coastal inlets, many in the form of stream-mouth estuaries and back-barrier lagoons (Collins et al. 2005). This stems from the complex shape of the coastline, the abundance of small stream valleys that intersect the shoreline, and the large number of barrier beaches, which often form or enclose small lagoons or estuaries. The small size of these features and their limited connection to the main body of the Sound diminishes the importance of wave action and beach processes while increasing the relative influence of tidal and fluvial processes in shaping the landform and maintaining ecological processes.

The terminology of embayments and estuaries is challenging (Nordstrom 1992). Puget Sound contains many scales of embayments. These range from the entirety of Puget Sound, Georgia Basin, and the Strait of Juan de Fuca, to moderate-size embayments such as Hood Canal, Case Inlet, Sequim Bay, and Drayton Harbor, to the much smaller stream-mouth estuaries and tidal lagoons that are the subject of this section. The larger embayments, largely because they are of sufficient size for wave action to be a significant process, contain a wide variety of shoreline types, including stream deltas, beaches, and smaller embayments, and we make no effort here to describe them as distinct geomorphic features.

Pritchard (1967) defined an estuary as "a semi-enclosed coastal body of water which has a free connection with the open sea and within which sea water is measurably diluted with fresh water derived from land drainage." This definition might include all of Puget Sound, but would not necessarily include small coastal lagoons where there is little freshwater input. The term pocket estuary has been used to describe these smaller features within the larger context of Puget Sound. The term has been applied to back-barrier estuaries (Fetherston and Abbe 2001), the term pocket reflecting their shape, small size, and relative isolation from one another. Beamer et al. (2003) use the term pocket estuary to distinguish small estuaries and lagoons from the larger river deltas (in particular, as it relates to the presence or absence of natal runs of salmon).

Small embayments on Puget Sound reflect several different geologic origins (Figure 10) related to the inherited shape of the glacial landscape, the formation of stream valleys during periods of lower sea level, and the role of subsequent barrier formation. These features provide a template on which subsequent geomorphic processes operate, including the deposition of marine and terrestrial sediment within the embayment. Even among embayments with the same geologic origin and the same initial geometry, these secondary geomorphic processes can lead to a wide range of landforms.

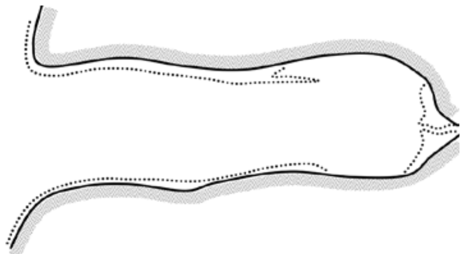
Numerous factors influence the differentiation of coastal embayments and estuaries, including:

- the discharge of the river or streams (if any) flowing into the embayment
- the influx of fluvial sediment from the contributing watershed
- the influx of coastal sediment from shorelines outside the embayment
- the volume of accumulated sediment relative to the size and depth of the embayment
- the extent to which the embayment is isolated from the marine environment by a barrier
- the tidal range and the resulting tidal prism of the embayment
- the configuration and geologic setting of the embayment (e.g barrier type)
- the relative influence of tidal, wave, and fluvial energy on the entrance to the embayment

The large number of factors suggests many different ways of organizing or classifying coastal inlets and embayments. Two that are relatively easy to distinguish on observation and that have significant consequences for barrier behavior and internal processes, are the extent of freshwater influence and the degree of tidal connection with the rest of Puget Sound. These two factors allow the division of small embayments into four general landform types.

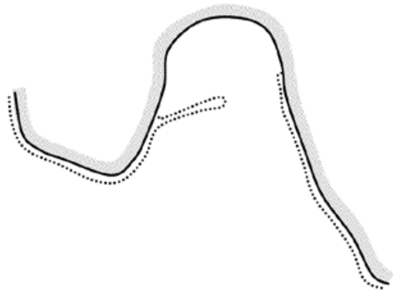
- **Open Coastal Inlets**. These describe inlets or estuaries whose size or configuration precludes significant wave action, but where the inlet itself is not significantly enclosed by a barrier or other restriction. These include drowned stream valleys (Figure 10c) such as Port Madison or Wollochet Bay and the heads of many larger inlets, such as Discovery Bay or Eld Inlet. The term would also apply to the protected areas in the lee of spits, but where the spit does not restrict circulation to a singular tidal inlet, as in a barrier estuary.
- **Barrier Estuaries.** Many small estuaries in Puget Sound are partially isolated from open marine water by a barrier, with tidal exchange occurring through a narrow entrance channel. The estuary itself may include open water, a stream channel, tidal channels, and salt marsh Examples include Ollala Creek, Stavis Bay (Figure 11a), and Chimacum Creek.
- **Barrier Lagoons.** These are tidal embayments, similar in many ways to barrier estuaries, but that lack a significant freshwater source (a perennial stream, for example). They are typically barrier-built embayments (Figure 10d) – often associated with cuspate forelands, double tombolos, or recurved spits – since these landforms are only coincidentally associated with

Figure 10. Geologic settings of coastal embayments.



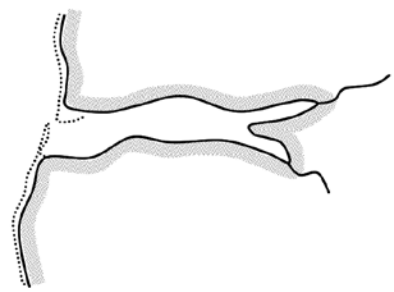
a. Glacial trough or fjord. Relatively elongate (straight-sided, deep). Beaches may dominate shorelines except towards the heads of bays where wave action becomes limited and fluvial and tidal deposition of fine grained sediment dominates.

Examples: south Sound inlets, Discovery Bay, Sequim Bay, Lynch Cove



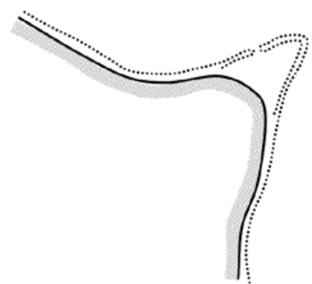
b. Glacial depression embayment. Broad valley in glacial landscape that has subsequently been flooded by rising sea level. Gradually sloped sides and limited depth typically lead to formation of shallow bays. Barrier beaches commonly form, creating protected lagoons and salt marshes. May be estuaries or lagoons, depending on discharge of associated watershed.

Examples: Elger Bay, Oak Bay, Useless Bay, Oak Harbor



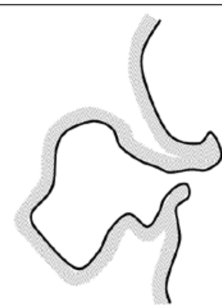
c. Drowned stream valley. Steep-sided valley formed by fluvial erosion and subsequently drowned by rising Holocene sea level. Because these form within valleys, they are typically fed by streams and are distinctly estuarine. Barriers commonly form at or across the mouths of these embayments. An embayment may become filled with fluvial or coastal sediment over time, forming an alluvial valley.

Examples: Ollala Creek, Gull Harbor, Port Madison, Chimacum Creek , Dewato Bay



d. Barrier-built embayment (or coastal salient). Embayment formed by growth of a barrier beach seaward of the original coastline. These do not necessarily coincide with terrestrial valleys or drainages and therefore usually have a limited input of fresh water or fluvial sediment. Result is a tidal lagoon or closed barrier wetland. Example shows a cuspate foreland or recurved spit with a tidal inlet.

Examples: Kala Point, Foulweather Bluff Salt Marsh, Spencer Spit, Brace Point



e. Rocky embayment. Partially enclosed embayment formed as result of configuration of a rocky or otherwise resistant shoreline.

Examples: Mats Mats Bay, portions of Garrison and Westcott Bays streams or significant upland catchment areas. They may contain a lagoon or a salt marsh, depending on the extent of sedimentation within the feature. Kala Point, Point Monroe (Figure 11b), and historic conditions at Seattle's West Point are all examples of barrier lagoons.

- **Closed marshes and lagoons.** These are back-barrier wetlands that typically maintain a subsurface hydrologic linkage with marine waters, but that lack a persistent tidal channel. They include isolated lagoons, salt marshes and pannes, and ponds. Some may have originated as tidally-accessible lagoons and salt marshes, but due to sedimentation or diminished tidal prism, a tidal inlet could no longer be maintained (Figure 13). Wetlands in these systems may be influenced by marine waters and exhibit tidal fluctuations and saline conditions. Closed lagoons may be subject to periodic saltwater inundation during storms or periodic breaching of the barrier, but do not maintain a persistent connection. Examples include Foulweather Bluff Preserve (Figure 11c), Beckett Point, and Perego's Lagoon.

Coastal inlets and embayments are comprised of a combination of more geomorphic components (Figure 12). Elements common to most embayments include both high tidal flats (typically occupied by salt marsh) and intertidal flats (often unvegetated). Some embayments may have a central basin or lagoon that does not completely drain at low tide, either because it is subtidal or because it is lies below the elevation of the inlet channel. Small fluvial deltas are common where streams enter an estuarine embayment. Embayments with restricted tidal inlets (usually formed by a barrier beach) have an entrance channel and may have both ebb- and flood-tidal deltas. The shoreline itself may consist of salt marsh or a low-energy beach (by definition, these embayments lack the active beaches characteristic of shorelines with more substantial wave action). The margins of the embayment may be marked by either gradual upland slopes or by steeper banks and bluffs.

Many of these barrier-associated estuaries and lagoons vary only by degree from one another, in part because in some cases they represent different stages of the evolution of the landform as the barrier grows or migrates, as sea level rises, and as the tidal circulation changes (Figure 13).

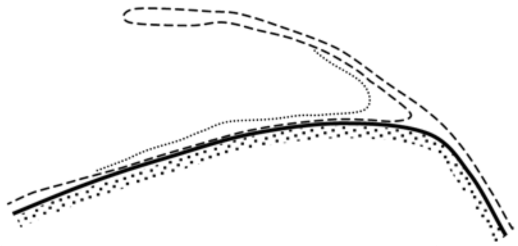
Figure 11. Barrier estuaries and lagoons. Photos courtesy of the WDOE.

a. Barrier estuary at the mouth of Stavis Creek on Hood Canal. A small delta has formed at the bottom of the photo where the stream enters the embayment. Spits have formed across the mouth of the bay.

b. Recurved spit at Point Monroe, on the north end of Bainbridge Island. Barrier forms a tidal lagoon.

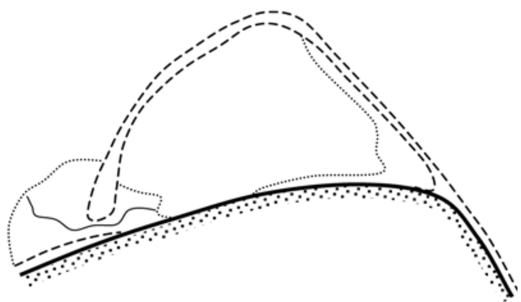
c. Closed barrier lagoon and wetland south of Foulweather Bluff in Kitsap County.

Figure 12. Evolution of a barrier lagoon complex over time.



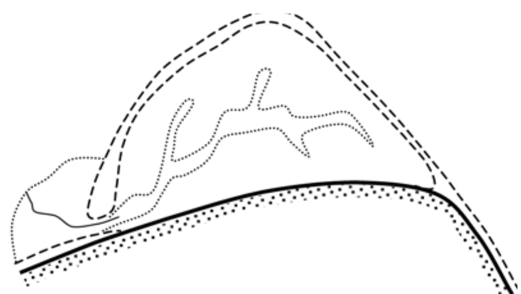
Simple spit creating protected embayment, in this case an open coastal inlet. Fringing marsh forms where the shoreline is protected from wave action and there is sufficient sediment deposition to build into upper intertidal zone.

Example: Ala Spit, Ediz Hook



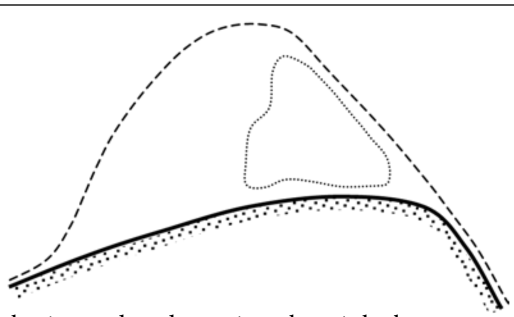
Continued growth of spit results in formation of a barrier lagoon, possibly with tidal deltas at entrance.

Examples: Point Monroe, Dungeness Spit



Increased sedimentation within the barrier lagoon, primarily from marine sediment, results in higher elevations and more salt marsh. Tidal channels develop within marsh.

Examples: Foulweather Bluff Spit, Point Heyer, Stretch Point



Tidal prism reduced to point where inlet becomes unstable and closes, leaving a closed lagoon and marsh.

Examples: Lowell Point, Brace Point, Point Roberts

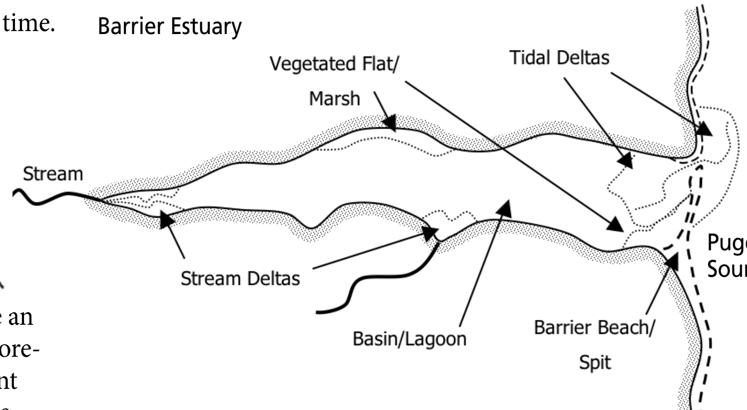


Figure 13. Example of a barrier estuary developed in a drowned stream valley, as seen in Figure 11a. Common components include stream deltas, unvegetated fine-grained flats in the central basin, flood and ebb-tidal deltas, a tidal entrance channel, a barrier and the bluffs or banks that border the feature. Common sources of variability among this class of features include the extent and configuration of the barrier enclosure, the input of freshwater and sediment from the upland watershed, the degree to which the estuary has become filled with sediment and the relative extent of the various components.

Deltas

Deltas form at the mouths of streams and rivers where flows decrease and the capacity of the river to carry sediment diminishes. Numerous factors influence the shape and size of stream and river deltas, but two primary controls are 1) the discharge and sediment load of the stream and 2) the configuration of coastline in the vicinity of the river mouth. The first affects the amount and type of sediment available to build the delta, whereas the second determines how that sediment will be distributed between the river mouth, adjacent shorelines, and deeper waters offshore. Other factors include the gradient of the lower river channel, the character of mixing within the river mouth and its estuary, and the relative influence of wave and tidal action in redistributing deltaic sediments (Wright 1985, Woodroffe 2002, Bird 2000).

The Puget Lowland can generally be divided into two broad classes of watersheds, those that drain the Cascade and Olympic Mountains and those that lie completely within the Lowland itself (Figure 1). The former give rise to about a dozen relatively large rivers, each of which has built a significant delta at its mouth. The seven large rivers[2] that drain the Cascades, along with the Skokomish River that drains the southwestern side of the Olympics, all reach the coastline in large low-gradient alluvial valleys and have formed complex estuarine deltas in which marine influences (salin-

2. From north to south, the Nooksak, Skagit, Stilliguamish, Snohomish, Duwamish, Puyallup, and Nisqually rivers. The Cedar River originally drained through the Duwamish/Green River system, but was rerouted through Lake Washington and now drains to the Sound from Salmon Bay in north Seattle.

ity and tides) extend significant distances upstream (Figure 14a). In addition, several smaller rivers drain into Hood Canal from steep valleys on the eastern side of the Olympic Mountains, forming distinctive fan-shaped deltas (Figure 14c). These deltas are highly confined between their steep upstream drainages and the deep waters of Hood Canal. Finally, the Dungeness and Elwha Rivers, which drain into the Strait of Juan de Fuca from the north side of the Olympics, are exposed to significant wave action and barrier beaches have formed at their mouths (Figure 14b).

In contrast to these large rivers, much of the Puget Lowland is drained by relatively small streams that flow from watersheds located within a few kilometers of the Sound. Some of these streams enter Puget Sound within protected estuarine embayments, while others emerge directly onto exposed shorelines and beaches. Sediment yields are typically small and these deltas are often dominated by tidal or wave processes and heavily influenced by the influx of coastal and marine sediments, making them difficult to identify as distinct deltaic landforms. In the framework developed in this report, we consider these smaller stream mouth deltas as components within other geomorphic systems such as beaches or estuaries.

Deltas typically consist of several major geomorphic components: a delta front, a delta plain, distributary channels, and a variety of tidal channels. The delta front normally refers to where the flat-lying portion of the delta drops steeply into deeper water offshore. The largest component of most deltas is the relatively horizontal delta plain, which includes an alluvial upper portion, an intertidal portion that may include both higher (salt marsh) and lower (tidal flats), and a subtidal portion. Larger deltas may have multiple distributary channels and a variety of tidal channels within the upper portions of the delta plain (Simenstad 1983).

Deltas often can be divided into active and inactive regions. The active delta describes areas associated with the current river mouth that are strongly influenced by modern fluvial processes, including freshwater discharge and rapid sediment deposition. In contrast, inactive portions of the delta are those associated with older, abandoned river channels, where modern fluvial processes are much less significant. In these environments, the delta may remain relatively stable, or may actually erode in response to wave action, subsidence, and the lack of sediment input. This can lead to erosion of salt marsh, changes to tidal channel morphology (Grossman 2005), and over many decades, can lead to significant differences in both geomorphic and ecological processes between different portions of large deltas.

Figure 14. Large river deltas. Photos courtesy of the WDOE.

a. Large river-dominated delta at mouth of Stilliguamish River. Upper delta plain and alluvial floodplain has been diked and drained. Photo shows channels across intertidal delta plain.

b. Elwha River along Strait of Juan de Fuca. Delta is strongly wave-dominated, with barrier spits forming across the river mouth.

c. Fan-shaped delta at the mouth of Dosewallips River on Hood Canal. Delta is steeper and generally coarser-grained than river-dominated delta above.

Applications

Many efforts are currently underway or are planned on Puget Sound to characterize shoreline conditions and to develop strategies for protecting or restoring coastal environments. Within each of the geomorphic settings described in this report, the natural resources and ecological functions are different, in part because the underlying geomorphic processes are different. In addition, within each of these different environments, land use patterns, development issues, natural hazards, and environmental stressors are often different as well. Regional efforts to address shoreline issues will be more effective if the tools used are appropriately tuned to the specific geomorphic environments.

The geomorphic typology developed in this report might be used in a variety of applications, including:

- Developing a common terminology to describe and compare Puget Sound shorelines
- Characterizing shoreline environmental conditions
- Evaluating historic shoreline change
- Identifying and prioritizing restoration actions
- Creating spatially-explicit conceptual models
- Selecting reference sites for comparisons and long-term monitoring
- Organizing research programs
- Assessing impacts of regional environmental stressors, such as population growth, species invasions, or sea level rise

In the remainder of the section, we elaborate on two of these: the characterization of shoreline environmental conditions and the evaluation of historic shoreline change.

Shoreline Characterization

Numerous groups are conducting shoreline inventories and characterizations on Puget Sound, typically in support of salmon recovery planning or the development of updated Shoreline Master Programs. These efforts require assessment of nearshore habitats and ecological functions in a spatially explicit manner – evaluating individual segments of shoreline and identifying specific problem areas and restoration opportunities. Most nearshore assessments have used the ShoreZone Inventory (Washington Department of Natural Resources 2001) which provides limited information about geomorphic process, except as it might be reflected in substrate or very local indicators of erosion or accretion. Segments are evaluated independently of others in the vicinity, precluding consideration of the influence of off-site disruptions such as reductions in sediment supply. In reviewing several nearshore assessments, Thom and Sargeant (2003) pointed out the need for a scaling system that reflects natural processes.

Bainbridge Island employed a geomorphic classification in its shoreline assessment (Best 2003, Williams et al. 2004), categorizing each segment of shoreline by one of a limited number of geomorphic descriptors. Although the basic units of analysis were based on DNR's ShoreZone Inventory, the model employed to evaluate conditions within individual shoreline segments was specific to their respective geomorphologic character. This improves the quality of the model itself, as it can be more responsive to processes specific to that shoreline type, and it makes comparisons of shoreline within distinct types more reliable.

The typology provides a basis for defining a small number of geomorphologically distinct landforms and for identifying the appropriate processes that need to be considered in evaluating specific reaches of shoreline. In addition, the hierarchical nature of the typology informs assessment of the relationships between different types of shoreline – for example, between coastal bluffs and downdrift barrier beaches, or between beaches and barrier estuaries.

Evaluation of Historic Shoreline Changes

A geomorphic framework provides a starting point for characterizing and analyzing historical shoreline changes. Geomorphic processes determine both the character and the rate of change expected for a given shoreline type, and these processes differ systematically among different landforms. This informs interpretations of changes that have occurred over time, including both natural changes and those that result from human activities. This typology allows analysis to be focused on those types of change and anthropogenic modifications most relevant in a particular environment. Questions asked, and methods employed, to investigate changes within a large estuarine delta should be different than those appropriate for evaluating change along a beach or a rocky coastline.

Different geomorphic processes operate over characteristic time scales (Wolman and Miller 1960). The processes associated with a specific type of shoreline therefore affect:

- the rate and magnitude of natural shoreline change
- the rate of response to a disturbance (natural or human)
- the time it takes for a disturbance to propagate or affect a nearby location
- the frequency and magnitude of short-term changes, which in turn determine the natural variability of a system and its disturbance regime
- the long-term trajectory of shoreline change, with or without the influence of anthropogenic modifications.

Table 4 identifies the short-term and long-term variability associated with different shoreline types as well as those anthropogenic modifications that might be identified within each shore type. While direct modifications to the shoreline are often observable, indirect changes to the shoreline that result from the disruption of geomorphic processes, such as narrowing of a beach due to the diminishment of sediment supplies (Macdonald et al. 1994) or the filling of tidal channels as the tidal prism is reduced by diking (Hood 2004), may be difficult to distinguish from natural variability.

Table 4. Characteristic shoreline change among selected shore types. Short-term variability describes changes on the scale of days to months. Long-term variability addresses changes that occur over years or decades. In general, changes and modifications attributed to system level (beach, embayment, delta, rocky) are also applicable to the landforms they encompass.

Shoreline Type	Short-term variation (days to months)	Long-term variation (years to centuries)	Human modifications
ROCKY COASTS	Mass-wasting (infrequent)	Erosion and retreat (slow)	Intertidal fill Armoring of pocket beaches
BEACHES	Profile variability Substrate variability	Shoreline retreat Shoreline accretion	Armoring Intertidal fills Groins and jetties Overwater structures
Bluff	Mass-wasting events	Bluff retreat	Armoring/slope stabilization Fill at base of bluff Upland hydrologic changes Stream mouth modification
Barrier	Overwash/breaching	Landward migration Seaward accretion Configuration change	Armoring/dikes Backshore fill Intertidal fill Inlet stabilization
EMBAYMENTS	Flood events Seasonal sedimentation	Sedimentation/shoaling Diminished tidal prism Channel development March accretion	Watershed modifications: hydrology, sediment loading Fill Bank armoring
Barrier estuaries	Sedimentation at inlet	Flood-tidal delta growth Stream delta growth Shift in tidal inlet position Change in barrier configuration Sediment/marsh accretion	Inlet modifications: relocation, stabilization, closure, dredging Wetland and intertidal fill Bank armoring Barrier modification
LARGE DELTAS	Flood deposition Channel avulsions	Channel switching Delta advance/growth Subsidence Sediment accretion Tidal channel development Shift in relative proportions of components	Channelization Diking Draining Cultivation Watershed changes Dredging

Summary

This report describes a hierarchical classification of Puget Sound coastal landforms. It emphasizes geomorphic processes at a landscape scale and over time frames relevant to shoreline managers and restoration planners. These processes influence how landforms change over time, including how the shoreline responds to natural changes and to human actions. Geomorphic processes also determine relationships among landforms related to the movement of sediment from one environment to another (e.g., in a large river delta or along an exposed beach).

Puget Sound's shoreline can be divided into four major geomorphic systems – rocky coasts, beaches, protected estuaries and lagoons (embayments) and large river deltas. These systems can be further divided into a suite of distinct landforms that generally represent different mechanisms and patterns of erosion and deposition of sediment. The nature and distribution of these landforms reflects large regional variation in controlling factors such as climate, sea-level history, tidal range, geology and the antecedent glacial topography of the Puget Lowland.

Landforms are the underlying template on which smaller-scale geomorphic and ecological processes operate. Although landforms imply a distinct arrangement of elevation and substrate, they also define the physical processes that create and maintain habitats, determine hydrologic interactions and establish disturbance regimes that together influence ecosystem characteristics.

Management objectives for shorelines depend on the geomorphic setting (Carter 1988, Nordstrom 1989). Environmental problems, shoreline modifications and development patterns are different in different places. Questions and analytical approaches appropriate for one environment may be inappropriate for another. A landform-based typology provides a tool to identify which processes are important within a large, complex landscape. This should aid efforts to manage shorelines, develop restoration strategies and organize research programs. Specific examples might include interpreting historical environmental changes, targeting specific shoreline policies or restoration measures to specific places, or selecting reference sites for a long-term monitoring program. Assessments of the vulnerability of the coastline to accelerated sea-level rise will be improved by recognizing that different geomorphic environments will respond very differently to higher water levels (Pethick and Crooks 2000).

In this report, a fairly simple typology of coastal landforms relevant to Puget Sound has been described. Not all shorelines will fit neatly into these categories and practitioners on the Sound may need to modify the framework to better resolve factors important to their particular locations and projects. Within each major geomorphic system, much more work could and should be done investigating and describing the sources of geomorphic variability. Finally, mapping the shoreline according to this classification should be approached cautiously. The shoreline types described in this classification are largely defined by geomorphic processes, which do not lend themselves to precise delineation, whereas mapping is typically based on classification of observable characteristics of the landscape such as substrate or elevation.

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Appendix A. Glossary

The following sources were consulted in compiling this glossary. Definitions were adapted where appropriate to conform to typical usage on Puget Sound and in this report.

- American Geological Institute. 1976. Dictionary of Geological Terms. Anchor Press, Garden City, New York.
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Accretion. The gradual addition of sediment to a beach or to marsh surface as a result of deposition by flowing water or air, resulting in the increase in elevation of a marsh surface, the seaward building of the coastline or an increase in the elevation of a beach profile (the opposite of erosion).

Backshore. The upper zone of a beach beyond the reach of normal waves and tides, landward of the beach face. Subject to periodic flooding by storms and extreme tides, often the site of dunes and back-barrier wetlands.

Barrier beach. A linear ridge of sand or gravel extending above high tide, built by wave action and sediment deposition seaward of the original coastline. Includes variety of depositional coastal landforms such as spits, tombolos, cuspate forelands, and barrier islands.

Beach. The gently-sloping zone of unconsolidated sediment along the shoreline that is moved by waves, wind and tidal currents.

Beach face. The portion of the beach exposed to normal wave and tide action, generally extending from ordinary low tide to the berm crest. Also referred to as the *foreshore*.

Bedrock. A general term for older, resistant geologic materials that underlie soil or other unconsolidated alluvial, glacial and beach sediments.

Berm. A nearly horizontal portion of the beach or backshore formed by deposition of sand or gravel by wave action. Typically occurs above high water. Multiple berms may be present.

Bluff. A steep bank or slope rising from the shoreline, generally formed by erosion of poorly consolidated material such as glacial or fluvial sediments

Delta. A deposit of sediment formed at a stream or river mouth, or other locations where slowing of flow results in sediment deposition. Deltas can occur at many scales and, in this report, large river deltas – complex systems in themselves – are distinguished from smaller stream and tidal deltas commonly found in a wide variety of geomorphic settings.

Embayment. A broad term for an inlet or indentation in the coastline. In this report, the definition of embayments is restricted to features partly isolated from the rest of Puget Sound by their configuration and sufficiently small to limit wave action and beach processes. Also included are wetlands or other back-barrier water bodies isolated from direct tidal influence (surface exchange). Embayments include barrier estuaries and lagoons and may include some stream mouths and the heads of small bays.

Erosion. The wearing away of land by the action of natural forces. On a beach, the carrying away of beach material by wave action, tidal currents, littoral currents or by deflation (opposite of accretion).

Estuary. Pritchard (1967) defined an estuary as "a semi-enclosed coastal body of water which has a free connection with the open sea and within which sea water is measurably diluted with fresh water derived from land drainage." Sometimes defined more broadly to include other coastal inlets that connect coastal lagoons and swamps to the sea. See also *Pocket Estuary*.

Flat. Broad, nearly horizontal deposits of sand or mud in coastal environments. Tidal flats refer to flats within the range of tides. Flats may be found in beach environments (low-tide terrace), in large embayments, within estuaries and lagoons and on river deltas.

Foreshore. The beach between mean normal high and low tides, generally synonymous with *beach face*.

Holocene. The later, more recent epoch of the Quaternary Period. It follows the Pleistocene and is generally considered to describe the 10-15,000 years since the end of the last major glaciation, up to and including the present.

Lagoon. A shallow body of water, such as a pond or a lake, isolated from Puget Sound by a *barrier beach* or other narrow body of land. Lagoons may or may not have a permanent tidal connection to the sea.

Longshore transport. Transport of sediment parallel to the shoreline by waves and currents.

Low-tide terrace. The broad flat portion of the beach profile located near or below ordinary low tides.

Mass-wasting. Transport of soil and rock downslope by gravity alone, in the absence of a transporting medium such as water. Examples include landslides, rock falls and soil creep.

Morphology. The shape or form of the land surface or of the seabed and the study of its change over time.

Nearshore. On Puget Sound, this term is often used to define a broad zone extending landward from the top of coastal bluffs and the head of tide of coastal streams seaward to the offshore limit of the photic zone. More traditionally, and more narrowly, defined as an indefinite zone extending seaward from the shoreline well beyond the breaker zone, defining the area in which water and sedimentary material are moved by wave action.

Overwash. The flow of marine waters and associated sediment over the top of a barrier beach, usually when storms coincide with high tides. Leads to deposition of sediment in backshore areas and the gradual shifting of a barrier beach landward.

Platform. The relatively flat-lying bench or shelf that extends offshore of most shorelines, particularly those with beaches, on Puget Sound.

Pocket estuary. Term used in the Puget Sound region to describe small estuaries and lagoons, partially isolated by their configuration from the main body of Puget Sound.

Puget Lowland. The broad low-lying region between, but not including, the Olympic and Cascade mountains. Generally coincides with the maximum extent of Holocene glaciation.

Puget Sound. Defined here to include all inland marine waters of Washington State inside of the entrance to the Strait of Juan de Fuca and including Georgia Strait south of the Canadian border.

Tidal delta. Accumulations of sand and gravel deposited inside or outside of tidal inlets when tidal currents slow. Flood tide and ebb tidal deltas can be distinguished and are commonly associated with barrier lagoons and estuaries.

Typology. Systematic classification or study of types. Used in this report to describe a descriptive classification of shoreline landforms that emphasizes synthesis and explanation and that provides a conceptual model of landform variability on Puget Sound.

Appendix B. Data Sources for Evaluating and Mapping Puget Sound Coastal Landforms

This report emphasizes a broad, conceptual framework for incorporating geomorphic landforms into regional shoreline planning and restoration efforts. Specific approaches to mapping these landforms should depend on the purposes of the analysis, but in general, will rely on many of the following sources and types of geographic data.

Topography

The standard source of topography is USGS topographic mapping, now generally available as digital elevation models (DEMs). The resolution of these data are sufficient to characterize gross properties of coastal bluffs and to delineate landforms, but particularly along the shoreline, the topographic resolution is limiting. Bluff morphology, particularly when heavily vegetated, is often obscure or incorrect in existing data. Topography of low-lying landforms, such as deltas or barrier beaches, is of very limited usefulness.

Existing topographic data, particularly in digital form, are useful for delineating and characterizing small watersheds, many of which drain to Puget Sound. Data can be input into models to estimate discharge based on topography, precipitation and other watershed characteristics.

In recent years, much of the Puget Lowland high-resolution topographic data have been obtained with airborne laser ranging techniques (LIDAR). These data provides resolution of low-lying landforms that may greatly assist landform characterization and mapping. *(Available through the Puget Sound Lidar Consortium, http://pugetsoundlidar.ess.washington.edu/).*

Bathymetry

Most bathymetric data are in the form of navigational charts or site-specific surveys. Rarely are these data collected in shallow water or intertidal areas characteristic of nearshore areas. Recently, the use of bathymetric LIDAR has been piloted in a few locations on Puget Sound, and the results suggest that it may be an excellent means of characterizing the physiography of beaches, delta flats and channels, and small estuaries. At the moment, the methodology is highly experimental and the availability of data is low.

Geologic Mapping

Geologic maps are available for the entire Puget Lowland, although some are outdated or are only available at relatively low resolution. The Coastal Zone Atlas (1978 – 1980) maps geology at the shoreline at 1:24,000, but the field mapping on which it is based dates from the early or mid-1970s. Statewide coverage exists at a scale of 1:100,000, although newer 1:24,000 mapping is increasingly available. DNR provides regional geology in digital form.

Geologic data can be useful for discriminating rocky shorelines from bluffs composed of glacial sediment, for better delineating alluvial valleys and stream mouths, for evaluating sediment availability, and for identifying the location of large landslides. It can also be helpful for delineating and discriminating low-lying environments that may be obscured by subsequent modification, such as small estuaries, barrier beaches or the lowermost ends of small stream valleys.

Aerial Photography

Air photos are helpful in delineating landforms and characterizing land cover and may be the best tool for determining boundaries between adjacent landforms. Oblique photos provide a qualitative tool for identifying and mapping coastal landforms. Oblique images of the shoreline for several time periods are readily available at the Washington Department of Ecology's Web site *(http://www.ecy.wa.gov/programs/sea/sma/atlas_home.html).*

Historical aerial photography can be used to characterize and define shoreline change in areas where such changes are relatively large (e.g., changes within barrier systems, stream mouths and deltas).

Shore Zone Inventory

The Shore Zone database (Berry et al. 2001) has become the standard source of comprehensive marine shoreline data for Washington State. The basic mapping units are Shore Zone segments or units – linear stretches of relatively homogenous shoreline. For each segment, data describing cross-shore components are included. Shore Zone segments have become the basic analysis unit for many nearshore assessments. The original aerial videography is also available from DNR.

The emphasis is on substrate and biology, rather than broader aspects of landform, but each segment (each cross-shore unit, actually) includes a designation of FORM, which closely resembles the shoreline types we have described, at least in some environments. Other useful fields include the BC Class and the Dethier classification.

Shore Zone includes several proxies for wave energy (including fetch and orientation), indicates the presence of stream mouths and attempts (not always successfully) to attribute some basic sedimentary process information to many segments (source of sediment, direction of transport).

The basis for boundaries between Shore Zone segments is sometimes not clear, particularly in estuarine environments. Distinctions between barrier beaches and the back-barrier systems they protect appear inconsistent. Segments may contain significant portions of both barrier beach and marsh shoreline within back-barrier lagoons, despite significant differences between substrate or energy characteristics.

Coastal Zone Atlas

The Atlas contains several potentially useful coverages, all mapped at 1:24,000, and it covers most of the Puget Sound shoreline. The Atlas is out of print and much of the data has yet to be digitized.

- Bluff erosion. This mapping likely was based primarily on qualitative, visual observations of bluffs. It may more heavily weight slopes that had slid recently than slopes that had not. In general, these data indicate whether bluffs are significant sources of sediment to the beach.
- Slope stability. Slope stability mapping in the Atlas remains a standard reference for coastal jurisdictions, although much of the data are now out of date. This measure provides useful information regarding the stability of coastal slopes that may help characterize bluff morphology and potential sediment sources.
- Flooding. This may be helpful for identifying and delineating barrier beaches and in distinguishing them from other low-lying landforms.
- Coastal Processes. Maps illustrating coastal drift direction and beach characteristics may be useful, but the criteria for mapping are not well documented and the methodology for determining drift direction has proven problematic.
- Geology. Discussed previously.

Longshore Transport

Longshore transport is useful for identifying the direction of net longshore drift. It helps identify boundaries of individual littoral cells. Zones of divergence are generally subject to more rapid erosion and are significant sediment sources within littoral cells. The termini of cells generally coincide with barrier beaches.

Net shore-drift was mapped by Schwartz et al. (1989) for the Washington State Department of Ecology (WDOE) and compiled reports are available from Ecology. Mapping is based on relatively qualitative geomorphological indicators. Maps have been digitized and drift cell data are available as GIS coverage through WDOE and on WDOE's online Digital Coastal Atlas *(http://www.ecy.wa.gov/programs/sea/sma/atlas_home.html)*..

As previously mentioned, the Coastal Zone Atlas also contains maps of drift, but serious concerns exist about the reliability of this data.

Standard GIS Coverages

Numerous standard GIS coverages may be useful in defining coastal characteristics. Stream coverage can be used to identify and characterize stream mouths and freshwater inputs to shoreline. National Wetland Inventory mapping may indicate not only coastal wetlands, but freshwater wetlands located immediately landward of stream mouths.

Historical Mapping

Historical charts, such as NOAA topographic surveys (T-Sheets), can depict the shoreline prior to significant human alteration and have been used in a variety of ways to describe historical shoreline change (Bortleson 1980, Washington Conservation Commission 2000, Collins et al. 2006, Todd et al. 2006). These early maps typically record an accurate shoreline position, portray considerable detail of major channels within larger deltas and estuaries, and map with some consistency landscape components such as salt marshes and tidal flats. The spatial resolution of these maps is limited, however, and the maps often do not identify smaller coastal features, such as small barriers and stream-mouth estuaries, let alone changes in their configuration that would inform a change analysis.

Appendix Table B-1. Sources of geomorphological information.

Feature	Attribute	Data	Source
All Shoreline Types			
	Landscape shape/elevation	Topography	USGS topography LIDAR Photogrammetry
	Bathymetry	Bathymetry	NOAA charts Bathymetric LIDAR
	Wave Exposure	Orientation Fetch Wave climate	Shore Zone Inventory Wind/Wave modeling
Coastal Bluffs			
	Height and morphology	Topography Land cover	USGS topography Aerial photography LIDAR
	Platform width and slope	Bathymetry	NOAA charts Bathymetric LIDAR
	Wave Exposure	Fetch Wave climate	Shore Zone Inventory Wind/Wave modeling
	Mass-wasting	Erosion rates Slope stability Sediment supply	Coastal Zone Atlas Local studies Aerial photography
	Littoral drift regime		Net-shore drift maps
	Bluff composition	Geology	Geologic maps
Barrier Beaches Pocket Beaches			
	Morphology (shape, inlets)	Topography Land cover	LIDAR Aerial photography
	Substrate	Sediment character	Shore Zone Inventory Aerial photography
	Historical change	Historical shoreline position	Historical charts Historical aerial photography
Lagoons and Estuaries			
	Watershed influence	Watershed size Discharge Sediment yields	USGS topography USGS gauging reports
	Size and morphology Inlet position	Topography Land cover	USGS topography LIDAR
	Historical change	Shoreline or inlet position Modifications of tidal prism	Aerial photos Historical charts
River Deltas			
	River discharge		Gauging
	Sediment yields		Gauging, historical studies
Rocky Shores			
	Geology	Geology	Geologic maps

PSNERP and the Nearshore Partnership

The **Puget Sound Nearshore Ecosystem Restoration Project** (PSNERP) was formally initiated as a General Investigation (GI) Feasibility Study in September 2001 through a cost-share agreement between the U.S. Army Corps of Engineers and the State of Washington, represented by the Washington Department of Fish and Wildlife. This agreement describes our joint interests and responsibilities to complete a feasibility study to "*… evaluate significant ecosystem degradation in the Puget Sound Basin; to formulate, evaluate, and screen potential solutions to these problems; and to recommend a series of actions and projects that have a federal interest and are supported by a local entity willing to provide the necessary items of local cooperation.*"

Since that time, PSNERP has attracted considerable attention and support from a diverse group of individuals and organizations interested and involved in improving the health of Puget Sound nearshore ecosystems and the biological, cultural, and economic resources they support. The **Puget Sound Nearshore Partnership** is the name we have chosen to describe this growing and diverse group and the work we will collectively undertake, which ultimately supports the goals of PSNERP but is beyond the scope of the GI Study. We understand that the mission of PSNERP remains at the core of the Nearshore Partnership. However, restoration projects, information transfer, scientific studies and other activities can and should occur to advance our understanding and, ultimately, the health of the Puget Sound nearshore beyond the original focus and scope of the ongoing GI Study. As of the date of publication for this Technical Report, the Nearshore Partnership enjoys support and participation from the following entities:

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King Conservation District

King County

Lead Entities

National Wildlife Federation

NOAA Fisheries

Northwest Indian Fisheries Commission

Northwest Straits Commission

People for Puget Sound

Pierce County

Puget Sound Partnership

Recreation and Conservation Office

Salmon Recovery Funding Board

Taylor Shellfish Company

The Nature Conservancy

U.S. Army Corps of Engineers

U.S. Department of Energy – Pacific Northwest National Laboratory

U.S. Environmental Protection Agency

U.S. Geological Survey

U.S. Fish and Wildlife Service

U.S. Navy

University of Washington

Washington Department of Ecology

Washington Department of Fish and Wildlife

Washington Department of Natural Resources

Washington Public Ports Association

Washington Sea Grant

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Information about the Nearshore Partnership, including the PSNERP work plan, technical reports, the Estuary and Salmon Restoration Program, and other activities, can be found on our website at: *http://www.pugetsoundnearshore.org*.

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Puget Sound Nearshore Partnership

RESTORING OUR ECOSYSTEM HEALTH

Puget Sound Nearshore Partnership/
Puget Sound Nearshore Ecosystem Restoration Project

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