Technical Report 2011-03

Implications of Observed Anthropogenic Changes to the Nearshore Ecosystems in Puget Sound

Prepared in Support of Puget Sound Nearshore Ecosystem Restoration Project

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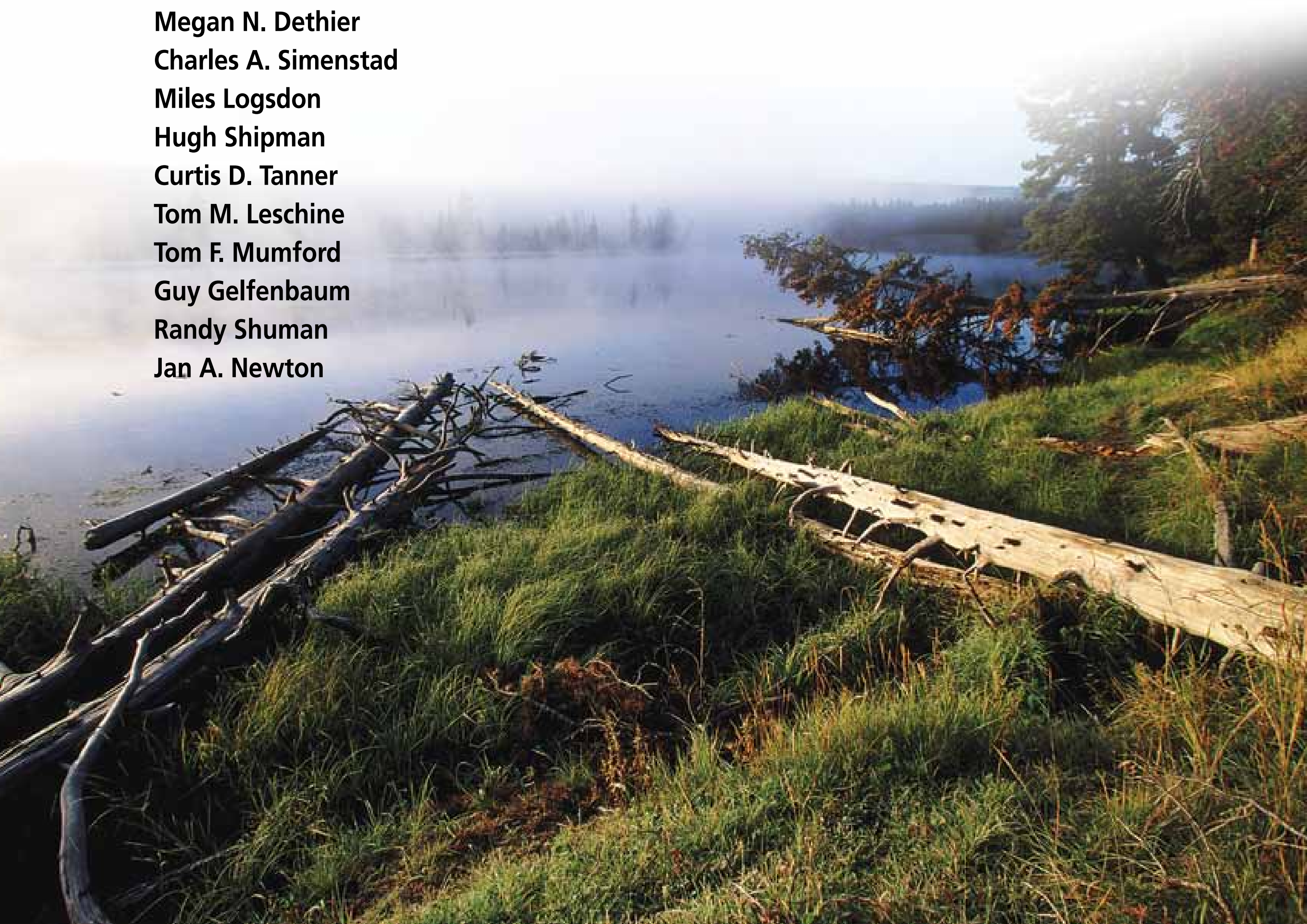

PUGET SOUND NEARSHORE
ECOSYSTEM RESTORATION PROJECT

Acknowledgments

The document was greatly improved by the reviews of Rachel Lipsky of the University of Washington, Ed Casillas of NOAA Fisheries and the PSNERP Strategic Science Peer Review Panel, especially Susan Peterson. We also wish to thank Dr. Denise Reed for her efforts leading this group and organizing the reviews. We also thank Melissa Holman and Bob Carey of the Nature Conservancy for their considerable help in preparing this report. We thank Greg Hood, Casey Rice, University of Washington and Washington Department of Ecology for photographs. Finally, the Nearshore Partnership would like to thank the Washington Sea Grant Communications Office for providing design and production services that made final publication of these papers possible.

Recommended bibliographical citation:

Fresh K., M. Dethier, C. Simenstad, M. Logsdon, H. Shipman, C. Tanner, T. Leschine, T. Mumford, G. Gelfenbaum, R. Shuman, J. Newton. 2011. Implications of Observed Anthropogenic Changes to the Nearshore Ecosystems in Puget Sound. Prepared for the Puget Sound Nearshore Ecosystem Restoration Project. Technical Report 2011-03.

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Cover photo: Washington Sea Grant

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Executive Summary

Puget Sound is a complex landscape that supports an abundance of terrestrial, freshwater, estuarine, and marine ecosystems, species, and habitats. It is home to enormous concentrations of waterfowl, shorebirds, and raptors; abundant shellfish; dozens of marine mammal species; and some of the largest runs of Pacific salmon in the lower 48 states. Nearshore ecosystems are among the more complex ecosystem types and form the interface between Puget Sound's terrestrial and marine landscapes. They occupy more than 4,000 km of shoreline, estuaries, and deltas of Puget Sound and are a critical part of the Sound because they connect terrestrial, freshwater, estuarine, and marine systems. Furthermore, their condition influences the productivity of the entire Puget Sound basin. Many of the ecosystem goods and services important to our human communities are supported by nearshore ecosystems.

The past 150+ years of European settlement and development have brought profound physical modifications to Puget Sound's nearshore ecosystems. This document presents a synthesis of the most significant physical changes to the nearshore ecosystems of Puget Sound and implications of these changes to ecosystem functions, goods, and services. Results are based upon the documented historical changes to the shoreline environment of Puget Sound between circa 1850-1880 and circa 2000-2006. Other types of changes to nearshore ecosystems, such as those related to sediment and water quality, have not been considered here.

We identified ***four major physical changes to*** Puget Sound's nearshore ecosystems:

- River deltas have experienced a dramatic loss of area and shoreline. For the 16 largest river deltas in Puget Sound combined, shoreline length has declined nearly 27% from historical conditions. The two primary stressors in the large river deltas are tidal barriers and armoring. Major changes in the watersheds of the largest deltas have also occurred.
- Many small, coastal embayments have been eliminated throughout Puget Sound. Puget Sound has experienced a loss of 305 embayment shoreforms (from 884 under historical conditions to 579 currently). Shoreforms are essentially geomorphic units of the shoreline, each distinguished by a characteristic suite of geomorphic landscape forming processes. Ninety-five embayment shoreforms were converted to a non-natural type of shoreform. The length of embayment shoreforms in Puget Sound declined nearly 46%, with the greatest decline in length of embayment shoreforms occurring in North Central Puget Sound (62%).
- Modifications to beaches and bluffs, primarily as a result of shoreline armoring, have resulted in the reduction or loss of sediment supply and the interruption of sediment transport processes. About 27% of the shoreline of Puget Sound is armored; 59% of divergent zones (a major source of sediment to Puget Sound beaches) have some armoring associated with them. One third of divergent zones have more than 50% of their length armored. A total of 33% of bluff-backed beaches, 27% of barrier beaches, and 8% of pocket beaches have been armored. One third of all bluff-backed beaches have been armored along half of their length.
- Puget Sound has experienced a dramatic loss of tidal wetlands, including a loss of 56% in the 16 largest river deltas. In particular, oligohaline and freshwater tidal wetlands have been almost completely eliminated (loss of 93%). The loss of tidal wetlands has been especially dramatic in the Puyallup and Duwamish deltas where almost no wetlands of any type remain.

We identified ***two major types of cumulative impacts*** associated with the interplay of these physical changes:

- Puget Sound's shoreline has become shorter, simpler, and significantly more artificial since Europeans began settling the region. Puget Sound's shoreline has had a net decline of 15% in length. While 1,062 km of natural shoreline was lost, 368 km of artificial shoreline (a type of shoreform that was very rare historically) was added. Artificial shoreforms now represent 10% of the shoreline of Puget Sound. A total of 366 natural shoreforms of all types were converted to an artificial shoreform, and 299 natural shoreforms were eliminated.
- Many places have experienced widespread, multiple, and compound changes. Forty percent of the shoreline of Puget Sound has been altered by one of the stressors we considered (e.g., overwater structures, roads, and marinas). Only 112 of 828 natural shoreline segments (encompassing all of Puget Sound's shoreline with the exception of large deltas) have no stressor associated with them. Armoring, the most dominant stressor in Puget Sound, is found in 78% of shoreline segments and along 27% of the shoreline of Puget Sound.

In aggregate, the anthropogenic changes to nearshore ecosystems we have documented have significantly degraded the physicochemical, social-cultural, and ecological processes that are responsible for a myriad of ecosystem goods and services that support our human communities. These services include filtration of water, protection from flooding and storm surge, and recreation (hunting, fishing, bird watching, clamming, etc.). For example, the production of many species of fish, shellfish, and wildlife has been impaired. Salmon spawning, migration, feeding, and growth have been impacted so much that several salmon species are now protected under the federal Endangered Species Act. These species depend upon nearshore ecosystems during parts of their life cycle. Resident killer whales that feed on salmon are also federally protected. We have lost forage fish spawning areas, while extensive shellfish beds are threatened by contamination from land-use practices. Population levels of some bird species that feed, nest, and roost along the nearshore have declined.

We have documented physical changes that have caused widespread losses in connectivity, increased fragmentation of the landscape and simplification of nearshore landscapes. Both changes in connectivity and fragmentation are occurring at multiple spatial scales. They have disrupted many nearshore ecosystem processes that support important species and have impaired the system's capacity to support biological diversity and production. As a result of these changes, natural, nearshore systems are at increased risk to further degradation from climate change and continued human development in the region. The condition of nearshore ecosystems influences the productivity of the entire Puget Sound Basin.

The nature and characteristics of the problems with nearshore ecosystems are significant because they directly relate to the solutions we must employ. The widespread, diverse, and spatially explicit changes to nearshore ecosystems necessitate multiple approaches to restore these places. Fragmentation, for instance, has reduced our options for protecting high-quality, natural places; many places have been altered or are adjacent to places that have been altered. As functioning, natural ecosystems are fragmented, they become less effective as species and biodiversity refuges, diminishing their conservation value. Coupling restoration with protection actions (which include reducing the likelihood of future degradation, such as through regulatory actions) offers the best opportunity to successfully restore Puget Sound.

Background

Puget Sound is a place of great physical and ecological complexity and productivity. It is one of the largest estuaries in the United States and, it is the only inland sea with fjords in the lower 48 states. It has more than 8,000 square kilometers (2 million acres) of marine waters and estuarine environment and has a watershed of more than 33,000 square kilometers (8.3 million acres). The headwaters of Puget Sound are generally of high quality as they originate from three national parks and numerous wilderness areas. When Captain George Vancouver sailed its waters more than 200 years ago, some 50,000 native peoples lived in this area (Sidebar 1). Now, the area is home to approximately 4 million people or about 70% of Washington state's population, with most concentrated in the metropolitan areas of Seattle, Tacoma, Everett, Bellingham, and Olympia. The population is growing by about 50,000 people (1.5%) per year and is expected to reach 5.33 million before 2020 (Puget Sound Regional Council 2004). The region's location, deep harbors, natural resources, and economic and cultural links to the Pacific Rim have made it a global trade center, an economic engine for much of the Pacific Northwest, and an important component of the national economy (Trade Development Alliance of Greater Seattle 2004; PSAT 2004).

The human development and use of Puget Sound for residential, commercial, industrial, and recreational purposes has come at great cost to the natural environment. Like a number of other large ecosystems in the United States (e.g., Missouri River, Florida Everglades, and Chesapeake Bay) (NRC 2002; Lotze et al. 2006; Sound Science 2007), Puget Sound is not healthy. Numerous symptoms or indicators that signal its degraded condition have been recently summarized in Sound Science (2007) and by the Puget Sound Action Team (PSAT 2007). The condition of Puget Sound is serious enough that Washington's governor established the Puget Sound Partnership (PSP) in 2007 to specifically address problems and define solutions to the region's environmental problems.

The factors contributing to the deterioration of Puget Sound are complex, and its degradation is not a result of a single problem such as water management, land loss, contaminants, or excessive nutrients. Rather, the declining condition of Puget Sound is a result of the cumulative effects of widespread degradation in many types of ecosystems (Sound Science 2007) that have occurred since Europeans began settling the region.

In particular, the nearshore ecosystems that straddle the 4,000 km of shoreline, estuaries, and deltas of Puget Sound have been significantly impacted by human use and development over the past century. Nearshore ecosystems represent the transitional area between land, freshwater, and the marine waters of Puget Sound. They are distributed along delta wetlands, shorelines, and beaches. They extend to the top of the coastal bank or bluffs in the protected waters from Puget Sound to Cape Flattery (at the western entrance to the Strait of Juan de Fuca) and northward into the Strait of Georgia—what many now refer to as the Salish Sea. They include shallow, tidal waters extending from the head of tidal influence to the lower limit of the photic zone (a depth of ~10 meters relative to Mean Lower Low Water). Thus, the entire shoreline is a contiguous band of diverse ecosystems shaped by coastal geomorphology and environmental conditions such as wind and wave energy.

Nearshore ecosystems are especially vulnerable to human impacts because they are ecotones or transitional zones between other major ecosystem types (air, terrestrial, freshwater, and marine). In addition, they are the focus of many human uses that often conflict with natural systems. Many people within the Puget Sound Basin live along the nearshore, and the long, narrow structure of the nearshore makes it more easily disrupted by people.

In this document, we provide a synthesis of the most significant physical problems with the nearshore ecosystems of Puget Sound. The problems presented here form the basis for the subsequent development of the Puget Sound Nearshore Ecosystem Restoration Project's (PSNERP) programmatic objectives, the strategies to address the objectives, and the selection of sites and actions to recover nearshore ecosystems. (Documents providing details on objectives, strategies, action, and site selection can be found as they become available at *www.pugetsoundnearshore.org*). The physical problems summarized here are derived from the documented historical changes to Puget Sound's shoreline environment between 1850-1880 and 2000-2006 (Simenstad et al. 2011). To define significance, we considered the scope and magnitude of change (e.g., how much of the shoreline has been affected) at both the scale of Puget Sound and its sub-basins and the effects of these changes to natural ecosystem functions, goods and services. Ecosystem functions and services are those that benefit human wellbeing (e.g., flood control, water quality improvement), and goods are the ecosystems' outputs (e.g., salmon, oysters, and Dungeness crab) that people value.

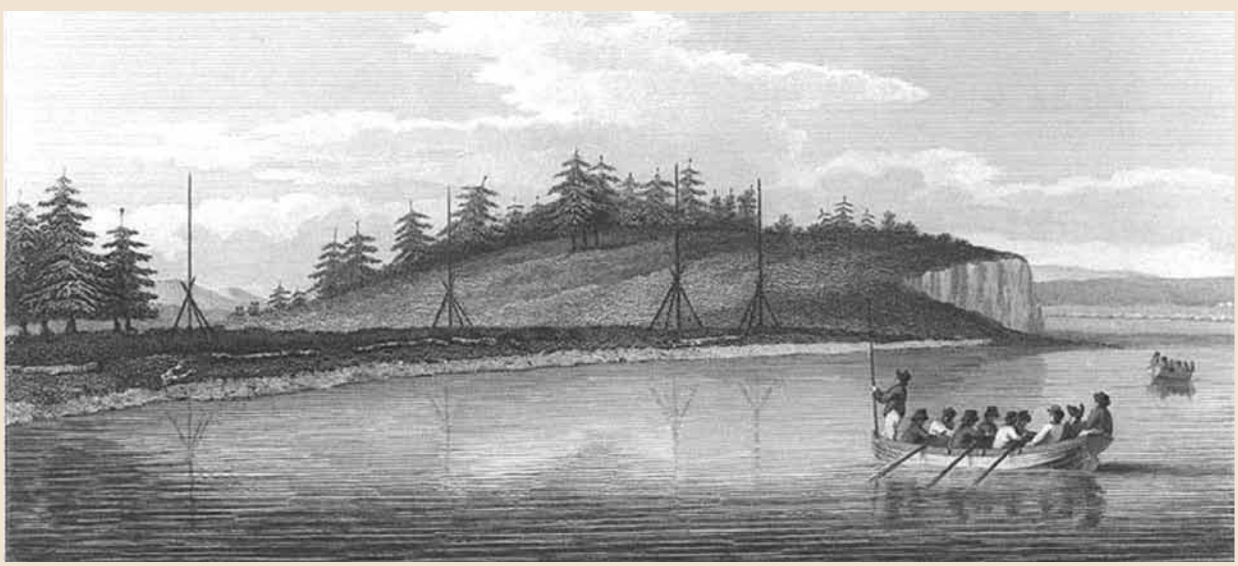
As elaborated in PSNERP's guidance documents (Fresh et al. 2004; Goetz et al. 2004; Simenstad et al. 2006), restoration science demonstrates that recovery of ecosystem processes results in more sustainable natural ecosystems than does simply recreating the structure of the system. Our focus was therefore to identify the most impaired physicochemical processes in the domain of the nearshore (e.g., movements of sediment, recruitment of large woody debris, and tidal hydrodynamics). Because measurements of impairment to nearshore ecosystem processes are unavailable at the scale of Puget Sound and its major geographic regions, our approach was to document changes in the physical structure and form of nearshore environments that we believe serve as surrogates for degradation in ecosystem processes. Other types of changes to nearshore ecosystems, such as those related to sediment and water quality, were not considered here. Descriptions of the physical processes considered in this evaluation can be found in PSNERP's Change Analysis (CA) (Simenstad et al. 2011) and Management Measures (Clancy et al. 2009) documents.

Sidebar 1

Staying Connected to Our Past

When the first Europeans found their way into Puget Sound, the native people living along the nearshore had established a regional culture rich in natural abundance and diverse in art and custom. The majority of settlements were near the mouths of major rivers. The Western red cedar was fashioned into homes, fibers, canoes, and dipnets for fishing. Individual tribes shared the Salish (Salishan) linguistic root, enabling trade and travel along the Puget Sound shoreline and creation of a network of local communities throughout the inland sea. In the spring of 1792 Captain George Vancouver assigned Lieutenant Peter Puget, an officer aboard His Britannic Majesty's sloop-of-war *Discovery*, to set sail for an "examination of the Inlet." Lieutenant Puget soon discovered that his long boat was being shadowed by two paddlers in a small dugout. By that afternoon, curiosity had led to polite introductions with natives in a nearby village. However, days later the survey team had a confrontation with native people who were insulted by Puget's fishing without asking permission. The exchange was resolved through a simple act of trade. After Puget's return to *Discovery*, Captain Vancouver commemorated the survey by naming the body of water Puget's Sound.

The resources of Puget Sound's nearshore have always played a critical role in the cultural foundation of its native peoples. Estimations from surveys between 1850 and 1890 suggest that there were approximately 29,500 ha of tidal wetland, including 12,000 ha of estuarine emergent marsh, 6000 ha of estuarine scrub-shrub wetland, and 11,500 hectares of tidal-freshwater wetlands. Crabs, clams, oysters, mussels, forage fish, kelp, eelgrass, salmon, and abalone are just a few of the species that used these nearshore habitats for part or all of their life histories. They were important food and cultural sources for the native peoples of these lands. The native people in this ecosystem prospered as a society through a connection to these resources and to the natural processes that supported them. The links between our history and our future, and between our environment and our culture in the Puget Sound region, are all closely tied to the nearshore.



Poles were for holding net to catch flying ducks. (University of Washington Libraries. Special Collections Division)

Changes to Nearshore Ecosystems

Introduction

We identified changes or problems with nearshore ecosystems primarily using information and data from two sources. First, we used PSNERP's CA (Simenstad et al. 2011), which is a documentation of changes to nearshore environments of Puget Sound that is derived by comparing historical (circa 1850-1880) and current (2000-2006) conditions. Second, we used the Strategic Needs Assessment Report (SNAR) (Schlenger et al. 2011) that uses the results of CA to define the most significant protection and restoration needs for the nearshore ecosystems of Puget Sound.

As described in detail in the CA (Simenstad et al. 2011), we considered four types of changes to nearshore ecosystems: ***1) complete changes*** ("transitions") in a geomorphic landform ("shoreform") from one type to another, where the shoreforms were defined by a unique analysis of Puget Sound's shoreline landforms (Shipman 2008); ***2) direct alterations of the shoreline itself*** (or within 25 m of the shoreline in the case of some shoreline alterations such as roads and railroads); ***3) modifications to the adjacent uplands within 200 m of the shoreline;*** and ***4) alterations to the watersheds that drain to nearshore segments.*** Each type of change (e.g., modification to adjacent uplands) was evaluated for Puget Sound as a whole and in each of seven sub-basins (Figure 1) (boundaries and descriptions of sub-basins are provided in Simenstad et al. 2011). Each sub-basin was further divided into segments, called process units, that represented two types of prominent nearshore ecosystem processes: 1) mixing of riverine and marine waters in the largest Puget Sound estuarine deltas (delta process units); and 2) delivery of sediments from shoreline bluffs and their transport and deposition along beaches, together organized as drift cells (shoreline process units). Overall, we analyzed 828 of these shoreline segments, which included 812 shoreline process units and 16 delta process units.

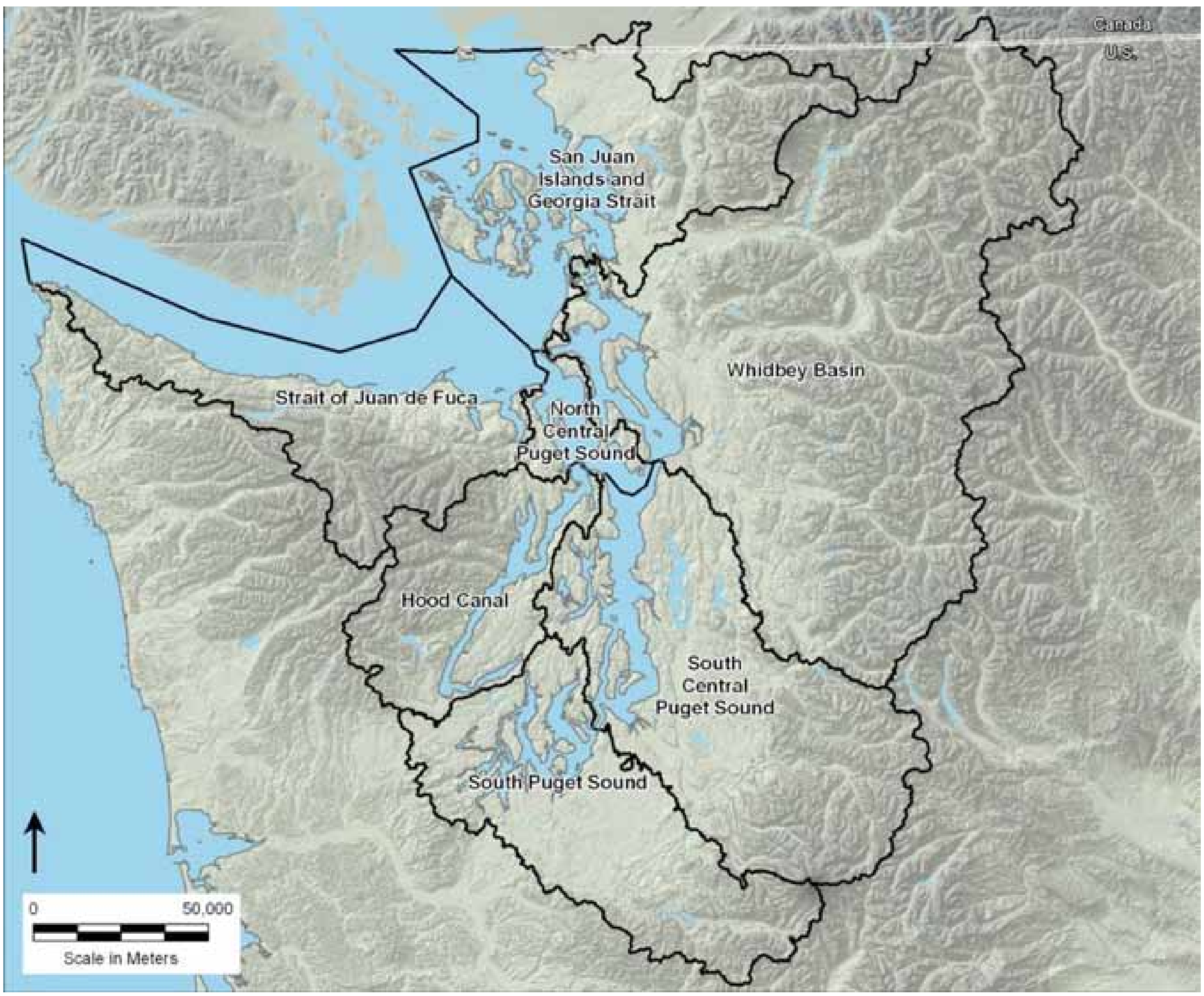


Figure 1. The Puget Sound study area and seven delineated sub-basins. See Simenstad et al. 2011 for detailed descriptions of the study area and sub-basins.

Within each process unit, the location of component shoreforms was delineated for historical and current conditions. The shoreforms were defined by the Shipman (2008) geomorphic classification, which describes four primary geomorphic systems that comprise Puget Sound's nearshore ecosystems (beaches, embayments, rocky coasts, and river deltas). Within these systems are 12 shoreforms (e.g., embayments include barrier estuaries, barrier lagoon, closed lagoons and marshes, and open coastal inlets) that are distinguished by a characteristic suite of geomorphic landscape forming processes. Because each represents a unique arrangement of nearshore ecosystems, they support different sets of ecological functions, goods, and services (Simenstad et al. 2011).

To analyze and evaluate changes, we applied a conceptual framework that identified physical changes to the nearshore and then determined how these changes likely resulted from changes in physical processes. We then linked changes in physical structure and processes to changes in ecosystem functions, goods, and services. Our ability to make these types of connections was greatest with data for changes occurring directly to nearshore ecosystems. This is not to say that human development of adjacent uplands and watersheds does not indirectly affect the physical condition of the nearshore, because it clearly can. For example, dams can affect the timing, amount, and frequency of sediment inputs to deltas.

We considered nine types of shoreline alterations or stressors. The selection of these depended in part upon our ability to obtain data for all of Puget Sound. The alterations we considered were: marinas, breakwaters/jetties, overwater structures, armoring, tidal barriers, nearshore fill, roads (within 25 m of the shoreline), and active and inactive railroads (within 25 m of the shoreline).

The changes we identified are data driven. However, our ability to define change, the changes we considered, and the implications of these changes was limited by the state of science on Puget Sound nearshore ecosystems, the data that were available, and the analytical tools that we could apply. In particular, because we were interested in a Sound-wide analysis, we needed data that were consistent and comparable for all areas of Puget Sound and could be used to define change at this scale. Further, we needed data that were spatially explicit. Thus, we could not evaluate some important processes or issues because we lacked data. Addressing these data gaps would improve our ability to define changes to nearshore ecosystems. For example, we were not able to assess Sound-wide changes in the upper intertidal zone, the marine riparian zone, forage fish spawning habitats, or eelgrass (*Zostera marina*) habitat, because spatially explicit data for either historical or current conditions did not exist for all of Puget Sound at the scale of our analysis (e.g., process unit). In some cases, we found local data sets that provided considerable detail in a limited area but were unable to use them, because there was nothing comparable in other areas. For example, although we could not assess changes in the marine riparian zone at the scale of Puget Sound, several areas in the San Juan Islands have detailed, comprehensive data on shoreline vegetation that could be used to examine changes to riparian vegetation in this limited area (MacLennan and Johannessen 2008).

Major Findings

1. Nearshore ecosystems have experienced significant direct changes.

a. Barriers to tidal hydrology have impacted large river deltas.

Deltas form at the mouths of streams and rivers where flows decrease and the capacity of the river to carry sediment diminishes (Downing 1983; Shipman 2008). Rivers and streams that discharge directly to Puget Sound can generally be divided into two broad classes of watersheds. The first type of watershed consists of systems that have relatively small flows and small sediment yields and are heavily influenced by the influx of coastal and marine sediments. They often have their headwaters in lowland areas and typically have small, indistinct deltas at the point they discharge into Puget Sound. The second type of watershed consists of systems that drain the Cascade or Olympic mountains and represent the largest rivers in the region; each of these had historically built a significant delta at its mouth. We identified 16 large river deltas, all of which drain >200 km^2 (Table 1). One of the most important features of all deltas is their estuarine wetlands, which are considered in greater detail in a following section.

Physical Changes. The 16 largest deltas of Puget Sound have all been extensively modified (Table 1). Combining all 16 deltas, the length of their shoreline has declined ~ 176 km or 26.6% from historical conditions. The two primary anthropogenic stressors in large deltas are tidal barriers, which account for 320 km of the current delta shoreline, and armoring, which accounts for 174 km of the current delta shoreline. Because many tidal barriers are also armored, there is considerable overlap between these two stressors in deltas. A total of 63.2% of the current nearshore zone of the large deltas is now classified as developed land (residential, commercial, or industrial uses). Changes to the wetlands of

Table 1. Summary information for the 16 largest Puget Sound deltas (this includes deltas that drain > 200 km^2). (After Simenstad et al. 2011).[1]

Delta	Drainage Area (km^2)	Nearshore Zone (km^2)	Shoreline Length (km)		Tidal Barriers (% length)	Roads (% length)	Armoring (% length)	Developed Land (% in Nearshore)	Total Wetlands (km^2)	
		Current	Historical	Current					Historical	Current
Dungeness	563	18.5	23.9	11.6	32.4	15.9	5.5	16.8	7.59	6.84
Elwha	838	2.6	5.5	4.1	3.9	1.3	0.0	7.8	0.33	0.82
Dosewallips	307	3.4	8.2	4.7	24.6	14.9	5.0	41.3	1.03	1.90
Duckabush	204	2.4	6.0	3.9	33.8	24.3	9.6	44.9	1.04	1.53
HammaHamma	222	2.5	5.8	5.1	42.1	14.2	0.8	29.3	1.60	1.64
Quilcene	295	5.4	14.3	8.1	49.8	10.9	13.2	17.3	2.84	3.07
Skokomish	653	12.4	26.5	13.7	82.1	27.9	16.3	16.1	8.96	7.79
Nisqually	2159	19.6	55.5	20.2	50.8	30.2	63.2	18.3	17.26	8.96
Deschutes	466	7.0	17.5	9.0	46.0	13.4	94.2	75.5	3.48	1.96
Duwamish	1257	18.9	13.3	32.5	69.2	10.9	97.8	83.0	15.12	0.17
Puyallup	2535	23.0	14.3	45.7	88.0	10.4	98.8	84.5	18.72	0.35
Skagit	7301	162.8	151.1	96.2	53.6	7.3	19.4	17.8	120.87	62.83
Snohomish	4748	112.9	120.6	95.3	98.2	7.2	7.8	51.4	84.64	18.33
Stillaguamish	1875	75.1	83.3	65.5	66.9	4.8	15.4	34.5	64.91	35.89
Nooksack	2083	59.7	50.3	40.5	33.5	16.7	33.3	16.7	40.59	20.16
Samish	402	52.0	65.2	29.0	58.6	9.4	76.2	14.3	32.91	15.80
Totals		578.2	661.3	485.1					421.91	188.04

[1]Tidal barriers, nearshore roads, and armoring are all reported as % of the shoreline length within the DPU. Developed land is reported as the percent in the nearshore and equals the sum of the four developed land cover classes within 200m of the shoreline (i.e., tier 3). Wetland totals are for all wetland types combined.

the large deltas have been especially dramatic. In aggregate, 55.5% of the wetlands (234 km^2) historically present in the 16 largest deltas of Puget Sound have been eliminated (Table 1).

The most altered large deltas are those associated with the Duwamish and Puyallup rivers (Table 1). Each of these two deltas has lost most of its nearshore zone, which has been extensively filled and developed (> 83% developed land in the nearshore zone); their shorelines have been almost completely armored, and each has extensive numbers of tidal barriers (Table 1). The least developed of the large deltas are associated with the Elwha and Samish rivers, where the proportion of developed land in the watersheds is 7.8% and 14.3%, respectively.

Watershed changes can also affect deltas in ways that were not directly detectable by the CA. For instance, water diversions can alter the equilibrium between sediment transport to deltas and sediment transport within them. Half of the watersheds associated with the large deltas of Puget Sound have at least one significant water diversion. Jay and Simenstad (1996) suggested that the effects of a 40% reduction in the average annual discharge of the Skokomish River due to a hydropower diversion could be responsible for a 15-19% loss of low intertidal area and a 17% loss of subtidal eelgrass on the outer delta.

Implications. Wetland loss in the large deltas is of considerable importance and is discussed in detail in a subsequent section. However, other changes to large deltas are also of significance. The loss of tidal prism (volume of water

Sidebar 2

Shorebirds, Tidal Flats and Shoreline Development

At low tide, vast areas of unvegetated mud and sand flats are exposed. Many of these flats are associated with our large river deltas, but many of the Sound's shorelines also have large flats. Although seemingly devoid of life, these flat areas are in fact "food factories," as they are populated by an abundance of invertebrates that live on or in the substrate. These invertebrates provide critical food for shorebirds and other birds associated with estuarine flats.

More than 30 species of shorebirds use estuarine tidal flats in Puget Sound. Most use tidal flats during their migrations along the Pacific flyway and for foraging during winter months. The invertebrates provide a rich source of food that allows some species to build up fat reserves needed during their long winter and spring migrations. Of the shorebirds found on Puget Sound's tidal flats, Dunlin (*Calidris alpine*) are the most abundant, representing more than 90% of the estuarine bird community from late fall to early spring. Flocks of thousands of Dunlin are not uncommon in winter on the tidal flats of the Skagit, Snohomish, and Stillaguamish deltas. Dunlin and other shorebirds have some fidelity to foraging areas, returning to the same tidal flats repeatedly over years.

Puget Sound has experienced significant loss of delta tidal flat habitat due to dredging, diking, filling, and dams that block sediment from moving downstream. Some deltas, such as the Duwamish, have sustained a nearly 100% loss of this important shorebird foraging habitat. Such losses have reduced the amount of food available to Dunlin, thus decreasing the number of birds able to use Puget Sound tidal deltas. This likely decreases their survival by reducing the fat reserves the birds need for their northward migration. Such reductions in numbers of birds using tidal flats have been found in other places, such as New England, that also have extensive tide flats.

exchanged by tides) can have ramifications to the local flooding regime, increasing freshwater flood peaks. It can also result in the simplification and loss of volume of tidal channel networks outside the area enclosed by tidal barriers (Hood 2004).

One significant implication of changes to deltas is that there is now less habitat area available for plants and animals. In particular, diking and filling of the deltas have eliminated most of the channels that historically cut through deltas and have thus restricted fish and wildlife to smaller areas than they once used. For example, in the Puyallup and Duwamish river deltas, salmon can use only one channel to migrate upstream or downstream. As a result, they are funneled into a smaller amount of habitat, which limits the number of refuges or options the fish have to avoid predators or stressful environmental conditions. In the late 1960s, low dissolved oxygen in the Duwamish River delta killed many adult Chinook salmon that were migrating upstream (Fujioka 1970). This likely occurred, at least in part, because the fish did not have alternative pathways they could use to avoid the water quality problem.

Loss of delta area has also affected the quantity and quality of habitats available for birds (Sidebar 2). As the amount of delta habitat diminishes, many birds have less space for feeding, roosting, or reproduction. At least 30 species of shorebirds use estuarine tide flats associated with Puget Sound's deltas (Buchanan 2006). Migratory birds use the tidal deltas to feed during their migrations, while several species of predatory birds, such as the imperiled peregrine falcon, forage upon the birds that use tidal delta habitats. Herons are one important species that use the nearshore for reproduction as well as foraging (Essinger 2007).

The loss of tidal prism in the delta and dams and diversions within the watershed can alter estuarine salinity structure, shifting the area and location of ecotones between wetland types sensitive to certain salinity regimes. In addition, watershed diversion and loss of tidal prism can alter the location and function of key hydrodynamic nodes such as estuarine turbidity maxima that in some estuaries regulate estuarine nutrient dynamics and food webs (Boynton et al. 1980; Sherwood et al. 1990; Simenstad et al. 1992; Simenstad et al. 1994).

b. Small coastal embayments have been eliminated throughout Puget Sound or had their connections to the Sound severed.

Puget Sound historically contained hundreds of small, protected embayments and open coastal inlets, many of which were in the form of stream mouth estuaries and barrier lagoons (Collins and Sheikh 2005; Simenstad et al. 2011). Embayment shoreforms (barrier estuaries, barrier lagoons, closed lagoons/marshes, and open coastal inlets) often include a barrier beach that wholly or partially encloses the lagoon or estuary; impacts to embayment shoreforms and associated beaches were assessed separately. Embayments tend to be dominated by tidal processes, although some lagoons and wetlands with no surface connection to Puget Sound are included in this shoreform type. The amount of freshwater influence varies widely between embayments, ranging from year round to intermittent (i.e., during rain events). The phrase "pocket estuary" is widely used in Puget Sound to describe small, connected (to Puget Sound) embayments (Beamer et al. 2005). Many embayments contain wetlands, although only 13.7% of all Puget Sound nearshore wetlands are currently found associated with small embayments, with the remainder associated with large deltas.

Physical Changes. Puget Sound has experienced a significant loss in the numbers of small, coastal embayment shoreforms. However, interpreting changes in embayment shoreform counts is complicated by the fact that some shoreforms were not completely eliminated but were divided into smaller segments by artificial shoreforms. As a result, some shoreform categories experienced an increase in numbers of that shoreform type.

Overall in Puget Sound, 884 embayment shoreforms were mapped historically and 579 were mapped under current conditions, representing a decline of 305 embayment shoreforms (Table 2). The loss in numbers of barrier estuaries, barrier lagoons, and closed marsh/estuaries was especially dramatic, declining from 711 to 422 (a 40% decline) (Table 2). Over all of Puget Sound, 418 small embayments either

Table 2. Shoreform changes in Puget Sound from historical conditions (circa 1875) to the present (circa 2005). Large deltas are not included. Note that interpreting changes in shoreform counts is complicated by the fact that some shoreforms were not eliminated but were divided into smaller segments by artificial shoreforms (i.e., one bluff-backed beach became two). As a result, some shoreform categories, especially those that can occur in large segments, could show an increase in shoreform count.

	Shoreform Counts		% Change in Length
	Historical	Current	
Bluff-backed beach	932	921	-7.7
Barrier beach	910	867	-11.9
Barrier estuary	240	179	-44.4
Barrier lagoon	222	142	-46.1
Closed lagoon marsh	249	101	-48.4
Open coastal inlet	173	157	-45.3
Plunging rocky	353	365	-9.3
Rocky platform	1371	1417	-10.4
Pocket beach	1015	1010	-9.5
Artificial	13	326	+3,443

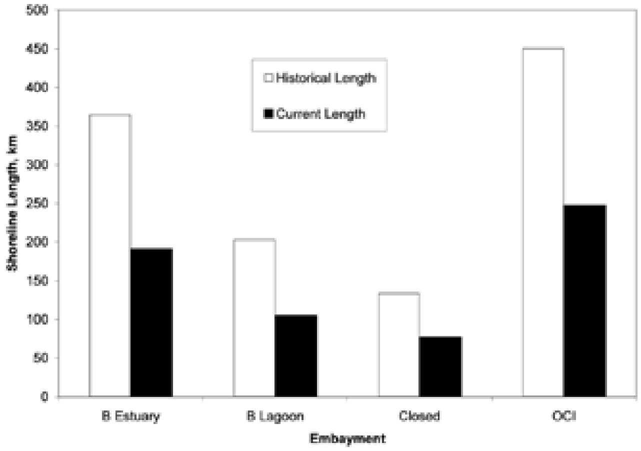


Figure 2. Change in length of embayment shoreforms from historical conditions (1850-1880) to the present (2000- 2006).

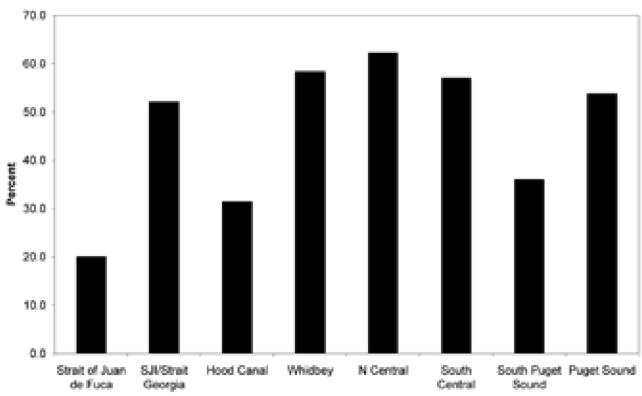


Figure 3. Percent change in length of embayment shoreforms by sub-basin from historical conditions (1850-1880) to the present (2000- 2006).

disappeared, were replaced by artificial shoreforms, or transitioned to another embayment shoreform type. A total of 53 open coastal inlets, 21 barrier estuaries, 16 barrier lagoons, and five closed lagoons/marshes were converted to an artificial shoreform, i.e., they no longer resemble a natural geomorphic shoreline feature.

Embayments historically accounted for 1,109 km of Puget Sound shoreline (23.2%) but now account for 604 km of shoreline (15.0%); this represents a decline in length of 45.5%. The loss in length of the four embayment shoreforms is comparable (ranging from 44 to 48%), although the proportional occurrence of each embayment type that has been lost varies considerably (Figure 2). Both historically and currently, the embayment shoreform that represents the greatest proportion of Puget Sound's shoreline is the open coastal inlet (Figure 2). Of the embayments that remain along Puget Sound, many have been extensively modified. Armoring is the main modification, with 18% of the shoreline length of embayments armored.

Changes to embayments varied considerably among sub-basins. The greatest percent decline in the number of embayment shoreforms occurred in South Central Puget Sound and Whidbey basins, which experienced declines of 53.5% and 52.1%, respectively. The greatest decline in length of embayment shoreforms has been in North Central Puget Sound (62.2% decline in length of embayment shoreforms) (Figure 3). The least change was observed in the Strait of Juan de Fuca, where the decline in length of embayment shoreforms was < 20.0% (Figure 3).

Implications. The sheltered condition of embayments makes them important habitat for native shellfish, fish, and shorebirds. For example, embayments can provide a sheltered, food-rich environment for a number of species of juvenile fish during certain times of the year. Recent evidence from the Whidbey sub-basin has found that large numbers of post-larval and juvenile surf smelt rear in some of the "pocket estuaries" within the Whidbey Basin (E. Beamer, Skagit River System Cooperative, La Conner, Washington; personal communication). In addition, during late winter and early spring, large numbers of juvenile Chinook and chum salmon can be found rearing in pocket estuaries of the Whidbey Basin. The juvenile Chinook salmon are part of federally protected populations and are considered to be one of the life history types that support viability of the species (Beamer et al. 2005; Sidebar 3).

Sidebar 3

"Pocket Estuaries" and Chinook Salmon Recovery in Puget Sound

The shorelines of Puget Sound were once dotted with hundreds of small, protected bays and inlets locally referred to as "pocket estuaries." Many have been replaced by roads, housing developments or marinas. Most remaining pocket estuaries have not escaped unscathed from human development; the character of their opening to the Sound has been modified, their water quality degraded, freshwater inputs modified, associated wetlands diminished, the surrounding land urbanized, and their size and shape altered.

Pocket estuaries provide a number of ecosystem functions, including the recent finding that, in Whidbey Basin, Chinook salmon fry originating from local spawning rivers such as the Skagit accumulate in pocket estuaries in winter and spring. The small Chinook salmon that use pocket estuaries appear to have higher growth rates and so spend less time at vulnerable small sizes. Further, predation appears to be lower in pocket estuaries than in adjacent open waters.

This level of use by juvenile Chinook salmon of pocket estuaries may be related to the dramatic loss of wetlands that has occurred in the Whidbey Basin. The Skagit River delta and Whidbey Basin have lost more than 50% of the emergent tidal marsh, 99% of tidal scrub-shrub, and almost 90% of its tidal forested wetlands that juvenile Chinook salmon used to occupy. Thus, Chinook salmon fry may occupy pocket estuary habitats because of a lack of wetland habitat associated with the large Skagit delta. Pocket estuaries thus have a role to play in supporting recovery of local populations of Chinook salmon in Puget Sound that were listed as threatened under the Endangered Species Act in 1999. Use of pocket estuaries represents one of the alternate life history pathways the fish can use to survive. Increasing the quality and quantity of this habitat type can help recover these threatened populations.

© Washington Department of Ecology Digital Coastal Atlas (Lonetree Lagoon)

c. Changes to beaches and bluffs have resulted in the loss of sediment supply and the interruption of sediment transport processes.

Beaches are the dominant nearshore shoreform in Puget Sound. Unlike many beach systems throughout the world, beaches in this region are composed of a mix of sediment types that are predominantly sand and gravel. In addition, Puget Sound beaches are influenced by a large tidal range and lie mostly within sheltered wave environments (Woodroffe 2002; Johannessen and MacLennan 2007; Shipman 2008). Most Puget Sound beaches (other than the pocket beaches along rocky coasts) are divided into distinct geomorphic units called littoral drift cells (or drift cells). Although movements of sediments along a Puget Sound beach are complex and can vary seasonally, there is generally a net longshore movement of sediment in one direction in each drift cell. Each drift cell has sediment sources, areas where sediments are deposited, and transport areas where sediments are moved by longshore processes. Our shoreline process units correspond to drift cells.

In Puget Sound, beaches consist of two primary shoreforms: 1) those associated with coastal bluffs (referred to as bluff-backed beaches), where the coastline has retreated landward; and 2) those associated with barrier beaches, where sediment has been deposited seaward of the original coastline. In aggregate, these two shoreforms account for 49.6% of Puget Sound's shoreline. In addition, Puget Sound also has pocket beaches, which are small beaches constrained by rocky headlands along rocky coastal areas (especially in the San Juan Island sub-basin). While these can reflect elements of beach geomorphic systems (Shipman 2008), they were not considered to be a beach shoreform. A total of 77.6% of all beaches in Puget Sound are currently bluff-backed beaches. In Puget Sound, the primary sources of sediment to beach shoreforms are portions of bluff-backed beaches that are often called "feeder bluffs" (Johannessen and MacLennan 2007; Simenstad et al. 2011; Schlenger et al. 2011). For example, in one area of the Whidbey Basin, bluff-backed beaches included 88.0% of sediment source feeder bluffs (Johannessen and Chase 2005).

Divergent zones are segments of drift cells where sediment sources from the bluff feed two drift cells; thus, two adjacent shoreline process units (drift cells) may share a divergent zone. In Puget Sound as a whole, 80.0% of the 350 identified divergent zones are associated with bluff-backed beaches (Schlenger et al. 2011). This figure ranges from 58.0% in the San Juan Island sub-basin to 97.0% in the Whidbey sub-basin.

A total of 10.7% of Puget Sound beaches are barrier beaches. This shoreform type forms spits, tombolos, and other depositional features that help make the Puget Sound shoreline complex. Barrier beaches often provide the protective berm that supports coastal embayment shoreforms such as barrier estuaries and lagoons.

Table 3. Percent change in the length of each beach shoretype from historical (circa 1875) to the present (circa 2005) by sub-basin.

Sub basin	Bluff-backed beach	Barrier beach
Hood Canal	-2.9	-9.8
Strait of Juan de Fuca	-4.2	-2.4
North Central	-3.6	-14.4
South Central	-16.6	-24.8
San Juans-Georgia Strait	-7.6	-13.8
South Puget Sound	-5.7	-11
Whidbey	-8.1	-6.4
Puget Sound	-7.7	-11.9

Table 4. Percent of the current length of bluff-backed beach and barrier beach shoretypes that has been modified by each of the nine stressors.

Stressor	Bluff-backed Beach (1529 km)%	Barrier Beach (440 km)%
Armoring	33	27
Breakwater/Jetty	0	0
Marinas	0	0
Fill	3	10
Overwater Structure	2	2
Roads	7	10
Railroad, Abandoned	1	1
Railroad, Active	1	0
Tidal Barrier	0	0

Physical Changes. As with other Puget Sound shoreforms, the amount of beach shoreline has declined from historic conditions, but the magnitude of changes was less pronounced than for embayments and large deltas. Historically, 38.5% of Puget Sound's shoreline (1,529 km) was composed of bluff-backed beach; it was (and remains) the dominant shoreform in Puget Sound. Barrier beaches were the fourth dominant shoreform, accounting for 440 km (11.1%) of the shoreline. From historical to current conditions, there was a decline in length of bluff-backed beach and barrier beach of 128 km and 60 km, respectively.

Changes to beaches varied considerably between sub-basins (Table 3). The greatest percent decline in both bluff-backed beach and barrier beach occurred in South Central Puget Sound. There was a loss of 16.6% of bluff-backed beach length and 24.8% of barrier beach length in this sub-basin (Table 3). The sub-basin with the smallest percent decline in beach length was the Strait of Juan de Fuca sub-basin. This sub-basin experienced a decline in length of bluff-backed beaches of 4.2% and of barrier beach of 2.4%. Many modifications have also occurred to Puget Sound beaches. Armoring (seawalls and revetments) is the most pervasive direct alteration to the beaches of Puget Sound. A total of 33.4% of bluff-backed beaches and 27.2% of barrier beaches have been armored (Table 4); 34.0% of all bluff-backed beaches are armored along more than half of their shoreline. Only 25.0% of all bluff-backed beaches are completely unarmored. Nearly 59.0% of all divergent zones had some armoring associated with them, while 35.0% of all divergent zones were armored along greater than half of their length; 18.0% of all divergent zones had >91% of their length armored.

The distribution of armoring associated with beaches varies considerably among sub-basins. The most armored sub-basin is the South-Central sub-basin, with 62.8% of the beach shoreline armored; the least armored are the three northern most sub-basins: Juan de Fuca, San Juan/Georgia Strait, and North Central.

Although other alterations are associated with Puget Sound's beaches and bluffs, the effect is considerably less than armoring (Table 4). Other than armoring, roads and nearshore fill are the most significant stressors affecting beaches in Puget Sound. For example, roads and nearshore fill each affect about 10% of the length of bluff-backed beaches (Table 4).

Implications. One of the most important physical processes occurring along beaches and bluffs is the erosion, transport, and distribution of sediment (Sidebar 4). Sediment processes, in combination with other factors, such as disturbance regimes, directly affect characteristics of beaches and the composition, abundance, and diversity of plant and animal communities associated with them (Turner et al. 1995; Farina 2000). Sediment processes are dynamic and driven by storms, wave action, and tidal processes. They also vary sig-

Sidebar 4

Feeder Bluffs

Much of Puget Sound's shoreline is lined by steep coastal bluffs that have been shaped by thousands of years of erosion by wave action and the downward pull of gravity. The bluffs, which can range from just a few feet to hundreds of feet in height, are composed of sediment deposited during the ice ages. They may erode slowly and gradually, or they may fail in large landslides; in either case the sand and gravel become part of the beach. Beaches on Puget Sound serve as conveyor belts, with waves transporting the eroded sand and gravel down the shoreline to form beaches and spits, sometimes miles away. For this reason, some bluffs are called feeder bluffs, because they feed sand and gravel to the beaches.

Bluff-top property is highly prized on Puget Sound for its spectacular views. Not surprisingly, homeowners are alarmed when their slopes begin to slide. Their common reaction is to build a seawall or bulkhead on the beach to prevent waves from eating away the toe of the bluff. This also prevents the erosion that builds and maintains the beach. While seawalls may protect the bluff itself from erosion, they do nothing to prevent the ongoing erosion of the beach; this can lead to the loss of the upper beach over time.

Beaches armored with seawalls and deprived of natural sediment sources are less able to support important shoreline habitats. Seawalls create an artificial boundary between terrestrial and marine environments. They can affect the amount of natural shoreline vegetation and prevent the accumulation of logs and beach wrack, which are an important part of the beach ecosystem. Changes to the upper beach can threaten spawning habitat of smelt and sand lance.

Puget Sound residents and tourists walk, cruise, paddle, fish, explore, and collect shellfish along our beaches. Where beaches have lost their natural sources of sediment, recreational use and enjoyment can be diminished. In addition, loss of natural sediment supplies can lead to increased erosion along shorelines that were previously stable. This can lead to expensive efforts to artificially restore or maintain beaches.

nificantly alongshore and from one part of Puget Sound to another, due to variability in wave action, geology, and the shape of the inherited glacial landscape (Finlayson 2006).

Disruption of sediment processes can result from structures placed either laterally or across (perpendicular to) the shoreline, which can affect the amount and size (grain size) of sediment delivered to the beach, and how and where it is transported. In particular, one of the most apparent anthropogenic changes to a beach is placement of structures (e.g., nearshore fill or armoring) parallel to the shore that cuts off or isolates bluffs that are sediment sources (so-called feeder bluffs) (Shipman et al. 2010). This is because the primary source of sediment to the non-delta shoreforms of Puget Sound is the feeder bluffs associated with bluff-backed beaches. Downing (1983) estimated that erosion of coastal bluffs supplies ~ 90% of the sediment to Puget Sound beaches, and shoreline armoring occurs along approximately 33 percent of those bluffs (Schlenger et al. 2011). Erosion rates naturally vary between locations, from a fraction of a centimeter to meters in a year, while the frequency of erosion occurrences is also highly variable, ranging from time scales of annually or more frequently in some places to intervals of 100 years or more.

Disruptions in sediment processes can change the physical characteristics of a beach, including changes in sediment composition (e.g., coarsening of the material), beach slope, and beach width (Pilkey and Wright 1988; Shipman et al. 2010). Down-drift beaches in the vicinity can disappear, and beach width can decline (Griggs 2005). HEC (2005) conducted an assessment of beach characteristics in Thurston County in 2003 and found that beach width tended to decline in front of armored structures. They also found a negative relationship between the amount of upper beach area and the amount of armoring along a shoreline. Barriers placed in a location where the coastline is undergoing net, long-term erosion can result in the loss of beach area in front of the structure. This type of change, called passive erosion, was demonstrated in Hawaii by Fletcher et al. (1997) and, although it has not yet been studied in Puget Sound, it seems likely that this type of change can occur here as well.

Engineered structures may also change the hydrodynamic environment of the beach. Wave reflection off the hard surfaces of armored structures may cause local scour/erosion effects and affect sediment transport. Several studies in Monterey Bay, California, suggested that armoring of bluffs altered erosion, scour, and beach characteristics. At times, there were indications of effects a considerable distance from the structure (Griggs and Tait 1988; Griggs et al. 1994).

A variety of biological effects can result from changes in sediment processes (Shipman et al. 2010), including: 1) changes in invertebrate communities, 2) loss of forage fish spawning habitat, and 3) loss of feeding and migration habi-

Sidebar 5

Recovering Olympia Oysters

Olympia oysters once carpeted much of the intertidal and shallow subtidal flats in some areas of Puget Sound such as Hood Canal and the inlets of South Puget Sound. By the late 1800s they were nearly obliterated by overzealous harvesting. While harvest of Olympia oysters has been minimal since the early 1900s, habitat loss due to shoreline development, siltation, and pollution has helped maintain low abundance levels. A global assessment of shellfish reef habitats has rated Olympia oyster abundance throughout the Pacific Northwest at less than 10% of its former numbers. These levels are too low to support significant levels of commercial, tribal or recreational harvest.

Efforts to increase abundance of Olympia oysters to harvestable levels have intensified in recent years. Restoration is limited by a lack of suitable habitat, especially a lack of appropriate substrate conditions. Primary factors are dredging, filling, pollution, and other shoreline development. Such development has adversely affected many of the ecosystem processes that support the habitat conditions needed by native shellfish.

In particular, all native bivalve shellfish require particular types of sediment for their larvae to settle, grow, and avoid mortality. The armoring of more than 25% of Puget Sound's shorelines, especially its beaches, has altered the sediment processes that help to create and maintain Olympia oyster habitats. Armoring has restricted coastal bluff erosion in places, resulting in a loss of fine sediments from beaches. This loss can transform relatively fine beach substrates to those that are largely cobble and gravel, or can even expose underlying clay, none of which is suitable for native shellfish. To help recover Olympia oysters, sediment processes in areas capable of supporting oysters will need to be restored.

tat for juvenile salmon and forage fish. Armoring can affect benthic and epibenthic invertebrates due to a loss of beach area, changes in beach slope, and changes in substrate characteristics. Because the composition of intertidal invertebrates is strongly linked to substrate characteristics (Dethier and Schoch 2005), changes in local sediment characteristics due to armoring (e.g., resulting from wave reflection or blocking of sediment sources) can alter the abundance and composition of infaunal and epifaunal organisms, including shellfish. Changes in invertebrate communities due to armoring have been widely documented outside of Puget Sound (Davis et al. 2002; Jackson et al. 2002; Griggs 2005; Shipman et al. 2010). In one study, Peterson et al. (2006) determined that changes to benthic invertebrates along a beach had cascading effects, impacting other trophic levels such as shorebirds. Similarly, Dugan and Hubbard (2006) and Dugan et al. (2008) found that taxa richness and abundance of amphipods and insects was less on armored beaches than unarmored beaches near Santa Barbara, California.

In Puget Sound, Sobocinski et al. (2010) found that armoring affected abundance and density of insects, amphipods, and isopods associated with beaches. The small invertebrates they studied typically live on beaches and are often important sources of food for fish and birds. While the specific mechanisms of impact were linked to changes in beach characteristics, Sobocinski et al. (2010) also concluded that changes in abundance of some invertebrate taxa could be related to the amount of wrack or decaying vegetation that collects on the upper beach and is used as habitat by some invertebrates. Armoring can prevent wrack from collecting.

Armoring may also be having an effect on recovery of the Olympia oyster. Present densities of the native Olympia oyster are at least an order of magnitude lower than they were historically (Beck et al. 2009) (Sidebar 5) and efforts to increase their abundance to harvestable levels have intensified in recent years. One limitation to restoration of Olympia oysters is a lack of suitable habitat due to the effects of dredging, filling, pollution, and other shoreline development. Such development has adversely affected many of the ecosystem processes that support the habitat conditions needed by native shellfish. The armoring of coastal bluffs, for example, can result in a loss of fine sediments from beaches. This loss can transform relatively fine beach substrates to those that are largely cobble and gravel, or can even expose underlying clay, none of which is especially suitable for native shellfish.

Armoring also affects reproduction of several species of forage fish (e.g., Rice 2006) (Sidebar 6). Forage fish are small pelagic fish that are major contributors to Puget Sound food webs. They are eaten by a wide variety of fish, birds, and mammals, such as pigeon guillemots, surf scoters, Chinook salmon, steelhead, and harbor seals (Fresh et al. 1981; Litzow et al. 2000; Penttila 2006; Anderson et al. 2009). Population sizes of some predator species can be highly dependent upon abundance levels of forage fish. For example, surf scoters are closely associated with some nearshore habitats such as eelgrass that are especially important during molting. Changes in surf scoter populations seem to be closely linked to spawning biomass of herring (Anderson et al. 2009), one species of forage fish. Changes in herring spawning biomass were positively correlated with the abundance of the scoters.

There are several ways in which armoring can affect reproduction of forage fish. First, armoring that is constructed low enough in the intertidal zone can eliminate the spawning habitat of several species (surf smelt and sand lance), which spawn on fine-grained substrates on the upper beach (Penttila 2007). Second, by blocking sediment input to the beach, armoring can cause spawning areas to convert from the fine-grained material that the fish need for spawning to coarser materials such as gravel and cobble that are unsuitable for spawning. Third, armoring can negatively affect forage fish populations by increasing sediment temperatures on the upper beach, where shading by natural shoreline vegetation has been removed; this reduces the survival of incubating embryos (Rice 2006).

In addition to effects on reproduction of forage fish, armoring can affect feeding behavior of juvenile forage fish (as well as juvenile Pacific salmon), which often feed in shallow water at high tide. When shoreline modifications extend lower on the shore, the truncation of intertidal shallow water habitat by armoring reduces foraging by juvenile fish on riparian insects (Toft et al. 2007).

Sidebar 6

Forage Fish Spawning and the Beaches of Puget Sound

In Puget Sound, the most abundant of all fishes are small pelagic species referred to as forage fish. The species are categorized this way because they are consumed by a wide variety of larger fish, birds, and mammals; they represent the primary pathway in the marine food web of Puget Sound leading from lower (plankton) to upper (birds) trophic levels. Without healthy populations of forage fish, the Puget Sound ecosystem would likely crash.

Forage fish in Puget Sound consist of three primary species: surf smelt, Pacific sand lance, and Pacific herring. Herring spawn on marine plants in specific intertidal and shallow sub-tidal areas, while sand lance and surf smelt spawn on sand and small gravel along the upper beach. While the spawning areas of all three species are vulnerable to the effects of shoreline development, surf smelt and sand lance are most vulnerable to changes to beaches, because they spawn where people want to live. While we still know very little about the reasons the three species choose to spawn where they do, it is apparent that at least herring and surf smelt tend to be site-specific spawners.

Human development has affected forage fish spawning in several ways. Armoring is one of the more prominent changes that have occurred to Puget Sound beaches; it can eliminate forage fish habitat when it is built on or seaward of a spawning area. Many types of shoreline modifications (e.g., armoring, marinas, roads, and railroads) also affect sediment processes: the erosion, transport, and redistribution of sediment. Sediment naturally erodes from coastal bluffs, is transported by waves along beaches, and is deposited elsewhere. By blocking sediment input to the beach, armoring can cause upper beaches to convert from the fine-grained material that fish need for spawning to coarser materials such as gravel and cobble that are unsuitable for spawning. Another mechanism by which armoring can affect forage fish populations is by increasing the sediment temperature on the upper beach, where shading by natural shoreline vegetation has been removed, thus reducing the survival of incubating embryos. We can only surmise how much forage fish spawning habitat we have lost because we lack comprehensive historical data on spawning areas. Also, we do not know if forage fish populations can naturally shift spawning sites when they are prevented from spawning in their accustomed place.

d. Extensive losses of estuarine wetlands have occurred throughout Puget Sound.

Wetlands are generally areas of land whose soil is saturated with moisture either permanently or seasonally. Puget Sound's estuarine wetlands are regularly inundated by the interaction of tides and river flow. Tidal inundation is the dominant factor determining the nature of sediment and soil development. It is also the primary factor determining the types of plant and animal communities living in the sediments and on the surface of tidal swamps, scrub-shrub, and emergent marsh ecosystems. Even unvegetated (mud and sand) intertidal flats harbor distinct biotic communities.

There are four tidal wetland types in Puget Sound's estuarine/delta environments. They are, in decreasing order in the relative salinity regimes they experience: 1) euryhaline (high salinity) unvegetated; 2) estuarine (mid-salinity) mixing; 3) oligohaline (low salinity) transitional; and, 4) tidal freshwater. All differ in the characteristics of the plants and animals they support and the salinity and temperature regimes they experience. Euryhaline unvegetated mudflats and emergent marshes that comprise estuarine mixing wetlands are both generally associated with the outer portions of deltas; oligohaline wetlands are the scrub-shrub environments that occupy the transitional zone in the lower salinity reaches of deltas; and tidal freshwater wetlands are the unique forested ecosystems that extend from the upper end of the oligohaline to the head of tide. Wetlands can be grouped into those occurring in the large deltas and those associated with other shoreforms, mostly coastal embayments and the mouths of small streams. However, in analyzing wetland changes, it is important to note that the euryhaline unvegetated data was only reliable for the 16 large deltas.

Physical Changes. Puget Sound has experienced a dramatic loss of tidal wetlands. Most estuarine wetlands are associated with the 16 large deltas. These delta systems historically contained 416 km^2 of tidal wetlands (all categories combined), compared with the current 183 km^2, a decline of 56.0% (Tables 1 and 5). For shoreforms other than large deltas (mostly embayments), the historically estimated 102 km^2 of wetlands has declined to 33.3 km^2 currently, a loss of 69% (because the euryhaline, unvegetated data is only reliable for the large deltas, this estimate does not include that wetland type). Considering just the estuarine mixing, oligohaline, and tidal freshwater wetland types, there has been a loss of 74.2% of wetlands that historically surrounded the shores of Puget Sound. Tidal freshwater and oligohaline transitional wetlands have been almost completely eliminated from Puget Sound. Taken together and combining all shoreforms, 93.1% of these two wetland types have been lost throughout Puget Sound. Of the 64 km^2 of oligohaline marsh that existed historically, only 1.5 km^2 remain.

The loss of tidal wetlands has been especially dramatic in several sub-basins and in several large deltas in particular (Table 6). In both the Duwamish and Puyallup river deltas, almost no wetlands remain of any type (Table 1). In the Whidbey Basin, the amount of oligohaline transitional and tidal freshwater wetlands declined from 60 km^2 to 0.6 km^2 and from 88 km^2 to 9.0 km^2, respectively (Table 6). Most of this loss was in the three large deltas found in this sub-basin.

Implications. Wetlands are one of the most important ecosystem types, wherever they occur, because they provide a wide variety of functions, including primary production; nutrient cycling; biophysical mediation of contaminants; fish and wildlife habitat, particularly for reproduction and feeding; and support of coastal fisheries species (Boesch and Turner 1987; Mitsch and Gosselink 2007) (Sidebar 7). Except perhaps for the largest of river-dominated estuaries (however, see Maier and Simenstad 2009 for instances of rivers extensively developed and managed for hydropower), they are typically the primary organic matter source for the detritus-based food webs of estuaries (e.g., as demonstrated using stable isotopes by Kwak and Zedler 1997).

In the Northeast Pacific, one of the most prominent functions of estuarine wetlands, especially those associated with large deltas, is that they support extended rearing of several species of juvenile salmon (Healey 1982; Levy and Northcote 1982; Simenstad et al. 1982; Bottom et al. 2005a, 200b; Henning et al. 2006). Recent evidence from throughout this region has demonstrated that the loss of delta wetlands has affected viability of Chinook salmon populations and has contributed to the depressed condition of Chinook salmon

Table 5. Wetland loss by wetland type for large deltas and for other shoreform types. Values are in km^2. Due to data reliability issues, no data is presented for unvegetated wetlands in shoreforms other than large deltas.

	Large Deltas			Other Shoreforms		
	Historical	Current	% Loss	Historical	Current	% Loss
Euryhaline Unvegetated	166.4	125.8	24.3	--	--	--
Estuarine Mixing	85.6	45.9	46.3	75.0	31.7	20.3
Oligohaline	55.3	0.8	98.2	8.7	0.7	92.0
Freshwater Tidal	108.5	10.7	90.0	18.3	0.9	95.1
Total- Puget Sound	415.7	183.2	56.0	102.0	33.3	68.7

Table 6. Changes in emergent (estuarine mixing), oligohaline, and tidal freshwater wetlands for each of the seven sub-basins of Puget Sound. All areas are in km^2 (after Simenstad et al. 2011) and include all shoreform types. Euryhaline unvegetated wetlands are not included.

Geographic Area	Estuarine Mixing			Oligohaline			Tidal FW		
	Historic Area	Current Area	% Change	Historic Area	Current Area	% Change	Historic Area	Current Area	% Change
Strait of Juan de Fuca	3.6	3.2	-13.1	0.3	0.1	-46.2	0.7	0.6	-18.0
San Juan Islands/Georgia Strait	13.4	11.7	-78.0	40.3	0.2	-98.8	20.3	0.8	-97.3
Hood Canal	13.0	19.7	35.2	0.8	0.3	-63	0.9	0.8	-8.9
North Central Puget Sound	12.3	4.6	-62.8	0.3	0	-86.1	0.1	0.2	73.9
Whidbey	46.4	29.2	-49.4	60.0	0.6	-98.7	88.0	8.9	-89.9
South Central Puget Sound	19.6	3.1	-83.4	0.4	0.1	-84.0	4.6	0	-99.9
South Puget Sound	25.4	8.4	-40.3	0	0.1	680.9	2.4	0.4	-84.4
Puget Sound Basin	157.1	73	-53.5	64.1	1.4	-97.8	126.8	11.6	-90.9

Sidebar 7

The Ghosts of Tidal Swamps

In many ways, it is ironic that the modern Pacific Northwest culture has come to revere and even preserve the grand old growth forests of the Olympic and Cascade mountains, but has virtually ignored the great tidal swamps of Puget Sound's deltas and large estuaries, which today are but ghosts of their past majesty. Tidal wetlands of majestic structure and diversity once persisted in the upper reaches of these estuaries, where tidal forces create fluctuating water levels and dilute seawater to brackish or no measurable salt at all. From the few locations where they still survive, such as in the outer coastal estuaries of Washington and Oregon and the Columbia River estuary, it is clear that tidal swamps once dominated much of the area of estuaries. Near the ocean, these estuarine areas are dominated by salt-marsh plants, which diminish with decreasing salinity upriver. In low-salinity areas, woody, scrub-shrub and forested wetlands outlined the mainstem of the river and the distributary channels and sloughs that sinuously subdivided tidal surge plains. In areas that were still influenced by the tide, but had almost no salt, dense thickets of smaller shrubs such as willow, vine maple, red osier dogwood, blackberry, and sweet gale gradually gave way to the true forests of Sitka spruce, western red cedar, and red alder that occupied the tidal freshwater terminus of the estuary.

Historically, these low-salinity and tidal freshwater swamps covered >190 km^2 of the Sound's big deltas, with additional swamps associated with many of the smaller estuaries. Today, represented by a few isolated remnants, such as Otter Island in the Snohomish River estuary, tidal swamps are now only 13 km^2, a combined loss of 93%. Tidal swamps have been virtually erased (>85% disappeared) from most of the large deltas (e.g., Duwamish, Puyallup, Nooksack, Stillaguamish, Skagit), and the only significant tidal swamp ecosystems that are >0.5 km^2 are remnants scattered in a few deltas (e.g., Snohomish, Skagit, Skokomish).

With these losses of tidal swamps, ecosystem goods and services unique to Puget Sound have similarly been diminished. The swamps were the habitat of wildlife such as black bear, river otter, beaver, and muskrat and served as unique rearing habitat for juvenile salmon, particularly coho salmon, coastal cutthroat trout, and bull trout. These extensive wetlands served to absorb floodwaters like massive sponges and sustained lower water temperatures than in the mainstem rivers and open estuaries. Their distinctive and lush vegetation supplied a tremendous input of organic matter to estuarine detritus-based food webs, as well as to insects and other invertebrates that are prey to fishes and birds.

populations in the region (Greene et al. 2005; Beamer et al. 2005; Bottom et al. 2005b). These studies have demonstrated that particular life history types use delta wetland habitats for extended periods and depend on this habitat for initial, early growth (Fresh 2006). The production of these life history types is important to maintaining population resilience and supporting efforts to rebuild salmon populations (Bottom et al. 2005a). Because there is a strong relationship between juvenile salmon size and their survival (Duffy 2009), high estuarine growth rates are critical to the survival of this life history type and its contribution to population resilience.

A modeling study by Beamer et al. (2005) for the Skagit River concluded that elimination of estuarine wetlands has resulted in a quantifiable loss of returning adults and a subsequent loss of population resilience. This study estimated that restoring 1114 ha of Skagit River delta wetlands, especially tidal, drainage channels, could increase Chinook salmon smolt capacity by up to 1.3 million juveniles, depending on the assumptions used in the model. In addition, Bottom et al. (2005a) found that, as tidal wetlands in the Salmon River estuary, Oregon, were restored, the number of juvenile salmon reared in these habitats increased, the duration of that rearing increased, the number of adult returns of estuarine dependent life history types increased, the diversity of life history types increased dramatically, and the distribution of spawners changed. Ultimately, the resilience of the Salmon River Chinook salmon population and its ability to withstand other ecosystem stresses increased due to the restoration of its estuarine wetlands.

One of the more prominent, but least appreciated functions of tidal wetlands is nutrient cycling (Sidebar 8). This is a particularly important function of oligohaline wetlands because this part of an estuary is most enriched in inorganic particles and nutrients (Childers et al. 2000). For instance, Merrill and Cornwell (2000) found that oligohaline marshes in Chesapeake Bay trap 35% of the nitrogen and 81% of the phosphorus that would otherwise be recycled, exported, or buried in the subtidal sediments of the estuary.

Sidebar 8

Tidal Marshes and Water Quality

Many people think of the tidal marshes in Puget Sound's deltas, estuaries, and lagoons as aesthetically pleasing "seascapes" with abundant wildlife. Some even appreciate that tidal wetlands play important roles in the life histories of fish species such as juvenile salmon. However, the role of tidal marshes in the maintenance of water quality is less well understood. Because more than 55% of our tidal marshes have disappeared from the Sound, the impairment of natural water quality regulation is likely nontrivial.

Tidal wetlands help maintain high water quality by: 1) intercepting and physically filtering sediments and associated contaminants in freshwater runoff with subsequent burial in marsh sediments; 2) supporting geochemical environments in both oxygenated and non-oxygenated sediments, which promote denitrification and other chemical reactions that remove certain chemicals from the water; 3) supporting the extremely high productivity of marsh vegetation, which reduces the pool of inorganic nutrients that might drive eutrophication in the Sound through high nutrient uptake and subsequent burial in sediments; and 4) maintaining a diverse array of decomposers and decomposition processes that trap and remove organic matter from the tidal system.

It is noteworthy that many of these processes regulate water quality by trapping and sequestering sediments; not only do the marshes perform those functions, but these accretion processes enable the marsh to adjust to changes in sea level. This potentially delicate relationship with suspended sediment delivered from Puget Sound's watersheds also implies that the potential nearshore impacts resulting from climate change may depend to some degree on the extent and sustainability of its tidal marshes.

Thus, while wetlands are acknowledged to play significant factors in the global cycles of nitrogen, sulfur, methane, and carbon dioxide, these waving fields of sedges, grasses, and other herbaceous vegetation play important local roles in reducing the accumulation of organic matter and contaminants. This is particularly the case for enclosed embayments and inlets, that can be routinely inundated by a high percentage of marshlike water.

2. Changes to Puget Sound nearshore ecosystems are widespread and pervasive.

a. The shoreline has become shorter, simpler, and more artificial.

We compared the basic character of the shoreline of Puget Sound now and historically (1850-1880) by defining transitions from one shoreform type to another and by analyzing changes in the numbers and relative length of different shore types. Mapping errors and other data artifacts complicated this analysis and are discussed fully in Simenstad et al. (2011). However, when all of these issues are considered, we concluded that the relative changes (%) in shoreline length that we have reported are real.

Physical Changes. In addition to the types of structural changes (i.e., stressors) described previously (e.g., construction of bulkheads, roads, and overwater structures), the basic character of the shoreline has changed. In particular, the shoreline of Puget Sound has become shorter and simpler over the past 150 years. Over all of Puget Sound, the net decline in shoreline length has been 694 km or about 15% of the historical length of the shoreline (Table 2). While more than 1000 km of natural shoreline was eliminated (including all shoreforms), 368 km of artificial shoreline was added (by artificial, we mean manmade shoreforms such as seawalls backed by fill). Although the length of shoreline classified as artificial was negligible historically, artificial shoreline now represents about 9.5% of the shoreline of Puget Sound. All natural, geomorphic systems experienced a decline in length, with the loss of delta shoreline especially significant. Deltas experienced a 26.7% decline in shoreline length (or ~176 km of delta shoreline eliminated), which accounted for a large part of the overall simplification of Puget Sound's nearshore.

There was a strong association between fill placed in the nearshore and the artificial shoreform type, with fill occurring along 62% of the length of artificial shoreforms. We estimated that the area of fill in Puget Sound is now 39 km^2, which represents about 2% of the nearshore zone. However, this is a considerable underestimate due to limitations associated with the available datasets on fill. The South Central sub-basin and Whidbey sub-basin accounted for most of the fill in Puget Sound.

Puget Sound has experienced a 5.8% decline in the numbers of distinct, natural shoreforms. We identified 54 transitions of one natural shoreform type to another natural type and 337 natural shoreforms that were either wholly or partially converted to artificial shoreforms (Schlenger et al,. 2011); only 13 artificial shoreform segments existed historically. Of the 812 shoreline process units (SPUs) that were defined for Puget Sound, 195 have artificial shoreforms (Schlenger et al. 2011). Interpreting changes in shoreform counts is complicated by the fact that some shoreforms were not completely eliminated but were divided into smaller segments by artificial shoreforms (i.e., one bluff-backed beach became two). As a result, for some shoreform categories, especially those that can occur in large segments, shoreform counts increased.

The decline in numbers of natural shoreforms was especially significant for small, coastal embayment shoreforms (Table 2). PSNERP's analysis indicated that the number of embayment shoreforms declined from 884 to 579 (Schlenger et al. 2011). The decline in numbers of embayment shoreforms was reflected by the increase in average distance between embayment shoreforms from historical to the present. The average distance between closed marshes/estuaries increased from 18 km historically to 39 km at present, while for barrier lagoons the average distance between these shoreforms increased from 20 km historically to 28 km under current conditions. The average distance between barrier estuaries increased from 18 km to 22 km.

Implications. Although some of the changes in shoreline length and in shoreform were clearly due to natural processes such as erosion, waves, and floods, many are due to anthropogenic influences. The simplification and shortening of Puget Sound's shoreline has altered the fundamental way that nearshore ecosystems function. The way an ecosystem works depends in part upon characteristics of surrounding ecosystems and the spatial arrangement of their components, their sizes, their shape, and their location (Forman and Godron 1986; Turner 1989; Fahrig and Merriam 1994; Bell et al. 1997; Wiens 2002; Bilkovic and Roggero 2008; Partyka and Peterson 2008).

Simply by changing how Puget Sound's parts are arranged, we have changed how water and sediment moves around, where and how much sediment is deposited, and how detritus and nutrients are processed and cycled (Farina 2000; Lourie and Vincent 2004). Furthermore, we have modified the behavior and survival of species and altered the composition of plant and animal communities (Bell et al. 1997; Farina 2000; Wiens et al. 2002; Lourie and Vincent 2004). For example, many studies have shown that the configuration of wetland habitats affects fish community composition, species richness, and food web structure (Peterson and Turner 1994; West and Zedler 2000; Visintainer et al. 2006). In addition, as has been found for stream ecosystems (Frissell 1992; Reeves et al. 1993), Puget Sound ecosystems almost certainly have space threshold levels at which some ecosystem functions begin to change rapidly.

Changes to shoreline complexity and the loss of shoreline length have affected the rate, magnitude, and effectiveness of many ecosystem processes that depend upon the amount of space available. The loss of shoreline length has reduced the amount of space in Puget Sound for fish and wildlife to reproduce, feed, and grow (Dethier 2006; Coen et al. 2007). In addition, juvenile salmon, which are closely associated with nearshore ecosystems during their migration from Puget Sound, now have less space to feed, grow, and evade predators; such impacts have likely reduced their survival. Greene and Beechie (2004) and Greene et al. (2005) present evidence that we are exceeding the carrying capacity of some nearshore habitats due to habitat loss. In other words, the loss of space adversely affects density dependent processes.

The loss in shoreline length has likely impacted other habitats as well, such as eelgrass beds, although we lack historical data to quantify this change. While there have been no Sound-wide changes in eelgrass abundance since 2000, local areas in portions of Hood Canal and the San Juan Islands have experienced significant losses (J. Gaeckle, Washington Department of Natural Resources, unpublished data). Thom and Hallum (1991) estimated a 35% loss of eelgrass in Bellingham Bay and a 15% loss in the Snohomish River delta.

b. Many Places Have Experienced Multiple Types of Changes (Cumulative Impacts).

Physical Changes. Many shoreline segments have been altered, and many other segments have experienced multiple types of changes. Of the 812 shoreline segments (not including deltas) in Puget Sound, only 112 (14%) have no associated shoreline stressor (e.g., a dock, armoring, marina or fill). Sixty percent of shoreline segments have 2-4 stressors. Although none of the shoreline segments contained all nine stressors, 81% had more than one type of stressor, suggesting a high potential for cumulative impacts. As would be expected, the longest shoreline segments had the greatest number of shoreline alterations associated with them (Simenstad et al. 2011).

Of the nine shoreline stressors considered by PSNERP, armoring was clearly the dominant stressor, occurring in 78% of shoreline segments. Armoring occurred along 27% of the shoreline of Puget Sound. Other stressors often co-occurred with armoring. The two most commonly co-occurring stressors were nearshore roads and armoring, which co-occurred in 379 (46%) of process units. Seventy-two percent of active railroads and 71% of marinas also had armored shorelines.

A total of 31.3% of the length of Puget Sound's shoreline has not been modified (i.e., none of the nine shoreline stressors are found in these segments). Of the 3,969 km of shoreline in Puget Sound, 23% has one stressor associated with it, 12% has two stressors, and 6% has more than two.

Implications. It is highly likely that cumulative impacts are affecting nearshore ecosystem functions. Cumulative impacts refer to the combined, incremental effects of human activities on the environment (EPA 1999). Cumulative impacts may be synergistic, in that the overall effect is not equal to the sum of the individual impacts (Williams and Faber 2001; Peterson and Lowe 2009). While a small-scale alteration may be insignificant (and not even noticed) by itself, cumulative impacts from one or more sources often accumulate over time and space (Jordan et al. 2008; Peterson and Lowe 2009). Such changes to ecosystems are usually small-scale and can occur through persistent additions or losses of the same resources and through the compounding effects of two or more stressors (Reeves et al. 1993; May 1996). In the nearshore ecosystems of Puget Sound, cumulative effects include not only the physical changes upon which PSNERP has focused, but other impacts as well, such as changes to water and sediment quality.

tidal marsh

Synthesis

1. Problems

In aggregate, the anthropogenic changes to nearshore ecosystems documented by PSNERP have significantly degraded the integrity of Puget Sound. By integrity, we mean the soundness or wholeness of the ecosystems, processes, habitats, and biota comprising the shoreline environment. Integrity refers to the ability of the system to support and maintain a balanced, integrated, and adaptive biological community that has a species composition, diversity, and functional organization comparable to that of natural ecosystems in the region (Reynolds 1995; DeLeo and Levin 1997; Karr 2000). PSNERP's analysis has shown that new shoreforms (i.e., artificial) have been created, the shoreline has been shortened, distances between components of the nearshore altered, and various types of unnatural structures added to the landscape. Many places have been changed in multiple ways, and there is considerable variability in the types of changes that have occurred at different spatial scales.

An especially significant change to nearshore ecosystems has been the severe disruption in the connectivity of the landscape (Sidebar 9). Within large systems, the degree of

Sidebar 9

Connectivity and Complexity: Shorter, Straighter, and Less Diverse

As you paddle along the shoreline of Puget Sound, you will notice a variety of beaches, inlets, and stream mouths that are both large and small, bluffs covered in trees, eroding slopes, homes, docks, and even a few highways and railroads. At times, you may paddle for miles and observe very little change, while at other points in your journey you may constantly encounter a shoreline that is new and different, or perhaps even unique. In the past, the native people of Puget Sound, the fish, birds, and other wildlife, all depended upon a shoreline that offered a great diversity in its length, arrangement, and composition. Natural processes, such as those that move sediment along the beach or small inlets that provide a refuge for migrating fish and birds, played important roles in the ecology of the Puget Sound ecosystem. The historical shoreline, and the animals and people who lived here, evolved into a rich and complex connection of a system of what we call shoreforms.

Shoreline connectivity, or the ability for ecological functions to interact among sections of shoreline, determines in part how Puget Sound functions. Fragmenting the shoreline (disrupting its natural connectivity) directly alters how Puget Sound functions. This connectivity depends upon how frequently and where different shoreforms occur. A functioning shoreline requires a certain arrangement of its parts and a certain amount of complexity and variety. Puget Sound has become shorter, because of human actions that have removed many of its features, and it has become straighter, because we have replaced some complex and unusual shorelines with dikes and levees to protect valued lands. Our shoreline has become less diverse in the number and types of connected shoreline segments, because we have developed marinas and other features that break natural connections. Restoring connectivity and complexity along the shoreline ensures that our beaches and river deltas (and the organisms that depend upon them) will continue to enjoy the benefits of natural processes.

connectivity between components of an ecosystem and between different ecosystem types is critical to how they function (Turner 1989; Meyer 1997; Williams and Faber 2001; Bilkovic and Roggero 2008). Connectivity is especially critical in coastal systems where material, energy, and biota are constantly moving and being exchanged among ecosystems and their components (Meyer 1997).

The impacts on ecosystem connectivity are especially important for nearshore ecosystems, which are a unique type of ecotone and occupy an especially strategic part of the landscape. Ecotones are transitional areas between adjacent systems (Naiman and Descamps 1990) and have characteristics of the ecosystems to which they are connected. They are especially vulnerable to human impacts because their properties, dynamics, and functions depend upon the linkages to surrounding ecosystems (MEA 2005) and the integrity of the flow of energy, material, and organisms across them. Ecotones are significant for mobile animals such as salmon, which can exploit more than one set of habitats within a short distance.

We found that fragmentation was occurring at multiple scales in nearshore ecosystems, including between and within sub-regions and between and within shoreline segments. It has a variety of effects on the structure and function of a system, particularly for fish and wildlife species that move among different habitats. It can decrease the amount of habitat that is available, affect the proportions of different kinds of habitat such as edge and interior, and isolate some habitats (Dramstad et al. 1996; Bennett 1999; Farina 2000). Ultimately, fragmentation breaks up habitats into smaller units that are more isolated (Noss et al. 1997; Bennett 1999). The long and narrow structure of the shoreline makes it particularly easy for human development to fragment it and disrupt its functions. Fragmentation alters the behavior of species, affecting how they migrate through the landscape; reduces biodiversity; and alters the assemblage structure of organisms (Bennett 1999; Farina 2000; Valentine-Rose et al. 2007). Fragmentation is widely regarded as one of the major problems resulting from human development of ecosystems (Fahrig and Merriam 1994; Farina 2000). A number of states, including Washington and California, have specific management plans to deal with ecosystem fragmentation because of the damages it causes (e.g., Washington State Department of Transportation, Executive Order 1031.00).

Fragmentation affects the connectivity between nearshore ecosystems and other systems within Puget Sound, such as with terrestrial ecosystems. While the focus of our work has been on Puget Sound's nearshore systems, many of Puget Sound's natural goods and services depend upon connectivity and processes occurring at scales larger than the nearshore. The implications of lost connectivity among the diverse ecosystems in the Puget Sound Basin (land, freshwater, and marine waters) can be seen in the decline of many species that use multiple ecosystem types (e.g., salmon, which depend upon freshwater, nearshore, and marine systems).

Highly fragmented ecosystems are less resilient than those that are not as fragmented. Resilience refers to the amount of disturbance an ecosystem can accommodate without shifting to a fundamentally different state (Walker et al. 2004). A less resilient ecosystem will be increasingly vulnerable to additional change or stress and can undergo dramatic shifts in state resulting in reduced productivity and diversity (Farina 2000; MEA 2005). Future stresses on nearshore ecosystems will occur from the same types of actions that we have documented here (e.g., addition of armoring, increase in artificial shoreforms), which will occur as the human population increases. For example, shoreline armoring approximately doubled in Thurston County (currently the most rapidly growing county in the Puget Sound region) between 1977 and 1993 (Morrison et al. 1993). Future projections are that the Puget Sound region will have 2.5 million more people by the year 2060, which will increase human pressures on nearshore ecosystems. Nearshore ecosystems are especially vulnerable to human changes because these places are the focus of many human uses that often conflict with the natural system.

In addition, because nearshore ecosystems are now less resilient, they will be increasingly at risk to effects of climate change (Travis 2003) (Sidebar 10). One effect of climate change is acceleration in the rate of sea level rise. Even a small rise in sea level can potentially change the location of many ecosystem components. For example, the upper extent of tidal influences in estuarine deltas could move upstream of their current locations and potentially create new estuarine wetlands. Deltas and wetlands will be especially vulnerable to sea level rise. If the rate of change is too fast, then plant systems and sediment processes may not be able to keep pace. In addition, along modified shorelines, sea level rise will result in "coastal squeeze" along modified shorelines, when habitats and processes cannot move landward because of armoring or other human structures, causing nearshore habitats to narrow or disappear. This will result in fewer habitats for some animals such as shorebirds (Galbraith et al. 2002).

Many parts of Puget Sound's nearshore have experienced multiple types of changes or cumulative impacts (Peterson and Lowe 2009). In some cases, it is a challenge to separate or disentangle the cumulative effects of individual changes (e.g., docks and roads) documented by PSNERP from their aggregate effect, as well as from other stressors such as contaminants that we did not consider. For example, studies of the effects of urbanization typically look at the overall effect of development. Matzen and Berge (2008) studied Puget Sound lowland streams and found that stream biotic integrity rapidly declined as the extent of overall urbanization increased. Rice (2007) found a relationship between urban land cover within 2 km of the shoreline of Puget Sound and abundances of marine birds and waterfowl. Opportunistic and tolerant taxa (e.g., gulls and cormorants) were found more frequently, coinciding with a decline in the percent

Sidebar 10

Climate Change and Nearshore Ecosystems

Climate change is nothing new for Puget Sound. As the glaciers receded last from the Sound some 10,000-12,000 years ago, sea level fluctuated as a function of global (eustatic) changes in sea level and more regional differences in prior glaciation history and tectonism. After much of the Earth's water was locked up in huge continental ice sheets during millennia of planetary coldness, the relative position of sea level varied across the emerging Puget Sound, falling over 100 m where isostatic rebound exceeded global sea level rise, or rising up to 200 m in regions where the effects of glacial ice were minimal.

The glaciers left behind the sand and gravel that comprises much of the region's surficial geology. As water level stabilized some 5000 yr ago, waves have slowly eroded the gravelly bluffs, delivering the material that has built today's Puget Sound beaches. Waves and longshore currents worked and reworked this material into a complex series of barrier beaches, inlets, and other shoreforms. As the water continued to rise, new sand and gravel was delivered to build and maintain the beaches, keeping pace with slowly rising sea levels.

At the mouths of Puget Sound rivers, a similar process was occurring. Alluvial sediments brought down from higher elevations in the watershed helped create vast river deltas. In conjunction with these suspended sediments, which settled out at high tides, salt marsh plants and other vegetation grew rapidly in this fertile soil and built the estuary marshes higher, also responding to a changing sea level. The head ends of the narrow fjords carved by the glaciers filled with watershed and beach sediments, further enriching the diversity of Puget Sound's shorelines.

However, due to the effects of climate change, we now risk losing many of the beaches, wetlands, fish, wildlife, and plants that help make Puget Sound unique. Our concern is not climate change per se, but rather the accelerated rate of climate change due to anthropogenic sources of greenhouse gases. The natural processes of sediment delivery, transport, accretion, and erosion have helped to maintain a dynamic equilibrium between sea level and shoreline for millennia. Left unaltered by humans, this equilibrium would likely persist, and these natural processes might even buffer our shorelines and estuaries from accelerated sea level rise. While this is a question we cannot answer, we know that, over the past 150 years of human development of the region, we have jeopardized this balance. Shoreline armoring slows or even halts the sediment delivery process that sustains beaches. Dikes and river levees deprive marshes of sediments and limit the slow landward movement necessary to keep salt marshes from drowning. In short, the natural ecosystem processes that help make our shorelines naturally resilient to the effects of sea level changes have been halted or interrupted, putting Puget Sound's nearshore ecosystems and their associated goods and services at increasing risk.

frequency of wading and shallow bottom feeding birds such as dabbling ducks, herons, and various shorebirds. Percent frequency of diving ducks along the shore declined as the amount of developed land increased.

In general, we found that the most urban areas suffered the most changes to nearshore ecosystems. For example, the most pronounced watershed impacts occurred in the South Central Puget Sound; compared to other sub-basins, this sub-basin had the greatest amount of developed land, roads, and impervious surface. The watersheds of this sub-basin had large numbers of dams, stream crossings, and fish passage barriers. Only 1% of the shoreline segments in this sub-basin had not been modified. In contrast, the highest proportion of shoreline segments with no impairment (17%) occurred in the San Juan Islands-Strait of Georgia sub-basin followed by South Puget Sound. The greatest loss of shoreforms occurred in the North Central, South Central, and South Puget Sound sub-basins while the fewest losses occurred in the Strait of Juan de Fuca sub-basin.

We conclude that the types, scope, and magnitude of physical changes to nearshore ecosystems that we have identified have affected the ability of nearshore ecosystems to deliver certain valued goods and services. In particular, the ability of nearshore ecosystems to help support the rich flora and fauna of Puget Sound has declined, to the detriment of Puget Sound's economy, society, and culture. Hundreds of plant and animal species depend upon nearshore ecosystems for all or parts of their life cycles; many species that occur in nearshore ecosystems are found in no other place in Puget Sound. Eelgrass in this region only grows within nearshore ecosystems; Olympia oysters require intertidal habitats; and overwintering shorebirds must feed on estuarine sand and mud flats in order to be able to fly to breeding grounds. Of the eight Puget Sound fish species listed as threatened or endangered by the federal government as of 2010, five inhabit nearshore ecosystems and all are recreationally or commercially harvested.

2. Solutions

The nature and characteristics of the changes to nearshore ecosystems, — although relatively small — demand attention, because even small changes can alter ecosystem functions, and dramatic changes can occur once threshold levels are crossed, as suggested by studies in other ecosystem types. For example, in the James River, Virginia, Bilkovic and Roggero (2008) found that when land development exceeded a level of 23%, the integrity of nekton assemblages was reduced within a 200-1,000 m buffer. In a study of small streams within the Puget Sound Lowlands, May (1996) found that once the amount of impervious surface in a watershed exceeded 10%, ecosystem impacts rapidly increased. In coniferous forest ecosystems of the Pacific Northwest, Reeves et al. (1993) found that when timber harvest levels exceed 25%, impacts to salmonid fishes became dramatically more severe. Similarly, Coats and Miller (1981) found that substantial sedimentation impacts in streams occurred above a timber harvest level of 30%.

It is clear that recovery of Puget Sound's nearshore ecosystems will require actions directed at many places and many types of problems (cumulative impacts). In particular, restoration strategies must recognize the considerable spatial variability in the changes occurring to nearshore ecosystems because scale is an important part of defining conservation strategies (Mangel et al. 1996: Wiens et al. 2002). Impacts vary at the scale of individual shoreline segments, within shoreline categories, and across Puget Sound at the scale of sub-basins. Variability in historical change between subregions was substantial and will require restoration and protection solutions that are tailored to each sub-basin.

The fragmentation that is occurring among nearshore ecosystems, and between nearshore ecosystems and other systems within Puget Sound (such as between the nearshore and terrestrial ecosystem), is an important consideration in protection and restoration strategies. For example, as organisms' habitats become smaller, their conservation value diminishes, and they become less effective as species and biodiversity refuges. Fragmentation has reduced our options for protecting high quality, natural places, since so many places have been altered or are adjacent to those that have been altered.

It is important to recognize that the recovery of many of Puget Sound's functions, goods, and services will require restoration of ecosystems other than those in the nearshore, including terrestrial and riverine ecosystems. While restoring nearshore ecosystems is a necessary part of the recovery of Puget Sound, it must fit within the context of a broad plan that addresses the full suite of problems that face this system.

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