Encylopedia *of* PUGET SOUND

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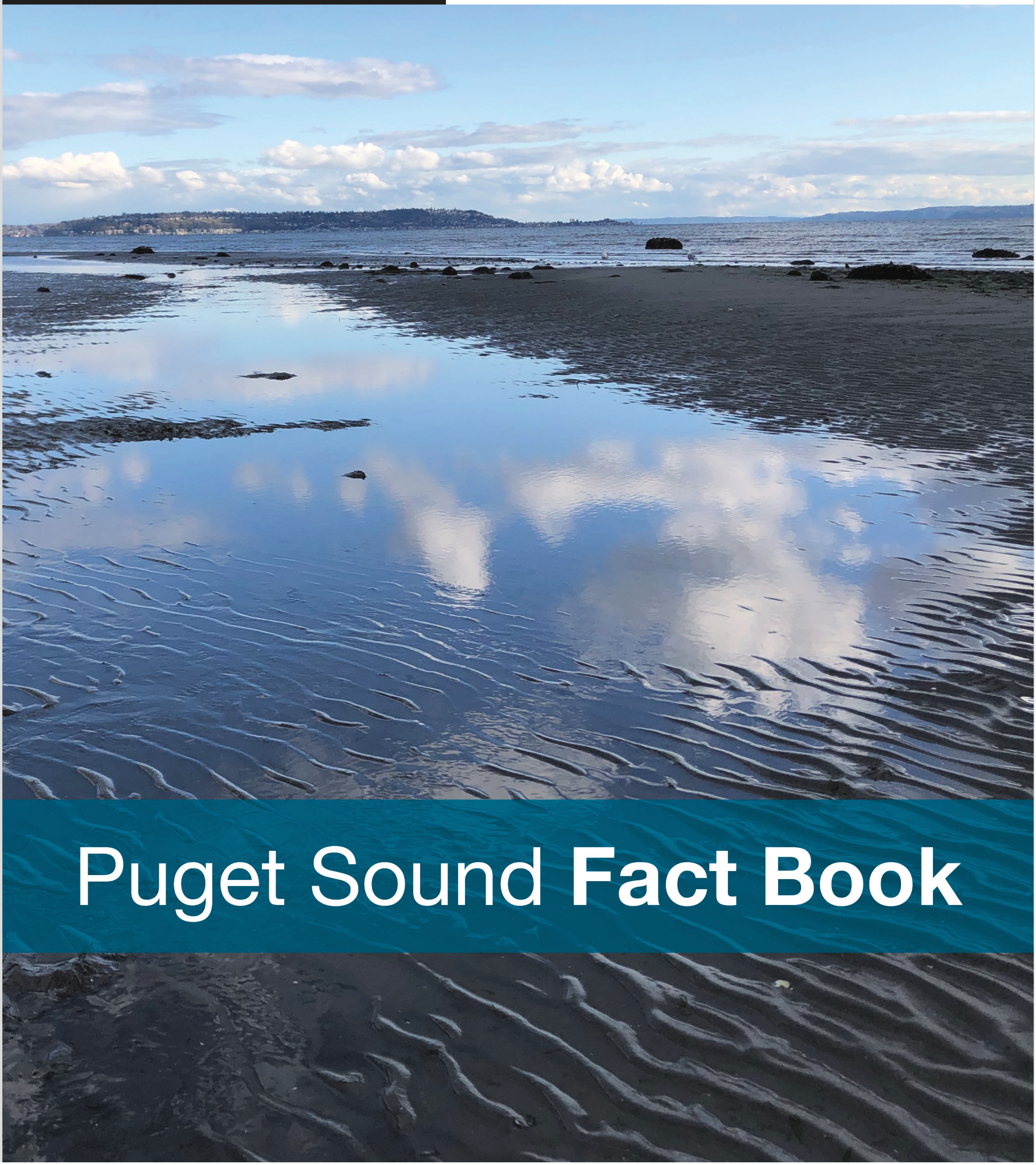

Puget Sound **Fact Book**

About the Puget Sound Institute

Established in 2010, the Puget Sound Institute is a network of leading scientists and policy makers based at the University of Washington and supported by the U.S. Environmental Protection Agency and the Puget Sound Partnership. PSI catalyzes rigorous, transparent analysis, synthesis, discussion and dissemination of science in support of the restoration and protection of the Puget Sound ecosystem.

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This project has been funded wholly or in part by the United States Environmental Protection Agency under Assistance Agreement #CE-00J63701. The contents of this document do not necessarily reflect the views and policies of the Environmental Protection Agency, nor does mention of trade names or commercial products constitute endorsement or recommendation for use.

Puget Sound Fact Book
Version 4.0
Published January 11, 2022
First Printing 2015
Puget Sound Institute
University of Washington Tacoma

Cover: Tacoma Narrows Bridges from Titlow Beach by Kris Symer. Map of the Salish Sea by Stefan Freelan, WWU.

Preface

The naturalist Rachel Carson wrote, “The more clearly we can focus our attention on the wonders and realities of the universe about us, the less taste we shall have for destruction (Carson & Lear, 1998).” This is a collection of some of those “wonders and realities.”

In these pages you will find a mixture of essays and well-documented facts related to key subjects and topics relevant to the Puget Sound and greater Salish Sea ecosystems. Where possible, facts have been brought together to correspond with state recovery priorities identified in the Puget Sound Action Agenda and the Puget Sound Partnership’s Vital Signs.

These facts provide vital statistics: the “who, what, when and where.” But the goal here is to provide a foundation for Puget Sound’s story. Figures like population growth, numbers of endangered species or even the depth of Puget Sound are all plot points that help us understand how the ecosystem connects. Other facts, like the stunningly long life of a rockfish—they can live to be 205 years old—or the weight of a giant Pacific octopus—the largest ever recorded was said to be close to 600 pounds—might fall into Rachel Carson’s “wonders” category.

At the same time, too much information can be overwhelming. Volumes upon volumes have been written about the makeup and health of the Puget Sound ecosystem, but few of us have the time to read them all. While no collection of this type can ever be considered ‘complete,’ our goal is to identify the most important, policy-relevant information. We asked close to two-dozen Puget Sound-based scientists and writers a simple, but challenging question: What do we really need to know about Puget Sound recovery? Their responses follow.

We would like to thank the editorial board of the Encyclopedia of Puget Sound for its guidance throughout this process, as well as the Puget Sound Partnership and the Environmental Protection Agency for providing funding for this document. Future updates to this material will be made available on the Encyclopedia of Puget Sound at www.eopugetsound.org.

References

Carson, R., & Lear, L. J. (1998). Lost woods: the discovered writing of Rachel Carson. Boston, Mass: Beacon Press.

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Introduction

Geographic boundaries

Puget Sound

There are several ways that scientists and managers have defined the boundaries of Puget Sound. To oceanographers, Puget Sound includes the waters from Admiralty Inlet and Deception Pass to the southern tip of Olympia (Ebbesmeyer et al., 1988).

However, many management and conservation efforts incorporate the entire watershed—the land where rivers and streams drain into Puget Sound—as well as the Strait of Juan de Fuca, Hood Canal and the San Juan Archipelago. Accordingly, "Puget Sound" is defined by the Washington State Legislature as:

> *"Puget Sound and related inland marine waters, including all salt waters of the state of Washington inside the international boundary line between Washington and British Columbia, and lying east of the junction of the Pacific Ocean and the Strait of Juan de Fuca, and the rivers and streams draining to Puget Sound as mapped by water resource inventory areas 1 through 19 in WAC 173-500-040 as it exists on July 1, 2007"* (RCW 90.71.010: Definitions, n.d.).

Because of these varying definitions, we identify specific boundaries where relevant.

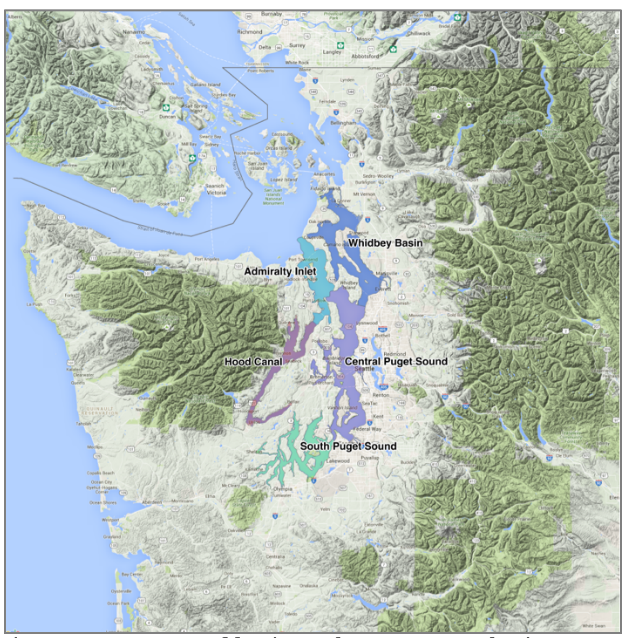

Figure 1. Puget Sound basins. The oceanographer's definition of Puget Sound is limited to the following marine basins: Hood Canal, Main Basin (Admiralty Inlet and the Central Basin), South Basin, and Whidbey Basin. Map: Kris Symer. Data source: WDFW.

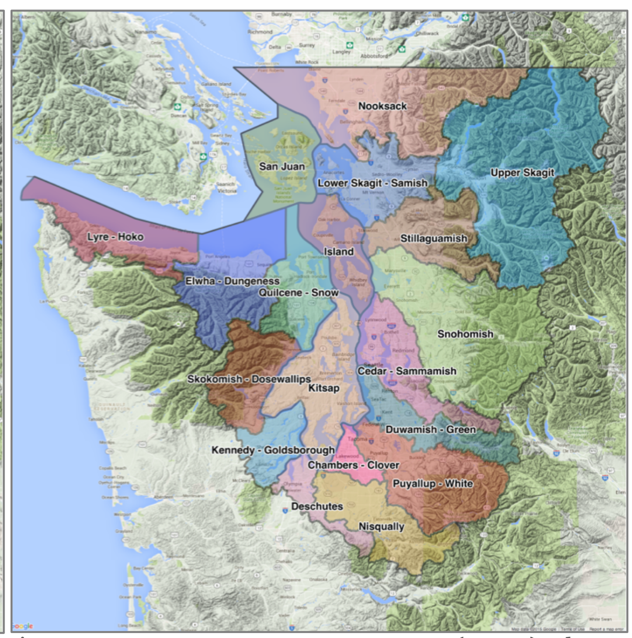

Figure 2. Water Resource Inventory Areas (WRIA). The Washington State Legislature defines Puget Sound as WRIA 1-19. These areas were first developed in 1970 and updated most recently in 2000. Map: Kris Symer. Data source: WAECY.

Salish Sea

The Salish Sea extends across the U.S.-Canada border, and includes the combined waters of the Strait of Georgia, the Strait of Juan de Fuca, Puget Sound and the San Juan Islands. The name Salish Sea was proposed in 1989 to reflect the entire cross-border ecosystem. Both Washington State and British Columbia voted to officially recognize the name in late 2009. The name honors the Coast Salish people, who were the first to live in the region (Salish Sea: Naming, n.d.).

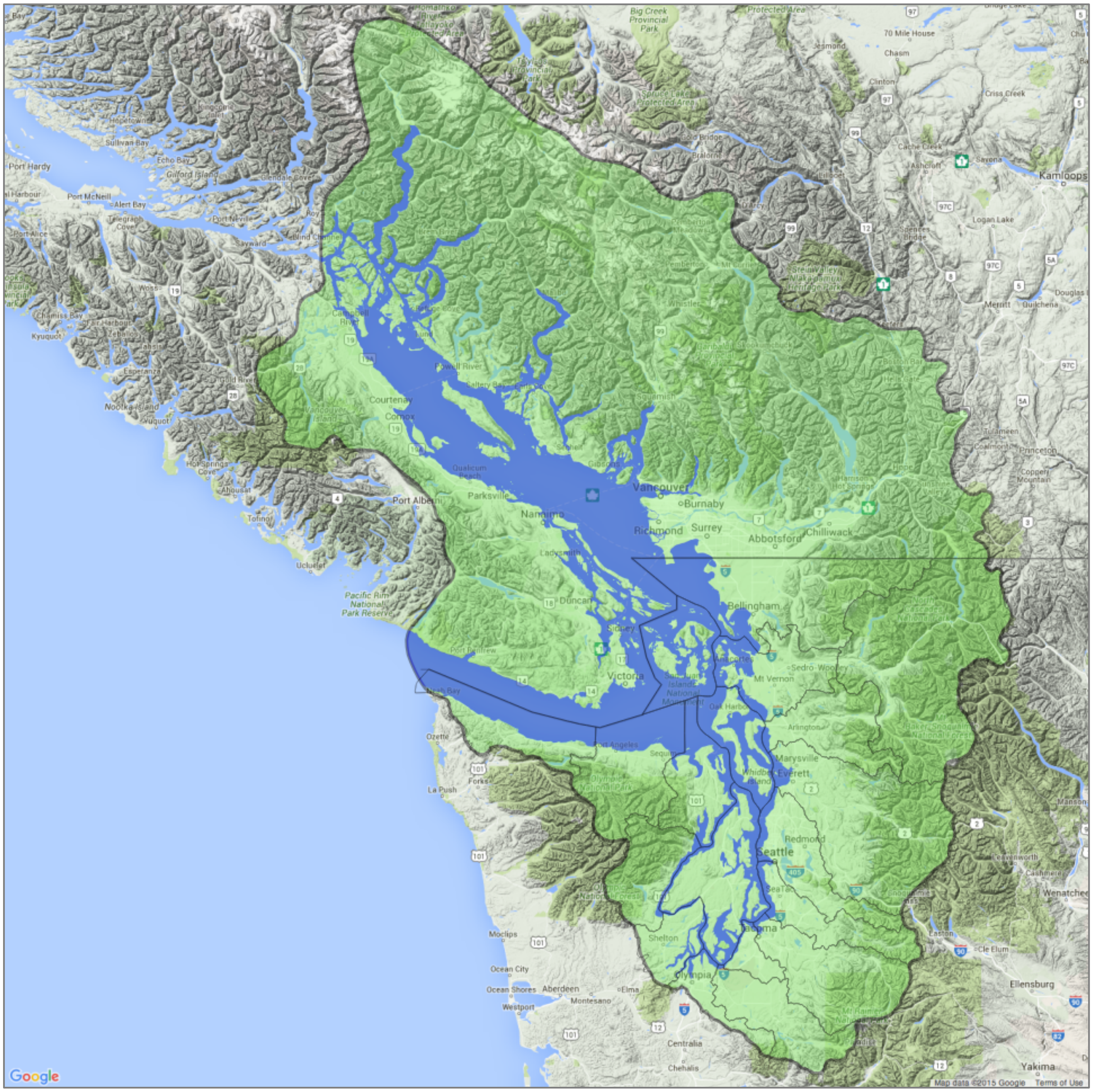

Figure 3. Salish Sea basin and water boundaries. The Salish Sea water boundary (blue) includes the Strait of Georgia, Desolation Sound, The Strait of Juan de Fuca, and Puget Sound. The larger watershed basin (green) is the area that drains into Salish Sea waters. WRIA boundary lines are shown for reference. Map: Kris Symer. Data: Stefan Freelan; WAECY.

See Appendix for additional maps and spatial data.

References

Ebbesmeyer, C. C., J. Q. Word, and C. A. Barnes (1988): Puget Sound: a fjord system homogenized with water recycled over sills by tidal mixing. Hydrodynamics of Estuaries: II Estuarine Case Studies, B. Kjerfve, Ed., CRC Press, 17-30.

Freelan, S. (2009). Salish Sea basin and water boundaries. Retrieved October 1, 2015, from https://erma.noaa.gov/northwest/erma.html#/x=-123.30659&y=49.05603&z=7&layers=3+7654+7499

Washington Department of Fish and Wildlife. Puget Sound Basins (WDFW). ERMA northwest. Retrieved September 30, 2015, from https://erma.noaa.gov/northwest/erma.html#/x=-123.44039&y=48.39419&z=8&layers=16+7531

RCW 90.71.010: Definitions. (n.d.). Retrieved August 31, 2015, from http://apps.leg.wa.gov/rcw/default.aspx?cite=90.71.010

Salish Sea: Naming. (n.d.). Retrieved August 31, 2015, from http://www.wwu.edu/salishsea/history.shtml

Washington State Department of Ecology. WAECY - Water Resource Inventory Areas (WRIA). Washington State Open Data Bridge. Filter: Puget Sound WRIA 1-19. Retrieved September 29, 2015, from http://geo.wa.gov/datasets/d3071915e69e45a3be63965f2305eeaa_0?orderByFields=WRIA_NR+ASC&where=WRIA_NR+%3E%3D+1+AND+WRIA_NR+%3C%3D+19&filterByExtent=true&geometry=-125.749%2C44.343%2C-118.96%2C48.712&mapSize=map-maximize

Overview: Puget Sound as an estuary

Essay by: Christopher Dunagan

Today, we understand that estuaries—where freshwater and saltwater merge—are among the most productive places for life to exist.

Sailing into Puget Sound in the spring of 1792, Capt. George Vancouver and his crew explored the nooks and crannies of an uncharted inland sea, recording the location of quiet bays, turbulent passages and all manner of rugged shoreline.

Two centuries later, cartographers still marvel at the precision of those first maps of Puget Sound—one of the largest and most productive estuaries in the United States.

Archibald Menzies, assigned to study the plants and animals discovered on the voyage, classified hundreds of “new” species, personally naming many of them. Menzies relished the variety of plants he found, while the ship’s crew feasted on native oysters, crabs, salmon, trout and a new species of flounder.

Long before Vancouver’s voyage, Native American culture embraced the bountiful flora and fauna of the region. Local tribes knew where to hunt, fish and gather plants—and they had their own names for places and things.

It would be nearly a century, however, before early ecologists began to understand that the variety of living things described so carefully by Menzies was a direct consequence of the physical associations among land, water and climate.

Today, we understand that estuaries—where freshwater and saltwater merge—are among the most productive places for life to exist. Plant and animal communities thrive in these protected areas of brackish water, where freshwater flowing from the land combines with seawater coming from the ocean. In all, an estimated 2,800 streams— from large rivers to small creeks— flow into Puget Sound.

Because salinity is a continuum from the freshwater rivers to the briny ocean, estuaries are not defined by size. River deltas are considered estuaries, as are the larger bays, inlets and sloughs. More broadly, Puget Sound is itself an estuary.

Complex food webs have evolved from the unique conditions found near the mouths of Puget Sound’s rivers. Sediments dislodged from upstream areas and from shoreline bluffs provide the substrate for plants, which flourish in the nutrients and sunlight of the shallow waters.

Geology, water depth, wave action, tides and river currents all influence the unique character of an estuary, including whether the bottom is rocky, sandy or muddy. Conditions hostile to some plants and animals are perfectly suited to others.

Young salmon migrating from rivers to the ocean linger in the estuaries, proceeding slowly as their bodies adjust to the salty water that would kill many freshwater fish. On their return to the river, spawning adult salmon reverse that acclimation process. In this way, salmon and steelhead take advantage of the most beneficial conditions in both streams and ocean.

Estuary formation

Puget Sound, as we know it today, owes much of its size and shape to massive ice sheets that periodically advanced from the north, gouging out deep grooves in the landscape. The most recent glacier advance, about 15,000 years ago, reached its fingers beyond Olympia. The ice sheet, known as the Vashon glacier, was more than a half-mile thick in Central Puget Sound and nearly a mile thick at the Canadian border.

As the glacier melted, freshwater filled in the holes, creating many lakes, including Lake Washington and portions of Puget Sound that later became inundated with seawater.

Puget Sound is actually four deep basins, three of which are separated by prominent “sills,” or rises in the seabed. These sills play a major role in the circulation of water in Puget Sound, impeding the waterway’s ability to flush out pollution and restore healthy oxygen levels. One sill at Admiralty Inlet reduces the flow of seawater from the Strait of Juan de Fuca into the Main Basin of Puget Sound. Other major sills provide partial barriers between the Main Basin and the basins of northern Hood Canal and the southern Sound at the Tacoma Narrows. (The Whidbey Basin has no sill at its entrance.)

Estuaries carved by glaciers, such as Puget Sound, are known as fjord estuaries. They are prominent in areas where the glaciers once loomed, including Alaska and Scandanavia in the Northern Hemisphere and Chile and New Zealand in the Southern hemisphere.

More common types of estuaries, called coastal plain estuaries, were formed when a rising sea level flooded a major river valley. Coastal plain estuaries, including Chesapeake Bay on the East Coast and Coos Estuary in Oregon, tend to be shallower with less physical diversity than fjord estuaries.

Chesapeake Bay, which filled the immense valley of an ancient Susquehanna River, covers about 4,480 square miles—more than four times the area of Puget Sound (not including waters north of Whidbey Island). But Chesapeake Bay is shallow, averaging just 21 feet deep. In comparison, Puget Sound averages 205 feet deep, with the deepest spot near Point Jefferson in Kitsap County at more than 900 feet.

Consequently, Puget Sound can hold a more massive volume of water—some 40 cubic miles, well beyond Chesapeake Bay’s volume of 18 cubic miles.

Another type of estuary is formed by tectonic activity, exemplified by San Francisco Bay, where the ground sank over time as a result of pressure at the junction of the San Andreas and Hayward faults. San Francisco Bay averages 25 feet deep with a maximum depth of 100 feet.

A fourth type of estuary, the bar-built estuary, is characterized by offshore sandbars or barrier islands built up from river deposits. The Outer Banks off the coast of North Carolina helps contain water flowing in from several major rivers to form Albemarle Sound and the adjacent Pamlico Sound, both shallow waterways.

The human factor

Puget Sound's complex estuarine character is also part of what makes it fragile. Close ties with the land mean that it has had a long and, over the past 100 years, increasingly fraught relationship with humans. Conditions in Puget Sound have changed greatly since Capt. George Vancouver explored the inland waterway, reporting back to England that the area was suitable for settlement. Even the name "Puget Sound" has changed its meaning.

When Vancouver's ship Discovery stopped at the south end of Bainbridge Island in May 1792, Vancouver sent Lt. Peter Puget and a crew in two small boats to explore every branching inlet to the south.

In 10 days, the work was done and the carefully prepared charts were handed over to Vancouver, who later declared, "by our joint efforts, we had completely explored every turning of this extensive inlet." He added, "To commemorate Mr. Puget's exertions, the south extremity of it I named 'Puget's Sound.'"

Because of this, the original Puget Sound covered just the waterway south of the Tacoma Narrows to Olympia. Later, after the name came into wider usage, the U.S. Board on Geographical Names placed the boundary of Puget Sound just inside the Strait of Juan de Fuca.

Puget Sound is also recognized as part of the Salish Sea, a vast interconnected estuary that stretches out 6,535 miles and

Water circulation

Water circulation—the net result of tides, winds and streamflows—varies from place to place in Puget Sound, playing a direct role in habitat formation and productivity.

Freshwater, being less dense than seawater, tends to float in a surface layer that generally moves toward the ocean. Meanwhile, a deep layer of heavy seawater from the ocean pushes into Puget Sound along the bottom. Both layers ebb and flood with the vigorous tides that drive Puget Sound water movements. Strong winds and underwater formations, including the sills at Admiralty Inlet and Tacoma Narrows, interact with the tides to facilitate mixing between the layers, making nutrients available for phytoplankton.

includes the Strait of Georgia in British Columbia, Canada. In 2009, the name "Salish Sea" was officially recognized by the U.S. and Canadian governments.

When creating the Puget Sound Partnership in 2007, the Washington Legislature changed the boundaries of Puget Sound again while declaring, "Puget Sound is in serious decline, and Hood Canal is in a serious crisis." The law created action areas, defining Puget Sound as all of the inland waterway south of the Canadian border, including the Strait of Juan de Fuca, Hood Canal and the San Juan Islands.

The law creating the Partnership identified many of Puget Sound's problems, including loss of habitats and native species, increases in nuisance species, contaminated sites, urbanization and stormwater pollution, closures of shellfish beaches and low-oxygen conditions.

"If left unchecked, these conditions will worsen," the Legislature declared, setting up the governing body that coordinates today's efforts to restore the health of Puget Sound.

Bibliography

Brennan, J. (2007). *Marine Riparian Vegetation Communities of Puget Sound*. Puget Sound Nearshore Partnership Report No. 2007-02. Seattle: U.S. Army Corps of Engineers.

Chesapeake Bay Program. (n.d.). *Facts and Figures*. Retrieved June 14, 2015, from Discover the Chesapeake: http://www.chesapeakebay.net/discover/bay101/facts.

Clayton, D. (1999). *Islands of Truth: The Imperial Fashioning of Vancouver Island*. Vancouver, British Columbia: UBC Press.

Cohen, A. (2000). *An Introduction to the San Francisco Bay Estuary*. Save the Bay, San Francisco Estuary Project, San Francisco Estuary Institute.

Collins, B. D. & A. J. Sheikh (2005). *Historical reconstruction, classification and change analysis of Puget Sound tidal marshes*. Olympia, Washington: Washington State Department of Natural Resources.

Dolan, R. H. & H. Lins (2000). *The Outer Banks of North Carolina*. U.S. Department of the Interior, U.S. Geological Survey. Reston, Virginia: Library of Congress.

Emmett, Robert, et. al. (2000). *Geographic Signatures of North American West Coast Estuaries*. Estuaries , 23 (6), 765-792.

Finlayson, D. (2006). *The Geomorphology of Puget Sound Beaches*. Seattle, Washington: Washington Sea Grant, University of Washington.

Fresh K., et. al. (2011). *Implications of Observed Anthropogenic Changes to the Nearshore Ecosystems in Puget Sound* (Technical Report 2011-03.). Prepared for the Puget Sound Nearshore Ecosystem Restoration Project.

Fresh K. (2006). *Juvenile Pacific Salmon in Puget Sound*. Puget Sound Nearshore Partnership. Seattle: U.S. Army Corps of Engineers.

Gaydos, Joseph & Scott Pearson (2011). Birds and Mammals that Depend on the Salish Sea: A Compilation. *Northwest Naturalist , 92*, 79-94.

Meany, E. S. (1942). *Vancouver's Discovery of Puget Sound*. New York: The Macmillan Company.

Menzies, A. (1923). *Menzies' Journal of Vancouver's Voyage*. (C. Newcombe, Ed.) Victoria, British Columbia: New York Botanical Gardens.

National Marine Fisheries Service, Shared Strategy Development Committee. (2007). *Puget Sound Salmon Recovery Plan*. National Oceanic and Atmospheric Administration, Department of Commerce, Seattle.

Ruckelshaus, M., & Michelle McClure, c. (2007). *Sound Science: Synthesizing ecological and socioeconomic information about the Puget Sound ecosystem*. Seattle, Washington: U.S. Dept. of Commerce, National Oceanic & Atmospheric Administration (NMFS), Northwest Fisheries Science Center.

Simenstad, C. M. (2011). *Historical Change and Impairment of Puget Sound Shorelines*. Olympia, Washington: Washington Department of Fish and Wildlife and U.S. Army Corps of Engineers.

Physical environment

Section author: Parker MacCready, University of Washington School of Oceanography

Summary

Oceanographers define Puget Sound as the region of marine and brackish waters extending landward from Admiralty Inlet.[1] It is part of the Salish Sea, a larger system of inland marine waters that includes the Strait of Georgia and the Strait of Juan de Fuca. The deep and complex troughs that make up Puget Sound were carved by glaciers, most recently about 10,000 years ago. The Sound has remarkable patterns of water circulation that support its thriving ecosystem, and which give rise to water quality problems such as hypoxia. The circulation patterns are a consequence of the shape of the Sound and the interaction of tides and rivers.

Puget Sound is about 161 km in length, going from Admiralty Inlet to Olympia. Long Island Sound, also carved by glaciers, is similar to Puget Sound at 182 km. Because of their glacial origins these systems are sometimes called fjords and have much in common with other high latitude estuaries in both hemispheres. At lower latitudes the most common estuarine type is a drowned river valley, meaning that the estuarine channel was originally a river valley that has since been filled in by the ocean as sea level has risen about 120 m since the Last Glacial Maximum. We refer here to all such systems as estuaries, loosely defined as any bay or channel off of the ocean that is influenced by rivers and tides.[2]

Chesapeake Bay, the largest estuary on the East Coast, is an example of a drowned river valley. The Chesapeake is about 322 km long, and San Francisco Bay, a West Coast drowned river valley is 97 km long. The length of an estuarine channel can be a region where ocean and river water mix, creating a gradual salinity variation to which the biology must adapt.

Coastline

The coastline around Puget Sound is 2,143 km (1,332 miles) long. It would take about 18 unceasing days and nights to walk the entire shoreline if it were passable—or legal—everywhere. Note: this distance refers to Puget Sound proper and does not include the San Juan Islands or the Strait of Juan de Fuca.

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[1] The facts in this section refer to this definition of Puget Sound, not the Puget Sound watershed or region as defined by Water Resource Inventory Areas. See the Geographic Boundaries section of the Fact Book for more information.

[2] Data regarding the shape, area, and depth of Puget Sound are nicely summarized in Ebbesmeyer et al. (1988), relying in part on McLellan (1954). The author confirmed many of the numbers using more modern bathymetry from Finlayson (2005).

Depth

Because of its glacial origins the Sound is deep, averaging 70 m, compared to an average of just 6 m for the shallow, muddy Chesapeake. The deepest spot in the Sound, offshore of Point Jefferson in Main Basin, is 286 m. If the tallest building in Seattle, the Columbia Center, had been built on this spot just 1 m would be visible above the water's surface at low tide. Puget Sound is deep by estuarine standards, but if we look north into the Strait of Georgia we can find waters up to 650 m.

Surface area

The surface area of the Sound is about 2,632 km^2, although this number varies a bit depending on whether the tide is high or low. If every resident of Seattle was in their own boat on the Sound, and the boats were spread out evenly, there would be about 60 m between each of them.

Volume

The volume of water in Puget Sound is about 168 km^3. This is substantially larger than the Chesapeake Bay and Long Island Sound, which both have a volume of about 68 km^3. By this measure it could be argued that Puget Sound is the largest estuary in the continental United States, but of course the whole Salish Sea is much bigger, and the separation of its parts is more a matter of national boundaries than ecosystem function.

Rivers

The annual average river flow into the Sound is about 1,174 $m^3 s^{-1}$, and a third to a half of this comes from the Skagit River flowing into Whidbey Basin. It would take about 5 years for all the rivers flowing into the Sound to fill up its volume, which suggests, correctly, that rivers alone do not play a dominant role in circulating water through the Sound. This is also apparent in the salinity of the Sound, which averages about 28.5 parts per thousand, compared to about 34 for the nearby Pacific. This means that the Sound is roughly 83% seawater. Even as far south as Budd Inlet near Olympia it is still two-thirds seawater. The sum of rivers entering the Chesapeake is about twice that of those entering Puget Sound, and they would fill the Bay in just a year. Because of the stronger river forcing, and because it is shallower, the Chesapeake is about 50% seawater, with salinity varying smoothly from oceanic to fresh over its length.[3]

Tides

Tides in the Sound are large, with ranges between 3 and 4 m. The tides are forced by the tidal variation of sea level at the mouth of the Salish Sea–the seaward end of the Strait of Juan de Fuca. However the tidal range actually increases as you move landward, and the biggest tidal range is at the extreme southward end. In addition high tide occurs about 1 to 2 hours later in Olympia than it does at Admiralty Inlet. The tides bring in about 8 km^3 of water each high tide, removing it roughly 12.4 hours later. The tides are what cause the strongest currents in the

[3] Banas et al. (2015) calculates how different rivers influence different parts of the Sound.

Sound, peaking around 2.2 m s^{-1} in Admiralty Inlet, 3.4 m s^{-1} in Tacoma Narrows and over 3.8 m s^{-1} in Deception Pass.[4]

While tidal currents are quite apparent to boaters, their importance to Puget Sound water quality is primarily because of the turbulent mixing they cause. In terms of the residence time of water in the Sound, the important currents are the persistent ones. Tidal currents mainly move water back and forth, over a distance called the tidal excursion. The tidal excursion in Admiralty Inlet is about 20 km, and in Main Basin it is about 1.5 km. However, if you put a current meter at any place in the Sound (or any other estuary) you will find that after averaging over many tidal periods the mean is not zero, but instead there is a persistent inflow of deep water and outflow of shallower water. This pattern is called the "estuarine circulation" or the "exchange flow" and it is a characteristic of every estuary in the world. In Puget Sound the estuarine circulation turns out to be very large, and exerts a profound influence on water properties.

Circulation

The strength of the estuarine circulation at Admiralty Inlet is estimated to be 20,000-30,000 m^3 s^{-1}, or about 20-30 times the total of all the rivers entering the Sound. This flow comes in through the deeper part of Admiralty Inlet, and then spills down into Main Basin and Hood Canal. At "hot spots" of tidal turbulence, like Tacoma Narrows, this dense ocean water is mixed with less dense river water, and the mixture rises to the surface. This provides the energy to keep the exchange flow going throughout the year, pulling ocean water into the deep Sound and expelling slightly fresher surface water back to the Pacific.[5]

We can calculate the "residence time" of water in any of the basins of Puget Sound as the ratio of the basin volume to the volume transport of the exchange flow coming into the basin. The result is that the average residence time in Puget Sound is about two months. It is shorter, more like a month, in Whidbey Basin and South Sound. Hood Canal has the longest residence time, 2-4 months. This is primarily because tidal currents, and hence tidal mixing, are relatively weak in Hood Canal. This residence time is long enough for biogeochemical processes to use up the dissolved oxygen in the deep water there, leading to a severe hypoxia problem almost every fall.[6]

The deep and shallow waters of the Sound are kept separate from each other by "stratification." The shallow waters tend to be fresher and warmer, and hence less dense, than the deep waters, and so the water forms horizontal layers. Anyone swimming in the Sound or our local lakes will be familiar with a thin layer of warm water near the surface; this is an example of stratification. The stratification in the Sound is created by the incoming branch of the exchange flow (which

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[4] By far the best references on tides in the Sound and Salish Sea are the excellent NOAA reports by Mofjeld and Larsen (1984) and Lavelle et al. (1988).

[5] Observations of the exchange flow at Admiralty Inlet are given in Geyer and Cannon (1984), and observations of tidal mixing there are reported in Seim and Gregg (1994).

[6] The exchange flow and residence times are estimated in Cokelet et al. (1991), Babson et al. (2006), and Sutherland et al. (2011).

makes the deep water dense), and rivers and sunshine (which make the surface water less dense). In Puget Sound the variation of density is mostly controlled by salinity. Tidal mixing destroys the stratification, and indeed there is very little stratification near the energetic sills. The actual density difference between surface and deep waters is surprisingly small, being about 0.5 kg m^{-3} in Main Basin. This is just 0.05% of the density of seawater, but it is enough to resist tidal mixing, which effectively isolates the deep water from the surface. Hood Canal, with weaker mixing, develops much stronger stratification, about 5 kg m^{-3}, and Dana Passage, where mixing is intense, is more like 0.25 kg m^{-3}. In addition to being colder and saltier and lower in oxygen, the deep waters have high concentrations of nutrients such as nitrate. It is the places and times where this deep water is brought to the surface that are especially favorable for phytoplankton blooms. Stratified waters can support "internal waves" which are wave-like undulations of the density surfaces. These waves can routinely be 50 m high and several km long in the Sound. Sometimes from a boat or plane you can see the subtle surface signature of these underwater giants as lines of alternating smooth and rough water. These are where the horizontal convergence of the internal wave velocity field near the surface has concentrated or excluded small wind waves.[7]

References

Babson, A. L., M. Kawase, P. MacCready (2006): Seasonal and interannual variability in the circulation of Puget Sound, Washington: A box model study. *Atmosphere-Oceans*, 44, 29-45.

Banas, N. S., L. Conway-Cranos, D. A. Sutherland, P. MacCready, P. Kiffney, and M. Plummer (2015) Patterns of River Influence and Connectivity Among Subbasins of Puget Sound, with Application to Bacterial and Nutrient Loading. *Estuaries and Coasts*, 38(3), 735-753, DOI 10.1007/s12237-014-9853-y.

Cokelet, E. D., R. J. Stewart, and C. C. Ebbesmeyer (1991): Concentrations and ages of conservative pollutants in Puget Sound. Puget Sound Research '91, Vol. 1, Puget Sound Water Quality Authority, 99-108.

Ebbesmeyer, C. C., J. Q. Word, and C. A. Barnes (1988): Puget Sound: a fjord system homogenized with water recycled over sills by tidal mixing. Hydrodynamics of Estuaries: II Estuarine Case Studies, B. Kjerfve, Ed., CRC Press, 17-30.

Finlayson, D. P. (2005): Combined bathymetry and topography of the Puget Lowland, Washington State. University of Washington, (http://www.ocean.washington.edu/data/pugetsound/)

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[7] Stratification numbers were estimated by the author using observations from the Washington State Department of Ecology. Data may be downloaded from http://www.ecy.wa.gov/apps/eap/marinewq/mwdataset.asp.

Geyer, W. R. and G. A. Cannon (1982): Sill processes related to deep water renewal in a fjord. *J. Geophys. Res.*, 87, 7985-7996.

Lavelle, J. W., H. O. Mofjeld, E. Lempriere-Doggett, G. A. Cannon, D. J. Pashinski, E. D. Cokelet, L. Lytle, and S. Gill (1988): A multiply-connected channel model of tides and tidal currents in Puget Sound, Washington and a comparison with updated observations. NOAA Tech. Memo. ERL PMEL-84, Pacific Marine Environmental Laboratory, NOAA.

McLellan, P. M. (1954): An area and volume study of Puget Sound. UW Dept. Of Oceanography Tech. Report, 21, 39.

Mofjeld, H. O. and L. H. Larsen (1984): Tides and Tidal Currents of the Inland Waters of Western Washington. NOAA Tech. Memo. ERL PMEL-56, Pacific Marine Environmental Laboratory, NOAA.

Seim, H. E. and M. C. Gregg (1994): Detailed observations of a naturally occurring shear instability. *J. Geophys. Res.*, 99, 10 049-10 073.

Sutherland, D. A., P. MacCready, N. S. Banas, and L. F. Smedstad (2011) A Model Study of the Salish Sea Estuarine Circulation. *J. Phys. Oceanogr.*, 41, 1125-1143.

Human dimensions

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Summary

The Puget Sound Partnership has the statutory goals of promoting “a healthy human population supported by a healthy Puget Sound that is not threatened by changes in the ecosystem” and “a quality of human life that is sustained by a functioning Puget Sound ecosystem.” This recognition of the interconnection between social and ecological systems is innovative yet difficult to quantify. This section initiates a description of the social dimensions of the Puget Sound system with a short list of facts about population growth trends, how humans interact with and depend on the Puget Sound ecosystem for their wellbeing (in the broadest sense), and the large-scale policies and individual human activities that have the greatest potential impact on the Puget Sound ecosystem. While the Puget Sound Partnership adopted Vital Sign indicators specific to human wellbeing in 2015, data for the majority of those indicators are not yet available and are thus not presented here.

Population and demographics

1. The Puget Sound coastal shoreline lies within 12 of Washington State’s 39 counties: Clallam, Island, Jefferson, King, Kitsap, Mason, Pierce, San Juan, Skagit, Snohomish, Thurston, and Whatcom. An additional two counties (Lewis County and Grays Harbor County) are also within the watershed basin, although they do not have Puget Sound coastal shorelines (based on a GIS overlay of NOAA’s ERMA watershed layer and the 2013 U.S. census county boundaries).

2. As of 2014, the 12 Puget Sound coastal shoreline counties accounted for 68% of the Washington State population, 4,779,172 out of 7,061,530. Over 2 million of these residents live in King County, the largest county in the Puget Sound and Washington State (US Bureau of the Census, 2015).

3. There are 19 federally recognized tribes and nations within the Puget Sound Region, including the Jamestown S’Klallam, Lower Elwha Klallam, Lummi, Makah, Muckleshoot, Nisqually, Nooksack, Port Gamble S’Klallam, Puyallup, Samish, Sauk-Suiattle, Snoqualmie, Stillaguamish, Squaxin Island, Swinomish, Suquamish, the Tulalip Tribes, and the Upper Skagit Indian tribes (US Bureau of Indian Affairs, 2015). All but two of these (the Samish Nation and Snoqualmie Tribe) are treaty tribes.

    a. There are several additional tribal communities without federal recognition. One of the more prominent examples is the Duwamish tribe, the tribe of Chief Seattle who is the namesake of the Puget Sound’s largest city. After 38 years of seeking

federal status, the Duwamish tribe's petition for federal recognition received a final denial in 2015 (U.S. Department of the Interior, 2015).

4. The population density of Puget Sound varies significantly, from 16.6 people per square mile in Jefferson County to 913 people per square mile in King County (US Bureau of the Census, 2015).

5. From 2010 to 2014, population growth in Puget Sound coastal counties was estimated to increase by 5.8%, while the population of WA State was estimated to increase by 5.0% (US Bureau of Census, 2015) and the projected growth of all U.S. coastal shoreline counties was 4.1% (NOAA, 2013). King County's growth rate (7.7%) was 18% higher than the second fastest growing Puget Sound county, Snohomish (6.5%), and 43% higher than the third fastest, Thurston (5.4%) (US Bureau of the Census, 2015). Between 1990-2010, the majority of growth in King County was due to immigration from Asia, Latin America, Eastern Europe, and Africa (King County, 2012).

6. Puget Sound population is estimated to reach over 5.7 million by 2030, an increase of 18.2% from 2014 population estimates (Washington State Office of Financial Management, 2012b). During this same time frame, population projections for the United States are 12.7% (US Bureau of the Census, 2015).

7. In King County, the median household income in 2011 was $70,000/year, with the highest incomes on the Eastside of Lake Washington (median $90,000/year). Between 1999 and 2007, the greatest changes in income distribution were in those households below the 50% poverty threshold ($33,625 in 2007 dollars) (a 25% increase in households) and households over the 180% poverty threshold ($121,000 in 2007 dollars) (a 17% increase in households) (King County, 2013).

Human health and wellbeing

8. 84% of Puget Sound residents say they frequently feel inspiration, awe or reduced stress as a result of being in the Puget Sound natural environment (Puget Sound Partnership, 2015).

9. About 51% of Puget Sound residents like to gather or hunt local wild foods, although 70% do so only occasionally or rarely. 71% of those who harvest are able to collect as much as they would like, with the primary barrier being personal time availability (65%) and access to the natural resources (54%) (Puget Sound Partnership, 2015).

10. 76% of Puget Sound residents say they are able to maintain cultural practices associated with the environment (Puget Sound Partnership, 2015).

11. Between 1990 and 2010, over 30.4 million pounds of fish and shellfish were kept for personal use by commercial fishing vessels whose homeports were located within the Puget Sound (Poe et al., 2014). The majority of this use (85%) was for tribal fisherman.

Except for steelhead, the market value of fish had no effect on the amount kept for subsistence.

Outdoor recreation

12. In 2014, total economic contribution of outdoor recreation to the 12 Puget Sound coastal counties totaled just over $10.1 billion and supported about 118,00 jobs (Earth Economics, 2015).

13. The 2011-2012 reported recreational salmon catch for Puget Sound was 229,654 salmon from a total of 424,114 marine angler trips. Over 50% of these were pink salmon, 25% were coho and about 12% were Chinook (Washington Department of Fish and Wildlife, 2014). This is about 43% less than the number reported in 1976.

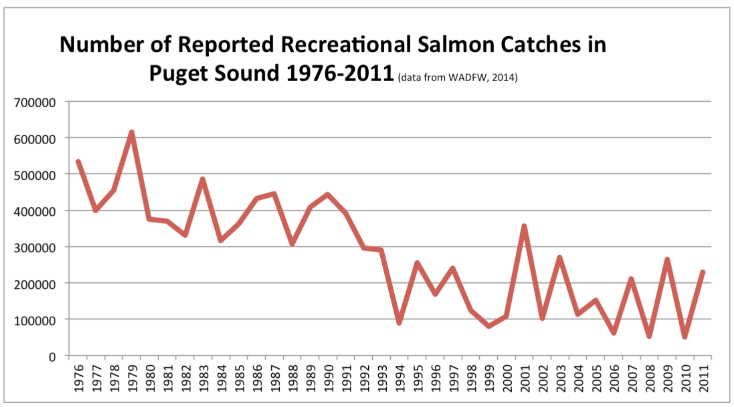

Figure 4. Reported recreational salmon catches in Puget Sound (1976-2011)

   a. Since 1999, the number of recreational fishing license sales has oscillated between about 150,000 and 225,000 per year. The variation in sales is driven mostly by pink salmon runs.

14. The 2011-2012 steelhead sport catch equaled 6,846 fish from the Puget Sound region (Washington Department of Fish and Wildlife, 2014).

15. There are 58 public fishing piers in the Puget Sound. Hundreds of other public boat and shoreline access sites are maintained by Washington Department of Fish and Wildlife, city and county parks, and other local land managers (Washington Department of Fish and Wildlife, 2015).

16. In 2011, nearly 145,000 boating vessels were registered in the counties that border Puget Sound with about 33,000 of those requiring sewage pumpout facilities or dump stations according to federal guidelines (Herrera, 2012).

   a. As of 2012, there were 115 publicly accessible pumpout stations in the Puget Sound (Herrera, 2012).

Key industries

17. Ports: Imports and exports at the ports of Seattle and Tacoma totaled a combined $77 billion in 2013. Taken together, the two seaports were the equivalent of the 4th largest U.S. seaport by export value in 2013 (Northwest Seaport Alliance, 2014).

18. Aerospace: Puget Sound's aerospace industry remains an economic leader, with Boeing contributing about 70 billion dollars to the state economy each year (Washington Aerospace Partnership, 2013).

19. Information technology: Seattle's information technology industry includes giants like Microsoft and Amazon, and according to the Washington Technology Industry Association, the state's tech companies bring in a combined $37 billion in annual revenues (Washington Technology Industry Association, 2015). Information technology provides 144,000 jobs in the Puget Sound region (Puget Sound Regional Council, 2015).

20. Fishing and seafood processing account for nearly half of all maritime-related employment in Puget Sound (Puget Sound Regional Council, 2015).

Shellfish aquaculture

21. Washington State is the leading producer of farmed bivalve shellfish in the United States, generating an estimated $77 million in sales and accounting for 86% of the West Coast's production in the year 2000 (Northern Economics, 2010). Within Puget Sound, farmed shellfish (clams, mussel, geoduck, oyster, and scallops) harvests have ranged from 3.8 million pounds in 1970 to 11.4 million pounds in 2008.

22. Overall, shellfish in Puget Sound have a commercial value of almost $100 million a year. The non-native Pacific oyster accounts for close to $60 million of this value, with the remainder coming from native crabs, clams, and mussels.(Dethier, 2006).

23. As of May 2015, the Department of Health (DOH) classified just over 190,000 acres as shellfish growing areas within 92 different growing areas in the Puget Sound (PSP, 2015). To ensure the health of those consuming shellfish harvested in these areas, the DOH additionally classifies these growing areas on a basis of approved, conditionally approved, restricted, and prohibited. As of May 2015, over 36,000 of the 190,000 acres were prohibited (PSP, 2015).

Governance and policy

24. Unlike many coastal states that maintain public ownership of shorelines, between 60-70% of Washington's tidelands and beaches are privately owned (Osterberg, 2012).

25. In 1854-1855, five treaties (Treaty of Medicine Creek, Treaty of Neah Bay, Treaty of Olympia, Treaty of Point Elliott, Treaty of Point No Point) were signed that provided tribally reserved rights to "taking fish at usual and accustomed grounds and stations" and "hunting and gathering roots and berries on open and unclaimed lands" (Treaty of Point Elliott, 1855). These rights received little attention, however, until the 1974 Boldt Decision defined tribal fishing rights to half the harvestable number of salmon passing through tribes' usual and accustomed fishing places, including salmon produced in hatcheries. Additionally, the Boldt Decision established tribes as co-mangers of the

state's salmon, restricted the state's ability to regulate tribal fishing, and established the duty of state and federal governments to protect salmon habitat (Northwest Indian Fisheries Commission, 2015).

   a. The Rafeedie Decision in 1994 extended this clarification of treaty rights to include half of all shellfish from usual and accustomed places, except for those "staked or cultivated" by citizens (Northwest Indian Fisheries Commission, 2015).

26. Since 1990, the State of Washington's Growth Management Act (36.70a RCW) has required state and local governments in counties with a population of 50,000 or more and population growth between 10-20% for the years 1985-1995 to manage growth by identifying and protecting critical areas and natural resource lands, designating urban growth areas, preparing comprehensive plans, and implementing them through capital investments and regulations (Washington State, 1990). While the state establishes goals and deadlines for compliance, local governments choose the specific content and implementation strategies of their comprehensive plans. This has resulted in significant collaboration among counties and cities to protect natural areas in fast-growing areas (Puget Sound Regional Council, 2009).
    a. Between 1986 and 2007, urban land cover increased from 8% to 19% in six Central Puget Sound counties (King, Pierce, Snohomish, Kitsap, Thurston, Island), with the largest and fastest increases happening outside urban growth boundaries (Hepinstall-Cymerman et al., 2013). During that same time, lowland forest coverage decreased from 21% to 13% and grass and agriculture decreased from 11% to 8%.

27. Washington's Shoreline Management Act requires all cities and counties to prepare and adopt a Shoreline Master Program (SMP) that designates shoreline use, environmental protection, and public access to all marine waters, streams and rivers with greater than 20 cubic feet per second mean annual flow, lakes 20 acres or larger, shorelands that extend 200 feet landward, wetlands, and floodplains. These programs must be approved by Washington State Department of Ecology. As of August 2015, 33 of Puget Sound's cities had completed SMPs. Six of Puget Sound's coastal counties had completed SMPs, three had SMPs under review, and three were still under development (Washington State Department of Ecology, 2015).

28. About 15% of Puget Sound falls within a marine protected area (Osterberg, 2012). There are 110 officially designated marine protected areas in Puget Sound, encompassing 366,503 acres and about 600 miles of shoreline (Van Cleve, 2009). These protected areas have been established and or managed by 10 different local, county, state and federal agencies and are classified into 12 different types, varying in allowed levels of access and harvest (Osterberg, 2012).

29. The Washington State Salmon Recovery Act, passed in 1998, required communities to write local salmon recovery plans to address Endangered Species Act listings. Two of the six plans that have been approved by the federal government are in the Puget Sound region (Puget Sound and Hood Canal). The development and implementation of plans has been led by collaborating tribes, government agencies and other recovery organizations (Washington State Recreation and Conservation Office, 2014).
    a. In 2014, $24.8 million state dollars were dedicated to salmon recovery efforts from the Salmon Recovery Funding Board and the Puget Sound Partnership (Washington State Recreation and Conservation Office, 2014).
30. In addition to the above policies, restoration of Puget Sound region is shaped by a plethora of federal policies, including, but not limited to:
    b. The federal Comprehensive Environmental Response, Compensation and Liability Act (CERCLA, or Superfund) and the state Model Toxics Control Act, which are management by the U.S. Environmental Protection Agency and the Washington State Department of Ecology, respectively. Both regulate the cleanup of toxic sites.
    c. The federal Clean Water Act which requires, among other things, long-term Combined Sewage Overflow planning.
    d. The federal Endangered Species Act and resulting recovery plans for listed species, including the Northern spotted owl, Puget Sound Chinook salmon, Hood Canal summer chum salmon, Puget Sound steelhead, Southern Resident Killer Whales.

Public opinion

31. 34% of Puget Sound residents trust local policymakers to make good decisions about Puget Sound restoration (Puget Sound Partnership, 2015b).
32. 91% of Puget Sound residents are proud to be from the Puget Sound region, and 81% feel a connection to the region (Puget Sound Partnership, 2015b).
33. 86% of Puget Sound residents agree that restoration of the Puget Sound is a good use of tax dollars (Puget Sound Partnership, 2015b).
34. 80% of Puget Sound residents agree that they feel a sense of stewardship for Puget Sound natural resources (Puget Sound Partnership, 2015b).

Human activities[8]

35. From 2010-2013, the number of housing units in Puget Sound increased 1.6% (from 1.96million houses to 1.99million). As of 2013, there were 23,689 active building permits in the Puget Sound region (US Bureau of the Census, 2015).

36. Between 1999 and 2014, travel in a single occupancy vehicle decreased by 6% in the Puget Sound region (from 48% of trips to 42% of trips). Travel trends have shifted to walking (about 6% increase in the same time period) and transit (about 1.5% increase) (Puget Sound Regional Council, 2015).

37. Waste Management, the largest company in the Puget Sound region that collects and disposes of household waste (parts or all of Snohomish, Island, King, Kitsap, Mason, and Skagit counties), reported a 1% decrease in 2013 revenues and 1.4% decrease in 2014 because of a decline in the total volume of waste generated. The company attributes the decline to economic conditions, pricing changes, competition, and diversion of waste by consumers (Waste Management, 2014).

38. Puget Sound Energy, serving over 1 million customers in the Puget Sound region, generates approximately 50% of its energy from renewable resources (Puget Sound Energy, 2015a). Seattle City Light, serving over 400,000 Puget Sound customers, generates over 94% of its energy from renewable sources (Seattle City Light, 2013).

    a. In 2013, Puget Sound Energy sold 22.9million megawatt hours to its over 1 million customers. (Puget Sound Energy, 2015b).

    b. From December 2011 to 2013, the number of customers participating in Puget Sound Energy's Green Power Program increased by 26%, from 32,459 to 41,000 customers. Correspondingly the kWh of renewable power that were purchased in this same time period increased by 10.8 %, from 343 million kWh to 380 million kWh of green power (Puget Sound Energy, 2015b; Puget Sound Energy, 2012).

    c. The average annual residential consumption for Seattle City Light has remained stable since 2009 (almost 9,000 kWh) while the rate as consistently increased from a little over 6cents/kWh in 2009 to over 8cents/kWh in 2013 (Seattle City Light, 2013).

39. Between 2013 to 2015, the Puget Sound population that usually or always engaged in behaviors that are helpful to the Puget Sound decreased from 56% to 54%. The most commonly practiced were picking up dog waste and checking one's vehicle for fluid leaks; the least commonly practiced were using pumpout stations, planting native plants along private property waterways, and getting annual septic inspections. During the same time period, the percentage of the population that seldom or never engaged in

[8] For more details on how human activities negatively impact ecological components, see the other chapters of the Fact Book.

individual behaviors that are known to harm the Puget Sound increased from 75% to 79%. The most avoided behaviors include disposing of chemicals, prescription drugs or cooking oil down the drain. The least avoided behaviors were fertilizing one's lawn and washing one's car in the driveway, street, or parking lot (Puget Sound Partnership, 2015a).

a. The 2015 Sound Behavior Index improved from 2013, with a score of .84 compared to .747.
b. The primary correlations to a high SBI score in 2015 were renting a home and having an income less than $50,000 per year. The primary correlations to a low SBI score in 2015 were being 18-24, income over $50,000, conservative political orientation, number of years lived in their county, and reported ethnicity of American Indian/Alaska Native.

References

Dethier, Megan N., (2006). Native Shellfish in Nearshore Ecosystsms of Puget Sound. Retrieved from: http://www.pugetsoundnearshore.org/technical_papers/shellfish.pdf.

Earth Economics. (2015). Economic Analysis of Outdoor Recreation in Washington State. Report prepared for WA Recreation and Conservation Office. Appendix F. www.rco.wa.gov/documents/ORTF/EconomicAnalysisOutdoorRec.pdf.

Hepinstall-Cymerman, J., S. Coe and L. Hutyra. (2013). Urban growth patterns and growth management boundaries in the Central Puget Sound, Washington, 1986-2007. Urban Ecosyst 16:109-119.

Herrera. (2012). Puget Sound No Discharge Zone for Vessel Sewage: Puget Sound Vessel Population and Pumpout Facilities. Prepared for WA State Department of Ecology. Publication No 12-10-031 Part 3.

King County. 2013. King County's Changing Demographics: A view of our increasing diversity. http://www.kingcounty.gov/exec/PSB/Demographics/DataReports.aspx. (with data from U.S. Census).

NOAA. 2013. State of the Coast. Retrieved May 2015 from http://stateofthecoast.noaa.gov.

Northern Economics (2010, April). *Assessment of Benefits and Costs Associated with Shellfish Production and Restoration in Puget Sound*. Retrieved from http://www.pacshell.org/pdf/AssessmentBenefitsCosts.pdf.

Northwest Indian Fisheries Commission. 2015. Understanding Tribal Treaty Rights in Western Washington. http://nwifc.org/member-tribes/treaties/.

Northwest Seaport Alliance. (2014). The Economic Impacts of Marine Cargo at the Ports of Tacoma & Seattle. Fact sheet. Retrieved on October 1st, 2015 from https://www.nwseaportalliance.com/stats-stories/economic-impact.

Osterberg, A. 2012. Developing a Network of Marine Protected Ares in Puget Sound: A synthesis report on challenges, opportunities and policy options. Retrieved from http://www.psp.wa.gov/downloads/MPA/MPANetwork_FINAL_0928%20copy.pdf.

Poe, M.R., Levin, P.S., Tolimieri, N., Norman, K. (2015, April 24). Subsistence fishing in a 21st century capitalist society: From commodity to gift. Ecological Economics, 116 (2015) 241-250. Retrieved from http://www.sciencedirect.com/science/article/pii/S0921800915002189.

Port of Seattle. (2015). Port of Seattle website. Retrieved September 2015 from: https://www.portseattle.org/Pages/default.aspx.

Puget Sound Energy. 2012. Thinking Green is Re-Energizing. Green Power Report. http://pse.com/savingsandenergycenter/GreenPower/Reports/Documents/GPR_Winter12.pdf.

Puget Sound Energy. (2015a). Electric Supply. https://pse.com/aboutpse/EnergySupply/Pages/Electric-Supply.aspx.

Puget Sound Energy. (2015b).About Puget Sound Energy. http://pse.com/aboutpse/PseNewsroom/MediaKit/020_About_PSE.pdf

Puget Sound Partnership (2015a). Sound Behavior Index-2015 Survey Report.

Puget Sound Partnership (2015b). General Public Opinion Survey 2015.

Puget Sound Partnership (2015). Puget Sound Vital Signs: Shellfish Beds. Retrieved from: http://www.psp.wa.gov/vitalsigns/shellfish_beds_reopened_indicator1.php

Puget Sound Regional Council. (2009). The Washington Growth Management Act with Applications for the Central Puget Sound Region. http://www.psrc.org/assets/2428/gma.pdf

Puget Sound Regional Council. (2015). Puget Sound Trends. NoT8, April 2015. http://www.psrc.org/assets/833/trend-t8.pdf

Seattle City Light. (2013). 2013 Annual Report. http://www.seattle.gov/light/AboutUs/AnnualReport/2013/2013_Annual_Report.pdf

Starcrest. (2007) Puget Sound Maritime Air Forum Maritime Air Emissions Inventory. Prepared by Starcrest Consulting Group LLC for the Puget Sound Maritime Air Forum. April 2007.

U.S. Bureau of the Census (2015). U.S. Bureau of the Census, Population Estimates Program (PEP). http://www.census.gov/popest/index.html

U.S. Bureau of Indian Affairs. (2015). Indian Affairs: Puget Sound Agency. Retrieved from: http://www.bia.gov/WhoWeAre/RegionalOffices/Northwest/WeAre/PugetSound/index.htm

U.S. Department of the Interior. 2015. Official letter accessed online, July 2015. https://turtletalk.files.wordpress.com/2015/07/idc1-030828.pdf.

U.S. Bureau of Indian Affairs. (2015). Indian Affairs: Puget Sound Agency. Retrieved from: http://www.bia.gov/WhoWeAre/RegionalOffices/Northwest/WeAre/PugetSound/index.htm

U.S. Energy and Information Agency (2014). Washington State Profile and Energy Estimates: Profile Analysis. Retrieved from: http://www.eia.gov/state/analysis.cfm?sid=WA.

Van Cleve, FB, G Bargmann, M Culver, and the MPA Work Group. 2009. Marine Protected Areas in Washington: Recommendations of the Marine Protected Areas Work Group to the Washington State Legislature. Washington Department of Fish and Wildlife, Olympia, WA.

Washington Aerospace Partnership. (2013). Retrieved September 25, 2015 from http://www.psrc.org/assets/10090/CAI_WAP_Impact_Estimates_2013_10-2-13_FINAL.pdf.

Washington State Department of Ecology. 2015. Introduction to the Shoreline Management Act. http://www.ecy.wa.gov/programs/sea/sma/st_guide/intro.html

Washington Department of Fish and Wildlife (2014). Washington State Sport Catch Report 2011. http://wdfw.wa.gov/publications/01688/wdfw01688.pdf

Washington Department of Fish and Wildlife. 2015. Public Fishing Piers of Puget Sound. http://wdfw.wa.gov/fishing/piers/

Washington State Legislature. 1990. Growth Management – Planning by Selected Counties and Cities (Chapter 36.70a RCW). http://apps.leg.wa.gov/rcw/default.aspx?cite=36.70a&full=true

Washington State Office of Financial Management (2012a). Census 2010 Data. Retrieved from Redistricting Data: http://www.ofm.wa.gov/pop/census2010/data.asp

Washington State Office of Financial Management (2012b). Washington state growth management act (GMA) population projections for counties: 2000 to 2030. Retrieved from: http://www.ofm.wa.gov/pop/gma/projections07.asp

Washington State Recreation and Conservation Office (2014). State Awards $24.8million dollars for salmon recovery projects in Puget Sound. http://www.rco.wa.gov/doc_pages/press/2014/135.shtml

Washington State Department of Ecology (2015). Inventory of Dams in the State of Washington. Retrieved from: https://fortress.wa.gov/ecy/publications/documents/94016.pdf

Washington Technology Industry Association. (2015). Information & Communication Technology Economic and Fiscal Impact Study. Retrieved September 25, 2015 from http://washingtontechnology.org/industry-resources/sign-up-to-receive-ict-study/

Waste Management. (2014). Annual Report. http://investors.wm.com/phoenix.zhtml?c=119743&p=irol-reportsannual

Pollutants

Persistent contaminants

Overcoming a toxic legacy

Essay by: Eric Wagner

In 1945, as World War II was winding down, Richard Foster, an inspector with the Washington Pollution Control Commission, was sent to do a survey of the Duwamish-Green River drainage. He started at the mouth of the Duwamish River, which empties into Elliott Bay. From there he worked his way to the Upper Green River watershed, past the city of Auburn. His aim was to document all the pollution—from source to type to amount—that was making its way into the Duwamish River Basin.

Foster didn't have to go far to uncover the lion's share of the mess. "The Duwamish Waterways within the City Limits of Seattle receives a larger volume and greater variety of polluting substances than all of the remaining watershed combined," he would write near the beginning of the report he submitted at the end of the year.

In all, Foster found 38 sources of pollution along the Lower Duwamish Waterway. These ranged from the Boeing Company's two manufacturing plants, to various shipyards, to concrete companies, to Isaacson Iron Works, to a number of slaughterhouses. Similarly diverse were the things they dumped into the river: oil, chromic acid waste, raw sewage, offal, more than 1,400 lbs. per day of acetylene generator waste from some shipyards, and on and on. ("While it is recognized that, during the existing war emergency, speed in the repair of ships is vital, the extensive and continued spilling of oil into the West Waterway and Elliott Bay does not seem justified," Foster observed.)

It was in part due to this toxic legacy that the Environmental Protection Agency (EPA) designated the Lower Duwamish Waterway a Superfund site in 2001. In November 2014, after more than 13 years, the agency released its Record of Decision—the final plan that outlined exactly how federal and state managers will oversee the cleansing of the river. The work is expected to take at least 17 years and will cost more than $340 million.

One of the principal challenges facing the Duwamish cleanup has been, and will be, stormwater. Every year, millions of gallons of rain washes into the Duwamish from its surrounding neighborhoods, bearing with it loads of metals, petroleum products, fertilizers, and other toxins. At a session of the Salish Sea Ecosystem Conference in May 2014, Beth Schmoyer, from Seattle Public Utilities, talked about how difficult it is to trace the origins of this pollution, to say nothing of stopping it. "It's really hard to control the source once you find it, and it's really hard to find it," she said. She pointed out that there are 237 sewage outfalls along the waterway, and 198 storm drains, and only a fraction of them are monitored. On top of that, over 100,000

metric tons of sediment enters the river every year from Auburn and Renton. That load is also rife with everything from motor oil to dog feces, but none of it is under the purview of Superfund legislation.

Still, even as Puget Sound residents have become its leading source of contemporary toxins, the chemical history from Seattle's period of commercial growth remains a formidable obstacle. Since Foster's work, government inspectors have detected more than 40 chemicals in the Lower Duwamish Waterway. The most harmful include dioxins and furans, arsenic, and polycyclic aromatic hydrocarbons (PAHs), all of which are byproducts of various industrial activities. But the most abundant pollutants by far are polychlorinated biphenyls, or PCBs.

Inflammable, chemically stable and insulating, PCBs were considered a miracle compound for their wide range of commercial applications when they were developed in the 1880s. They were used to make caulking and grout and paint, they were in carbon paper, they were in floor finishes, tapes and other adhesives, cable insulation. At the time, no one thought anything was wrong with PCBs. (They are not mentioned at all in Foster's report.) Now, of course, people know differently. Later research would reveal that PCBs cause cancer and birth defects. They suppress the immune system. Children with sustained exposure to them can develop learning disabilities or behavioral problems. Wildlife are also affected, especially those animals that are top-level consumers, such as seabirds or marine mammals.

Congress would eventually ban PCB manufacture in 1979. But all the things that made them so useful for industry mean they are now extremely hard to remove from the environment. This is especially true on the Duwamish River. Around 2,300 buildings along the Duwamish corridor contain PCBs in one form or another. They are so widely integrated into the landscape that researchers can detect them in the droppings of Canada geese.

Although to-date federal and state regulators have overseen extensive dredging and capping operations that have reduced the PCB load in sediments by 50%, in a sense, this was the easy work, concentrated as it was around five known hotspots. Now, dredges will have to get as much of the rest as possible, little of which is so conveniently centralized. Of the 412 acres within the boundaries of the waterway, the EPA will work to clean 177 of them. The rest—235 acres—will be left to what the EPA calls Monitored Natural Recovery. This means that EPA and state officials will watch and wait as the river goes about its daily business. They will trust the reduced flow of its deepened channel to carry the most dangerous sediments out to Elliott Bay, where the toxins will pose less of a risk; or bury them under a natural cap of fresher muds borne from the Green River, which itself is not much cleaner than the Duwamish. If all goes as intended, the level of PCBs in the river will drop by 90%.

Stormwater

Section author: Carla Milesi, Washington Stormwater Center

Summary

Stormwater runoff plays a major role, both directly and indirectly, in the declining health of Puget Sound (PSAT, 2005). Stormwater degrades habitat, affects aquatic environments, and contributes to flooding. It is considered by the Washington State Department of Ecology to be the biggest water pollution problem in the urban areas of Washington State.

This section focuses on facts related to stormwater, its prevalence, how it affects the Puget Sound ecosystem, and highlights a few of the environmental and economic impacts of the stormwater problem.

Annual rainfall

1. Puget Sound's urban areas receive up to 40 inches of rain each year (NOAA National Climatic Data Center, 2015). Historically, most of this water soaked into the ground or was taken up by plants. Over the past 100 years, human development has drastically altered this natural pattern by creating impervious surfaces that cause stormwater runoff. This runoff collects and carries toxic chemicals into Puget Sound.

Impervious surfaces and stormwater runoff

2. The total amount of impervious surface in the Puget Sound drainage basin increased from 319,409 acres in 1996 to 357,840 acres in 2006 (Parametrix, 2010). This represents an increase from 3.7% of the total basin to 4.1% of the total basin. Impervious coverage of approximately 10% within a watershed typically leads to measurable and often irreversible loss of functioning of aquatic systems (Booth and Reinelt, 1993).

3. The Puget Sound drainage basin encompasses 8,768,000 acres (USGS, 2000), of which 357,840 acres are made up of impervious surfaces (Parametrix, 2010). With an average annual rainfall at SeaTac airport of 38.2-inches (Rosenberg et al, 2009), Puget Sound basin sees an average of more than 370 billion gallons of stormwater runoff from these surfaces each year.

    a. The stormwater runoff value was calculated using 15,587,510,400 square feet (357,840 acres) of impervious surface multiplied by 3.183 feet of annual rainfall multiplied by 7.48 gallons/cubic feet.

Known pollutants in stormwater

4. At least 33 known pollutants are measured in Western Washington stormwater at a 50% or greater detection frequency (Ecology, 2015). This includes a group of polycyclic aromatic hydrocarbons that are categorized as carcinogenic. An additional 16 known pollutants were detected at frequencies of 20-49%. The most common pollutants,

detected in 90% of all samples analyzed, include metals, nutrients, suspended solids, and fecal coliform (Ecology, 2015).

a. This data was summarized from stormwater samples collected under the NPDES Phase I Municipal Permit between 2007 and 2013. The data represents 598 storm events, with up to 85 parameters analyzed in samples collected during these events. For statistical analyses Ecology followed a method outlined by Helsel (2012) which divided the results up in categories depending on detection frequencies. These categories included pollutants with <50% frequency of non-detects; pollutants with 50-80% frequency of non-detects; and pollutants with >80% frequency of non-detects.

5. On average, more than 52,000 – 66,000 lbs of pollutants are released into the Puget Sound Ecosystem each day (Ecology, 2011b). This includes oils and grease, petroleum, zinc, copper, and polycyclic aromatic hydrocarbons. In addition, an estimated 1,189,880 lbs of total suspended sediment enters the Puget Sound Ecosystem each day from surface runoff (Ecology 2011b).

   It should be noted, however, that only roughly 10% of the pollutant loadings for oils and grease, petroleum (TPH), zinc, copper, and polycyclic aromatic hydrocarbons are attributable to commercial/industrial, residential, or agricultural land uses. The majority of the loads come from lands categorized as forested/field/other. Furthermore, Oil and Grease and TPH concentrations from forested lands, which make up more than 80% of the total pollutant loads, have low frequency of detection. Load calculations for these parameters were strongly influenced by how the non-detects were treated in the analysis.

   a. Loading estimates were calculated using contaminant levels from samples collected for the study *Toxics in Surface Runoff to Puget Sound: Phase 3 Data and Load Estimates*. Contaminant levels were measured in baseflow and stormflow samples from 16 streams within the Puyallup River and Snohomish River watersheds. The total loading rates from the Phase 3 study were lower than initial estimates developed in Phase 1 and Phase 2 of the study (2011b). Phase 1 and Phase 2 relied on literature searches of data from stormwater conveyance systems and instream samples, whereas Phase 3 loading estimates were based solely on instream samples which are expected to have lower concentrations.

Stormwater effects on salmon

6. For more than a decade urban watersheds in Puget Sound have seen 60 to 100% of coho salmon die off before spawning (Scholz et al., 2011). Mortality rates this high have very negative impacts on maintaining coho salmon runs. Research has eliminated non-chemical explanations, and indicates the toxic effects of pollutants in stormwater runoff are the likely cause (Scholz et al., 2011). Within the urban watersheds a correlation was observed between the mortality rate and land cover, with mortality rates higher in basins with a greater "urban" land cover and land uses (Fiest et al., 2011).

   a. Research and forensic studies into the cause of the pre-spawn mortality ruled out "stream temperature, dissolved oxygen, poor overall spawner condition, tissue

pathology, pathogen prevalence or disease, and other factors commonly associated with fish kills in freshwater habitats" (Scholz et al., 2011). The forensic studies combined with the exhibited symptoms and rapid onset points to stormwater runoff from urban land cover and land uses as the likely cause of the high mortality rates (Fiest et al., 2011). Three variables within the urban watersheds were most important in predicting mortality rates: impervious surfaces, local roads, and commercial property type (Fiest et al., 2011).

7. Dissolved copper is a ubiquitous contaminant in stormwater runoff. Stormwater samples collected by NPDES Phase I Municipal Stormwater Permittees showed dissolved copper levels exceed acute aquatic life criteria 50% of the time and chronic aquatic life criteria 58% of the time. (Ecology, 2015). Median concentrations from industrial, commercial, high density residential, and low density residential land uses were 16.0 µg/L, 19.6 µg/L, 7.7 µg/L, and 2.8 µg/L, respectively. Copper can disrupt the salmon's olfactory system, affecting their ability to imprint on their natal streams, navigate during migration, and detect and avoid predators (McCarthy et al., 2008). These disruptions can occur at concentrations of 3.0 µg/L over background in freshwater (Baldwin, 2003).

Impaired waterbodies

8. Five hundred twenty-five (525) streams, rivers, lakes and marine waterbodies across the Puget Sound region are impaired by poor water quality (Ecology, 2014).

    a. According to the Washington State Department of Ecology's Puget Sound Characterization Project, there are 19 Water Resource Inventory Areas (WRIAs) within the Puget Sound drainage area (Ecology, 2013). These WRIAs (#1 through #19) include 544 fresh and marine waterbodies that are listed on Washington's 303(d) list of polluted waters (Ecology, 2012).

    b. The 303(d) list is comprised of waters that are considered impaired or threatened by one or more pollutants. Waters placed on this list require the creation of a Total Maximum Daily Load (TMDL) or other approved water cleanup plan, outlining how much of the pollutant of concern needs to be reduced to achieve clean water. The vast majority of 303(d) listings within the Puget Sound Basin are for 3 parameters—dissolved oxygen (37%), bacteria (31%), and temperature (20%) (Ecology, 2012).

    c. In addition to the 544 waterbodies currently on the 303(d) list, there are 241 waterbodies listed as "Waters of Concern" (Ecology, 2012). These waters show some evidence of a water quality problem, but not enough to require a TMDL or water cleanup plan.

Combined sewer overflows

9. In 2012 and 2013 combined sewer overflows (CSOs) into Puget Sound have been in excess of 1,559 million gallons (MG) and 423 MG, respectively (King County 2013, 2014; Seattle Public Utilities 2013, 2014). The U.S. Environmental Protection Agency (2004) estimates that exposure to these types of CSOs at state-recognized beaches account for

more than 800 gastrointestinal illnesses nationwide each year. These findings only include data from state-recognized beaches, and therefore only capture a portion of the likely number of annual illnesses attributed to CSOs (USEPA, 2004).

a. There are 168 permitted combined sewer overflow (CSO) outfalls that drain into Puget Sound. (Ecology, 2014). Of these, 126 are within the jurisdictions of King County and Seattle Public Utilities. In 1987 Ecology adopted Chapter 173-245 WAC which implemented a Water Pollution Control Act requirement and stated all CSO sites must be controlled in a manner that results in an average of one untreated discharge event per year.

b. In 1988 Ecology estimated that CSOs in Washington State discharged 3.3 billion gallons annually (Ecology 2011). Recent data from King County and SPU, the jurisdictions with 75% of the CSO outfalls, reported discharges of 1,559 MG in 2012 and 423 MG in 2013 (King County 2013, 2014; SPU 2013, 2014). While this is an improvement over estimated 1988 volumes, multiple outfalls are still seeing in excess of 15 untreated discharge events per year (King County 2013, 2014; SPU 2013, 2014).

References

Baldwin, David H., Jason F. Sandahl, Jana S. Labenia, and Nathaniel L. Scholz. (2003). Sublethal Effects of Copper on Coho Salmon: Impacts on Nonoverlapping Receptor Pathways in the Peripheral Olfactory Nervous System. Environmental Toxicology and Chemistry, Vol 22, No. 10, pp 2266-2274, 2003.

Booth, Derek B. and Lorin E. Reinelt. (1993). "Consequences of Urbanization on Aquatic Systems – Measured Effects, Degradation Thresholds, and Corrective Strategies". Proceedings Watershed '93, A National Conference on Watershed Management. Pp. 545-550. March 21-24, 1993. Alexandria Virginia.

Booth, Derek B. Ph.D., Bernadette Visitacion, Anne C. Steinemann, Ph.D. (2006). Damages and Costs of Stormwater Runoff in the Puget Sound Region. The Water Center, Department of Civil and Environmental Engineering, University of Washington. August 2006.

Ecology, State Department of. (2014). Numbers were provided by Ecology to the Puget Sound Partnership for the March 2014 Vital Signs update (Markus Van Prause and Ken Koch, Ecology; Jo Wilhelm, King County); http://www.psp.wa.gov/vitalsigns/fresh_water_quality_indicator2.php. Retrieved 2015.

Feist BE, Buhle ER, Arnold P, Davis JW, Scholz NL (2011). Landscape Ecotoxicology of Coho Salmon Spawner Mortality in Urban Streams. PLoS One 6(8):e23424. Doi:10.1371/journal.pone0023424

Helsel, D.R. (2012). Statistics for Censored Environmental Data Using Minitab® and R. Second Edition. John Wiley & sons, Inc. NJ, 342p.

King County Department of Natural Resources and Parks. (2013). Combined Sewer Overflow Control Program. 2012 Annual Report. July 2013.

King County Department of Natural Resources and Parks. (2014). Combined Sewer Overflow Control Program. 2013 Annual CSO and Consent Decree Report. July 2014 (Amended September 2014)

McCarthy, Sarah G., John P. Incardona, and Nathaniel L. Scholz. (2008). Coastal Storms, Toxic Runoff, and Sustainable Conservation of Fish and Fisheries. NOAA Fisheries, Northwest Fisheries Science Center Ecotoxicology and Environmental Fish Health Program.

NOAA National Climatic Data Center. (2015). http://www.ncdc.noaa.gov/climate-information. June 2015.

Parametrix. (2010). Puget Sound Stormwater Retrofit Cost Estimate. Appendix A. October 2010.

Puget Sound Action Team (2005). State of the Sound 2004. Publication No. PSAT 05-01. January 2005.

Puget Sound Partnership (2013). 2013 State of the Sound: A biennial Report on the Recovery of Puget Sound. Tacoma, WA.

Rosenberg, Eric A., Patrick E. Keys, Derek B. Booth, David Hartley, Jeff Burkey, Anne C. Steinemann, and Dennis P. Lettenmaier. (2009). Precipitation extremes and the impacts of climate change on stormwater infrastructure in Washington State.

Scholz, Nathaniel L., Mark S. Myers, Sarah G. McCarthy, Jasa S. Labenia, Jenifer K. McIntyre, Gina M. Ylitalo, Linda D. Rhodes, Cathy A. Laetz, Carla M. Stehr, Barbara L. French, Bill M cMillan, Dean Wilson, Laura Reed, Katherine D. Lunch, Steve Damm, Jay W. Davis, and Tracy K. Collier. (2011). Recurrent Die-Offs of Adult Coho Salmon Returning to Spawn in Puget Sound Lowland Urban Streams. December 14, 2011.

Seattle Public Utilities. (2013). 2012 Annual Report Combined Sewer Overflow (CSO) Reduction Program. March 2013.

Seattle Public Utilities. (2014). 2013 Annual Report CSO Reduction and CMOM Programs. March 2014.

United States Environmental Protection Agency. (2004). Report to Congress. Impacts and Control of CSOs and SSOs. EPA B33-R-04-001. August 2004.

United States Geological Survey. 2000. Water Quality in the Puget Sound Basin, Washington and British Columbia, 1996-1998. US Geological Survey Circular 1216.

Washington State Department of Ecology (2008). Focus on Puget Sound: Economic Facts. www.ecy.wa.gov/pubs/0601006.pdf. October 2008.

Washington State Department of Ecology (2011a). Focus on Sewage and Stormwater. Protecting Our Waters from Combined Sewer Overflows. February 2011.

Washington State Department of Ecology (2011b). Toxics in Runoff to Puget Sound. Phase 3 Data Loads and Estimates. April 2011.

Washington State Department of Ecology (2012). "Washington State's Water Quality Assessment [303(d)]," www.ecy.wa.gov/programs/wq/303d

Washington State Department of Ecology. (2013). Puget Sound Watershed Characterization Project. https://fortress.wa.gov/ecy/coastalatlas/wc/landingpage.html

Washington State Department of Ecology (2014). Combined Sewer Overflows. http://www.ecy.wa.gov/programs/wq/permits/cso.html

Washington State Department of Ecology. (2015). *Western Washington NPDES Phase I Stormwater Permit. Final S8.D Data Characterization 2009-2013*. (Publication No. 15-03-001)

Washington State Department of Health. (2012a). 2011 Annual Report: Commercial and Recreational Shellfish Areas in Washington State. Washington State Department of Health Office of Shellfish and Water Protection. September 2012.

Washington State Department of Health. (2012b). Status and Trends in Fecal Coliform Pollution in Shellfish Growing Areas of Puget Sound: Year 2011.

Climate change

An overview for Puget Sound

Essay by: Eric Scigliano

Thanks to the moderating influence of the Pacific Ocean and prevailing westerly winds, scientists say that average temperatures should actually rise less in the Pacific Northwest than in most of the United States. But Puget Sound will hardly be spared by climate change.

At first glance, some of the news seems positive (almost). Total annual precipitation will probably increase somewhat, in contrast to the severe chronic drought conditions predicted in the Southwest, Rocky Mountains, and Great Plains. Rising seas will inundate much less of Puget Sound's relatively steep shorelines than the wide coastal flatlands of Louisiana, Florida, New Jersey, and other Gulf and Eastern states. It's even believed that offshore tectonic shifts are slowly pushing up the land along Washington's shores, partially countering that sea-level rise—in contrast to California, which is sinking under the influence of plate tectonics.

But dig a little deeper and the situation becomes vastly more complex. Annual averages are crude measures that ignore changes in the highs and lows within a year. These changes will become more extreme at both the dry and wet ends of the spectrum. Hotter, drier summers (such as the one in 2015) will bring more frequent and severe droughts and heightened fire danger. In some Puget Sound watersheds, streamflows are projected to hit their peaks four to nine weeks earlier in the late 21st century than they did in the 20th. On average, winter flows will increase by 25 to 34 percent and summer flows will decline by 22 to 34 percent. Eighty percent of Washington's watersheds will suffer more severe low-flow conditions in summer.

Flooding and snow pack

That adds up to big changes for Puget Sound, especially in floodplains and along streams and rivers. More rain in autumn will mean more severe storms and flooding. Annual peak 24-hour rainfall is projected to rise 4 to 30 percent (depending on greenhouse emissions levels) by the late 21st century. Hundred-year peak stream flows will rise 15 to 90 percent at 17 selected sites around Puget Sound (Mote et al., 2013). In the flood-prone Skagit Valley, the volume of the 100-year flood of the 2080s will surpass today's by a quarter, and flooding and sea-level rise together will inundate 75 percent more area than flooding alone used to.

At the other extreme, water will become scarcer in the spring and summer. Mountain snowpack is Washington's water bank: a savings account that stores winter snowfall and gradually releases it through spring and summer, assuring streamflows for aquatic creatures and (with additional impoundment by dams and reservoirs) water supply for cities and farmers. But the state's average spring (April 1) snowpack declined by about a quarter between the mid-1900s and 2006. By the 2080s, average spring snowpack in the Puget Sound watershed is projected to

decline 56 to 74 percent from levels 100 years earlier. The decline will reach 80 percent by the 2040s in the headwaters of the four rivers (the Tolt, Cedar, Green, and Sultan) serving the cities of Seattle, Tacoma, and Everett—reflecting the fact that their snowpacks are already very low, hence vulnerable. By the 2080s, April snowpack will largely disappear from all four watersheds, leaving Puget Sound's major rivers low and dry in summer (Elsner et al., 2010).

Impacts on salmon

These shortfalls will have wider impacts. Salmon, keystone species and traditional cultural, subsistence, and economic mainstays along Puget Sound, will face new threats in addition to those that have already drastically diminished their runs. Rising stream temperatures can be deadly to fish that evolved to thrive at 12 degrees Celsius and endure no more than 18 degrees. To the traditional "four Hs" threatening salmon (harvest, hydropower, hatcheries, and habitat degradation), add a fifth: heat.

Earlier snowmelt, heightened streamflows, and increased flooding could also disrupt salmon's spawning cycles and sweep away their "redds," the gravel beds where they deposit their eggs. These effects will be augmented by losses in the region's once-great conifer forests. Trees are essential to the conditions salmon need to spawn and grow: they shade streams, create deep pools that help to contain stormwater, and stabilize soils, preventing floods and erosion. The salmon in turn convey fertilizing marine nutrients to the forests in the form of their own bodies, consumed and scattered by land-based predators and scavengers.

Increased algal blooms

Warming may have profound trophic effects in Puget Sound itself. Global ocean near-surface temperatures are projected to rise by as much as 2 degrees Celsius by century's end—an effect amplified in the shallow, sheltered bays of the South Sound. Already warmer waters are nurturing earlier and larger harmful algal blooms and creating the right conditions for types of harmful algae not previously seen in these waters. Warming and an increase of carbon dioxide in the atmosphere, coupled with nutrient runoff and discharges from industry, farms, lawns, and waste treatment systems, stimulate the growth of phytoplankton generally. When these and other organisms die and sink, their decomposition consumes oxygen and releases carbon dioxide into the water, promoting two climate-related syndromes deadly to many marine organisms: too little oxygen in the water and water that is so acidic that it eats away the calcium shells that protect so many of the small creatures of the ocean.

Ocean acidification

By 2100, the relative acidity of the global ocean is expected to be 50 to 100 percent above preindustrial levels. Regional factors will compound this effect in Puget Sound. Because colder water can absorb more carbon dioxide than warmer, much of humankind's rapidly accelerating atmospheric emissions of CO_2 concentrate in the deep ocean, then cycle back up some 30 to 50 years later off the Pacific Coast. Prevailing winds and currents drive these cold, CO_2-saturated, highly acidified waters into shore, and into the Strait of Juan de Fuca and Puget Sound. There, nutrient runoff and decomposition inject more CO_2 and acidity into the system. These inputs

could increase as population growth and urbanization continue, and if drought-induced cutbacks in Californian agriculture lead to more demand for farmland here, especially for dairy farms.

Another factor has also made the Northwest a frontline for acidification: the importance of its shellfish industry, together with the special vulnerability of one key component, larval oysters. University of Washington researchers recently identified worrisome effects on other species with vital commercial or ecological importance. Acidification affects the ability of mussels to produce *byssus,* the tough adhesive threads that anchor them to their rocks against waves and surf–a life-and-death matter for a mussel. The native bay mussel (*Mytilus trossulus)* also loses byssal strength when water temperatures surpass 20^{o}C, whereas Mediterranean mussels (*M. galloprovincialis)* grow more byssus as the waters warm (O'Donnell et al., 2013; Carrington & Friedman, 2015). This suggests a potential species succession, from native to introduced mussels, as Puget Sound becomes warmer and more acidic.

Potentially more ecologically devastating are acidification's effects on copepods and krill, small swimming crustaceans at the base of the marine food web. The copepod *Calanus pacificus,* common in Puget Sound, shows reduced hatching success at the pH levels expected by 2100, though impacts vary between broods and some continue to breed successfully. Overall, the copepods fare better than the likewise common krill *Euphausia pacifica,* which suffers both reduced growth and higher mortality at low pH (Keister & McElhany, 2015). Krill also inhabit deeper, more acidic waters than copepods, compounding their exposure. Their loss would be grievous for the fishes, seabirds, and whales that depend on them.

Sea level rise

Although Puget Sound's shoreline terrain is very different from flatbottom Florida's, it still includes dozens of deltas, estuaries, and shallow bays that are acutely exposed to rising seas, as well as the economically vital fill-dirt harbors of Seattle and Tacoma. Sea-level projections vary more than many others thanks to the many variables influencing them; the seas along Washington are expected to rise somewhere between 4 and 56 inches by 2100. At a midpoint outcome of 27 inches' rise, 91 percent of the estuarine beach and 77 percent of the brackish marsh along Port Susan, Padilla, and Skagit Bays will be inundated, with similar if less dramatic effects all the way down to Budd Inlet and the Skokomish delta (Glick et al., 2007). These inundations will certainly disrupt habitats, but they may in the end create valuable new ones. Many beaches, wetlands, and dry areas will become tidelands, saltwater marshes, and, possibly, eelgrass beds—valuable carbon sinks and nurseries for marine life. Urban inundation offers no such tradeoffs; protecting and relocating utilities, transportation, and other low-lying and underground infrastructure will be a multibillion-dollar challenge.

Higher ground?

In 2012, the National Research Council reported that north of Cape Mendocino, California, the Pacific Coast is rising 1.5 to 3.0 millimeters per year, thanks to uplift as the offshore Juan de Fuca Plate pushes under the North American Plate; south of the cape, where the two plates slide

past each other along the San Andreas Fault, the NRC found that the coast is sinking .6 to 3.7 mm/yr (National Research Council, 2012). On closer inspection, however, the picture along Washington's shores is more complicated and less cheery. The Pacific Plate isn't just pushing the North American Plate up; it's tilting it back. Since the 1980s, various observers have noted local variation in Washington's vertical land movement. New research by Washington Sea Grant and partner organizations clarifies this variation. Nearest to the fault, the Olympic Peninsula's northwest corner is indeed rising, by about 2.6 mm/yr, possibly enough to outpace sea-level rise in the near term (unless a major offshore earthquake suddenly drops Neah Bay a meter lower, as anticipated some day). Seventy miles to the east, Port Angeles is also rising, by what appears to be a little less than a millimeter a year. Farther from the fault the effect quickly drops off and reverses; Friday Harbor is sinking slightly and Port Townsend by about .8 mm/yr. The effect is most pronounced where it will prove most costly, along the densely developed heart of Puget Sound: Seattle appears to be sinking about 1.2 mm/year – enough to add another 4 inches to the sea's rise before the century is out (Miller et al., 2015).

These impacts, and others not discussed here, may not seem quite so severe as the desertification predicted for vast swathes of territory at lower latitudes. But that will be cold comfort for the Puget Sound region as it faces the complexity and sweep of its own climate challenges.

References

Carrington, E., & Friedman, C. S. (2015). *Impacts of Ocean Acidification on Wild and Farmed Mussels in Puget Sound* (Year 1 progress report). Washington Sea Grant.

Elsner, M. M., Cuo, L., Voisin, N., Deems, J. S., Hamlet, A. F., Vano, J. A., … Lettenmaier, D. P. (2010). Implications of 21st century climate change for the hydrology of Washington State. Climatic Change, 102(1-2), 225–260. http://doi.org/10.1007/s10584-010-9855-0.

Glick, P., Clough, J., & Nunley, B. (2007). *Sea-level rise and coastal habitats in the Pacific Northwest: An analysis for Puget Sound, southwestern Washington, and northwestern Oregon*. National Wildlife Federation.

Keister, J., & McElhany, P. (2015). *Effects of Ocean Acidification on Trophically-Important Crustacean Zooplankton of Washington State* (Final report). Washington Sea Grant.

Mass, C. (2014, July 28). Cliff Mass Weather Blog: Will the Pacific Northwest be a Climate Refuge Under Global Warming? Retrieved from http://cliffmass.blogspot.com/2014/07/will-pacific-northwest-be-climate.html.

Miller, I., et al (2015). "Localized sea level projections for the coastal communities on the Strait of Juan de Fuca" (draft).

National Research Council. (2012). *Sea-Level Rise for the Coasts of California, Oregon, and Washington: Past, Present, and Future*. Washington, DC: The National Academies Press. Retrieved from http://www.nap.edu/catalog/13389/sea-level-rise-for-the-coasts-of-california-oregon-and-washington.

O'Donnell, M. J., George, M. N., & Carrington, E. (2013). Mussel byssus attachment weakened by ocean acidification. *Nature Climate Change*, *3*(6), 587–590.

Expected impacts

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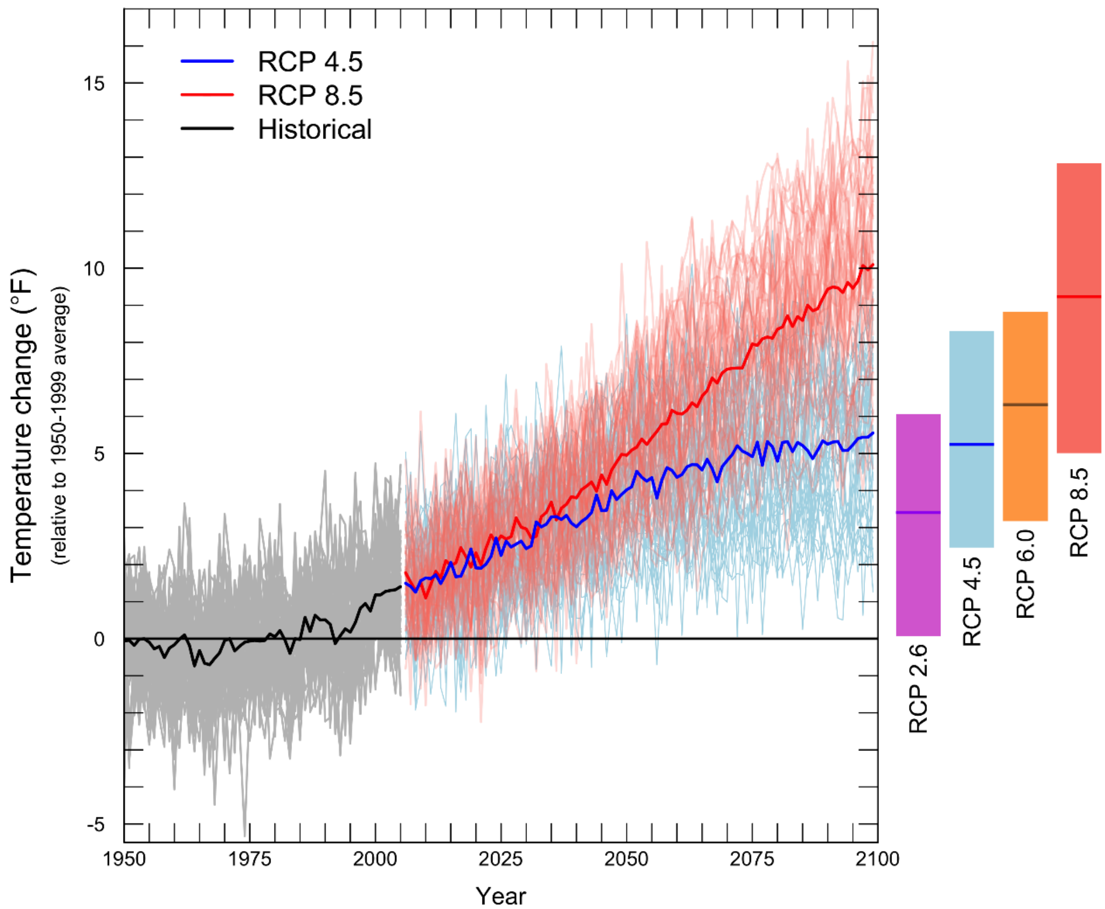

Figure 5. All scenarios project warming for the 21st century. The graph shows average yearly temperatures for the Pacific Northwest relative to the average for 1950-1999 (gray horizontal line). The black line shows the average simulated temperature for 1950–2011, while the grey lines show individual model results for the same time period. Thin colored lines show individual model projections for two emissions scenarios (low: RCP 4.5, and high: RCP 8.5)[9], and thick colored lines show the average among models projections for each scenario. Bars to the right of the plot show the mean, minimum, and maximum change projected for each of the four emissions scenarios for 2081-2100, ranging from a very low (RCP 2.6) to a high (RCP 8.5) scenario. Note that the bars are lower than the endpoints from the graph, because they represent the average for the final two decades of the century, rather than the final value at 2100. Figure source: Climate Impacts Group, based on climate projections used in the IPCC 2013 report.

[9] Greenhouse gas scenarios were developed by climate modeling centers for use in modeling global and regional climate impacts. These are described in the text as follows: "very low" refers to the RCP 2.6 scenario; "low" refers to RCP 4.5 or SRES B1; "medium" refers to RCP 6.0 or SRES A1B; and "high" refers to RCP 8.5, SRES A2, or SRES A1FI – descriptors are based on cumulative emissions by 2100 for each scenario (VanVuuren et al., 2011; Nakicenovic et al., 2000). Scenarios used in this fact sheet range from a low (B1, RCP 4.5) to a medium (A1B) or high (A2, RCP 8.5) greenhouse gas scenario. The implications of the lowest greenhouse gas scenario – RCP 2.6, which assumes aggressive reductions in emissions – are not discussed in the text of this section.

Summary

Puget Sound and the Pacific Northwest are experiencing a suite of long-term changes that are consistent with those observed globally as a result of human-caused climate change. These include increasing temperatures, decreased glacial area and spring snowpack, earlier peak streamflows in many rivers, and rising sea level at most locations. Natural variability can result in short-term trends that are opposite those expected from climate change, as evidenced by recent regional cooling and increases in spring snowpack.

Projections indicate continued increases in average annual Pacific Northwest temperatures as a result of global warming. Projected changes in annual precipitation are small, although heavy rainfall events are projected to become more severe. Regionally, sea level will continue to rise in concert with global sea level. Locally, sea level is projected to rise in most locations, with the amount of rise varying by location and over time. In addition, the Puget Sound basin is projected to experience decreases in snowpack, increases in stream temperatures, and widespread changes in streamflow timing, flooding, and summer minimum flows. Natural variability will continue to influence shorter-term (up to several decades) climate trends.

Note: *Only a few of the changes cited below are specific to the Puget Sound basin. However, many characteristics of Puget Sound's climate and climate vulnerabilities are similar to those of the broader Pacific Northwest region. Results for Puget Sound are therefore expected to generally align with those provided for the Pacific Northwest and Washington State, with potential for some variation at any specific location.*

Attribution

1. "*Human influence on the climate system is clear…Warming of the climate system is unequivocal, and since the 1950s, many of the observed changes are unprecedented over decades to millennia.*" – IPCC 2013

Greenhouse gases

2. *Observed rise in global greenhouse gas concentrations*. Human activities have increased atmospheric levels of greenhouse gases (carbon dioxide, methane, and nitrous oxide) to levels unprecedented in at least the past 800,000 years (IPCC, 2013).

Air temperature

3. *Observed increase in global temperature*. Average global temperature increased +1.5°F between 1880 and 2012.[10]

4. *Observed warming in Northern Hemisphere*. Each of the last three decades has been successively warmer than any preceding decade since 1850. In the Northern Hemisphere, 1983–2012 was likely the warmest 30-year period of the last 1400 years (IPCC 2013).

[10] Trends are only reported if they are statistically significant at the 90% level or more.

5. *Observed increase in average annual temperature for the Pacific Northwest.* The Pacific Northwest warmed about +1.3°F between 1895 and 2011, with statistically-significant warming occurring in all seasons except for spring (Kunkel et al., 2013; Mote et al., 2013). This trend is robust: similar 20th century trends are obtained using different analytical approaches (Mote et al., 2003). All but five of the years from 1980 to 2011 were warmer than the 1901-1960 average (Mote et al., 2013).[10]

6. *Projected increase in annual average temperature for Puget Sound.* Warming is projected to continue throughout the 21st century. For the 2050s (2041-2070)[11] relative to 1970-1999, temperature is projected to rise +5.5°F (range: +4.3 to +7.1°F) for a high greenhouse gas scenario (RCP 8.5). Much higher warming is possible after mid-century (Mote et al., 2015). Lower emissions of greenhouse gases will result in less warming.[9]**Error! Bookmark not defined.**

7. *Ongoing variability.* Natural variability will remain an important feature of global and regional climate, at times amplifying or counteracting the long-term trends caused by rising greenhouse gas emissions. Important modes of natural variability for the Pacific Northwest include the El Niño/Southern Oscillation (i.e., El Niño and La Niña) and the Pacific Decadal Oscillation.

8. *The size of projected change is large compared to observed variability.* The Pacific Northwest is likely to regularly experience average annual temperatures by mid-century that exceed what was observed in the 20th century. Specifically, all scenarios project that, by mid-century (2041-2070), annual temperatures will be warmer than the warmest year historically (1950-1999, Mote et al., 2013).

Precipitation

9. *No change observed in annual precipitation for the Pacific Northwest.* There is no statistically significant trend toward wetter or drier conditions in Pacific Northwest precipitation for the period 1895-2011.[10]

10. *Small changes projected for annual precipitation in Puget Sound.* Projected changes in total annual precipitation are small (relative to variability)[12] and show increases or decreases depending on models, which project a change of −2 % to +13 % for the 2050s (relative to 1970-1999, Mote et al., 2015).[9] [11]

11. *Projected increase in precipitation extremes for Puget Sound.* Heavy rainfall events are projected to become more severe by mid-century. Specifically, the yearly maximum 24-hour rainfall is projected to increase by +4% to +30% for the 2050s (relative to 1970-

[11] Results are often cited for the "2050s" or "2080s". These refer to the 30-year average centered on each decade (2041-2070 and 2071-2100, respectively).

[12] Year-to-year variations in precipitation are about ±10 to 15%, on average.

1999), based on results from 10 global models and a low (RCP 4.5) and high (RCP 8.5) greenhouse gas scenario (Mote et al., 2015).[13]

Ocean temperature

12. *Observed increase in global ocean temperature*. Ocean surface waters (top 250 ft.) warmed by +0.6 to +0.9°F from 1971 to 2009 (global average). Warming trends are evident at nearly all depths in the ocean (IPCC 2013).

13. *Projected increase in global ocean temperature*. The oceans will continue to warm, and heat will penetrate from the surface to the deep ocean. Projected warming in the top 330 feet of the ocean is +1.1°F to +3.6°F for 2081-2100 relative to 1986-2005 (IPCC 2013).

14. *Projected increase in Washington coastal ocean temperatures*. Ocean surface temperatures offshore of Washington are projected to rise by about +2°F by the 2040s (2030-2059, relative to 1970-1999) for a medium greenhouse gas scenario (the A1B scenario, Mote and Salathé 2010). Projected changes in winter sea surface temperatures in the North Pacific are expected to be as large as the range of natural variability by 2030-2050 (relative to 1950-1999) under a medium greenhouse gas scenario (Overland and Wang 2007).[14] However, coastal ocean temperatures are strongly affected by coastal upwelling of colder water from ocean depths, and by large scale climate variability such as El Niño – current research is unclear as to how these might be altered by climate change.

Sea level

15. *Observed rise in global sea level*. Global sea level has risen about +7 inches since 1901. The rate of global mean sea level rise has accelerated during the last two centuries (IPCC 2013).

16. *Coastal areas in Washington will experience sea level rise, although some areas may continue to experience decreases due to trends in vertical land movement*. According to a recent report by the National Research Council, sea level is projected to rise an additional +4 to +56 inches in Washington by 2100 (relative to 2000, NRC 2012). Locally, however, sea level will increase by different amounts in different places. Previous research projects a decline in sea level for the northwest Olympic Peninsula through 2100, for scenarios that assume very low rates of global sea level rise and high rates of vertical uplift (Mote et al., 2008; Reeder et al., 2013). These projections differ from the NRC projections due to different study approaches. Although most global

[13] Projection based on regional climate model simulations, from the North American Regional Climate Change Program (NARCCAP) multi-model ensemble (http://www.narccap.ucar.edu). These simulations are based on results from 6 different regional models driven by 4 different global model projections, all based on the A2 greenhouse gas scenario, which is slightly lower than the RCP 8.5 scenario used in IPCC 2013. Values denote the average and the standard deviation among model projections. Results are averaged over a large area and may not be applicable to a given locale in Washington State.

[14] Based on analyses of 10 global climate models and the A1B greenhouse gas scenario.

projections would result in sea level rise for the northwest Olympic Peninsula, it is not yet possible to conclusively rule out a decline in sea level for that region.

17. *Short-term sea level variations can temporarily offset or accelerate trends.* Sea level can be temporarily elevated or depressed by up to a foot in winter as a result of natural periodic cycles in climate patterns such as El Niño and the Pacific Decadal Oscillation (NRC 2012). This variability will continue in the future.

Ocean acidification

18. *Observed acidification of the global ocean.* The acidity of the global ocean has increased by about +26% since 1750. The current rate of acidification is nearly ten times faster than any time in the past 50 million years (IPCC 2013).[15]

19. *Ocean acidification.* The acidity of the ocean is projected to increase by +38 to +109% (IPCC 2013)[15] by 2100 relative to 1986-2005 (or increase roughly +150 to +200% relative to pre-industrial levels, Feely et al., 2009) as global oceans continue to absorb carbon dioxide from the atmosphere.

20. *Local changes in Ocean Acidification are modulated by upwelling and runoff.* Local conditions are also affected by seasonal upwelling of deeper Pacific Ocean water that is low in pH and high in nutrients, transport of nutrients and organic carbon from land, and oceanic absorption of other acidifying atmospheric gases.

Snow

21. *Observed decreases in spring snowpack in the Washington Cascades.* Spring (April 1st) snowpack fluctuates substantially from year-to-year, but declined by about −25% overall (range −15% to −35%) in the Washington Cascades from the mid-20th century to 2006 (Stoelinga et al., 2009; Mote et al., 2008).[16] This trend is due primarily to increasing regional temperature and reflects the influence of both climate variability and climate change (Hamlet et al., 2005; Pierce et al., 2008). Natural variability can dominate over shorter time scales, resulting (for example) in an increase in spring snow accumulation in recent decades (Stoelinga et al., 2009).

22. *Observed decreases in Washington glaciers.* About two-thirds of the glaciated area in the lower 48 states (174 out of 266 sq. miles) is in Washington (Fountain et al., 2007). Although there are some exceptions, most Washington glaciers are in decline. Declines range from a −7% loss of average glacier area in the North Cascades (1958-1998,

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[15] Although the acidity of the ocean is projected to increase, the ocean itself is not expected to become acidic (i.e., drop below pH 7.0). Ocean pH has decreased from 8.2 to 8.1 (a 26% increase in hydrogen ion concentration, which is what determines the acidity of a fluid) and is projected to fall to 7.8-7.9 by 2100. The term "ocean acidification" refers to this shift in pH towards the acidic end of the pH scale.

[16] These numbers indicate changes in April 1st Snow Water Equivalent (SWE). SWE is a measure of the total amount of water contained in the snowpack. April 1st is the approximate current timing of peak annual snowpack in the mountains of the Northwest.

Granshaw et al., 2006) to a –14% decline in average area on Mt. Rainier (1970-2007, Sisson et al., 2011). There are no published trends for glaciers in the Olympic Mountains.

23. *Projected decline in spring snowpack for Puget Sound.* On average spring (April 1st) snowpack in Puget Sound is projected to decline by –56 to –74% by the 2080s (2070-2099, relative to 1970-1999, Mote et al., 2015).[16] [17]

Streamflow

24. *Observed shift to earlier peak streamflow in the Pacific Northwest.* The spring peak in streamflow is occurring earlier in the year for many snowmelt-influenced rivers in the Pacific Northwest as a result of decreased snow accumulation and earlier spring melt – the shift ranges from no change to about 20 days earlier (observed over the period 1948-2002; Stewart et al., 2005).

25. *Projected shift to earlier peak streamflow timing in Puget Sound.* Peak streamflow is projected to occur 4 to 9 weeks earlier by the 2080s (2070-2099, relative to 1970-1999 Elsner et al., 2010) in four Puget Sound watersheds (Sultan, Cedar, Green, Tolt).[17]

26. *Projected increases in winter streamflow for Puget Sound.* Winter streamflow is projected to increase by +25 to +34% on average for Puget Sound by the 2080s (2070-2099, relative to 1970-1999; Hamlet et al., 2013).[17]

27. *Projected decreases in summer streamflow for Puget Sound.* Summer streamflow is projected to decrease by –22 to –31% on average for Puget Sound by the 2080s (2070-2099, relative to 1970-1999, Hamlet et al., 2013).[17]

28. Flooding

    a. *Projected increases in peak river flows for Puget Sound.* Projected increases for a selection of 17 streamflow sites across Puget Sound range from an increase of +15 to +90% for the magnitude of the 100-year peak flow event (Tohver et al., 2013). Changes depend on the location and specific characteristics of each watershed, such as the amount of winter snow accumulation within the basin.. Projections for specific Washington locations can be found here: http://warm.atmos.washington.edu/2860/products/sites/

    b. *Increases in heavy rainfall events could further increase flood risk.* Heavy rainfall events are projected to become more severe by mid-century. In Puget Sound, the yearly maximum 24-hour rainfall is projected to increase by +4 to +30% for the 2050s (relative to 1970-1999), based on results from 10 global models and a low (RCP 4.5) and high (RCP 8.5) greenhouse gas scenario (Mote et al., 2015). Preliminary results suggest an increase in the number of heavy rain

[17] Average projected change for ten global climate models, averaged over Washington State. Range spans from a low (B1) to a medium (A1B) greenhouse gas scenario.

events occurring in early fall (Salathé et al., 2014). These changes may result in more severe flooding in rain dominant and mixed rain and snow basins.

c. *Changes in flood management may not be sufficient to mitigate increases in flood risk*. In the upper Skagit basin, for instance, with current flood management practices, the 100-year flood is projected to increase by 24% by the 2080s (2070-2099, relative to 1916-2006)[18]; simulations indicate that changes in water management can only mitigate 7% of this projected increase (Lee and Hamlet 2011).

d. *Sea level rise will exacerbate coastal river flooding*. Higher sea level can increase the extent and depth of flooding by making it harder for flood waters in rivers and streams to drain to the ocean or Puget Sound. Initial research on this issue suggests that the amount of area flooded in the Skagit would increase by up to 74% by the 2080s when accounting for the combined effects of sea level rise and larger floods (Hamman 2012).

29. *Projected decreases in minimum flows for Washington State*. Low summer streamflow conditions are projected to become more severe in about 80% of watersheds across Washington State. Projected decreases for a selection of 17 streamflow sites across Puget Sound range from a decrease of –9 to –51% for the magnitude of the 10-year in average 7-day flows (Tohver et al., 2013). Changes depend on the location and specific characteristics of each watershed, such as the amount of winter snow accumulation within the basin. Projections for specific locations can be found here: http://warm.atmos.washington.edu/2860/products/sites/.[19]

Stream temperature

30. *Projected increases in stream temperatures for Washington State*. Stream temperatures are projected to increase in response to warming and decreases in summer streamflow. Projections for 124 stream temperature locations across the state find that more sites will experience temperatures that elevate stress for adult salmon (EPA, 2007). Many will exceed thermal tolerances for the entire summer season by 2080 (2070-2099), despite rarely being in excess of these temperatures in the recent past (Mantua et al., 2010).

References

Elsner, M.M. et al., 2010. Implications of 21st century climate change for the hydrology of Washington State. Climatic Change 102(1-2): 225-260.

Environmental Protection Agency, 2007. Biological evaluation of the revised Washington water quality standards. US EPA, Seattle.

[18] Projected change based on the ECHAM5 global climate model and the A1B greenhouse gas scenario.

[19] Results for a low (B1) and medium (A1B) greenhouse gas scenario for 112 medium-sized watersheds in Washington.

Feely, R.A. et al., 2009. Ocean acidification: Present conditions and future changes in a high-CO2 world. *Oceanography* 22(4):36–47, http://dx.doi.org/10.5670/oceanog.2009.95

Granshaw, F. D., and A. G. Fountain. 2006. Glacier change (1958-1998) in the North Cascades National Park Complex, Washington, USA. Journal of Glaciology 52(177):251-256

Hamlet, A. F. et al., 2005. Effects of temperature and precipitation variability on snowpack trends in the Western United States. Journal of Climate 18(21): 4545-4561.

(IPCC) Intergovernmental Panel on Climate Change. 2013. Working Group 1, Summary for Policymakers. Available at: http://www.climatechange2013.org/images/uploads/WGIAR5-SPM_Approved27Sep2013.pdf

Hamman, J.J., 2012. Effects of Projected Twenty-First Century Sea Level Rise, Storm Surge, and River Flooding on Water Levels in Puget Sound Floodplains and Estuaries. Master's Thesis, University of Washington.

Kunkel, K. E. et al., 2013: Part 6. Climate of the Northwest U.S., NOAA Technical Report NESDIS 142-6.

Lee, S-Y. and A.F. Hamlet, 2011. Skagit River Basin Climate Science Report, a summary report prepared for Skagit County and the Envision Skagit Project by the Department of Civil and Environmental Engineering and The Climate Impacts Group at the University of Washington.

Mantua, N. et al., 2010. Climate change impacts on streamflow extremes and summertime stream temperature and their possible consequences for freshwater salmon habitat in Washington State. Climatic Change 102(1-2): 187-223.Fountain, A.G. et al., 2007. Digital outlines and topography of the glaciers of the American West: U.S. Geological Survey Open-File Report 2006–1340, 23 pp.

Mote, P. W., Rupp, D. E., Abatzoglou, J. T., Hegewisch, K. C., Nijssen, B., Lettenmaier, D. P., Stumbaugh, M., Lee, S.-Y., & Bachelet, D., 2015. Integrated Scenarios for the Future Northwest Environment. Version [if relevant]. USGS ScienceBase. Data set accessed 2015-03-02 at https://www.sciencebase.gov/catalog/item/5006eb9de4b0abf7ce733f5c

Mote, P.W. et al., 2013. Climate: Variability and Change in the Past and the Future. Chapter 2, 25-40, in M.M. Dalton, P.W. Mote, and A.K. Snover (eds.) Climate Change in the Northwest: Implications for Our Landscapes, Waters, and Communities, Washington D.C.: Island Press.

Mote, P.W. et al., 2008. Has snowpack declined in the Washington Cascades? Hydrology and Earth System Sciences. 12: 193–206.

Mote, P.W. et al., 2008. Sea Level Rise in the Coastal Waters of Washington State. Report prepared by the Climate Impacts Group, Center for Science in the Earth System, Joint

Institute for the Study of the Atmosphere and Oceans, University of Washington, Seattle, and the Washington Department of Ecology, Lacey, WA.

Mote, P. W., and E.P. Salathé. 2010. Future climate in the Pacific Northwest. *Climatic Change* 102(1-2): 29-50, doi: 10.1007/s10584-010-9848-z.

Nakicenovic, N. et al., 2000. Special Report on Emissions Scenarios: A Special Report of Working Group III of the Intergovernmental Panel on Climate Change, Cambridge University Press, Cambridge, U.K., 599 pp. Available online at: http://www.grida.no/climate/ipcc/emission/index.htm

National Research Council. Sea-Level Rise for the Coasts of California, Oregon, and Washington: Past, Present, and Future. Washington, DC: The National Academies Press, 2012.

Overland, J. E., and M. Wang. 2007. Future climate of the North Pacific Ocean. *Eos, Transactions American Geophysical Union*, 88, 178, 182. doi: 10.1029/2007EO160003, 178, 182.

Pierce, D.W. et al., 2008. Attribution of declining western U.S. snowpack to human effects. Journal of Climate 21(23): 6425–6444, doi:10.1175/2008JCLI2405.1.

Reeder, W. S. et al., 2013. Coasts: Complex changes affecting the Northwest's diverse shorelines. Chapter 4 in M.M. Dalton, P.W. Mote, and A.K. Snover (eds.) Climate Change in the Northwest: Implications for Our Landscapes, Waters, and Communities, Washington D.C.: Island Press.

Salathé Jr, E. P., Hamlet, A. F., Mass, C. F., Lee, S. Y., Stumbaugh, M., & Steed, R. (2014). Estimates of twenty-first-century flood risk in the pacific northwest based on regional climate model simulations. Journal of Hydrometeorology, 15(5), 1881-1899.

Sisson, T.W. et al., 2011. Whole-edifice ice volume change AD 1970 to 2007/2008 at Mount Rainier, Washington, based on LiDAR surveying. Geology, 39(7): 639-642

Stewart, I. et al., 2005. Changes toward earlier streamflow timing across western North America. J. Climate, 18: 1136-1155.

Stoelinga, M.T. et al., 2009. A new look at snowpack trends in the Cascade Mountains. Journal of Climate. doi: 10.1175/2009JCLI2911.1

Tohver, I. et al., 2013. Impacts of 21st century climate change on hydrologic extremes in the Pacific Northwest region of North America. Journal of the American Water Resources Association, in press.

Van Vuuren, D. P. et al., 2011. The representative concentration pathways: An overview. Climatic Change 109(1-2): 5-31.

Habitats

This section focuses on several key habitats in the Puget Sound watershed, including estuarine, nearshore and the combined terrestrial and freshwater environment.

Estuaries

The mosaic of deltas and other estuarine ecosystems in Puget Sound[20]

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Summary

The diversity and complexity of estuarine ecosystems is vital to the overall health of Puget Sound. This document focuses on the current state of estuarine ecosystems in Puget Sound—large river deltas, embayments, their interconnecting beaches, and rocky coasts—and the historical changes that have occurred since the development of the Puget Sound coastline. Additional emphasis is placed on the historical losses of tidal wetlands within these estuaries.

The diverse estuarine ecosystems of the Puget Sound

1. Estuarine ecosystems in Puget Sound occur as three main types: large river deltas, embayments, and their interconnecting beaches. Rocky coasts also occur prevalently in northern Puget Sound (Shipman, 2008).

2. Puget Sound as we now know it:

    a. **River deltas:** River deltas develop at the mouths of large rivers and are formed by river sediment that is deposited over broad and low-lying plains (Shipman, 2008). There are 16 recognizable deltas that now cover just over 188 km^2 (Simenstad et al., 2011)—equivalent to more than twice the area of Lake Washington.

    b. **Embayments:** Embayments are semi- or total enclosed estuaries and lagoons often formed behind barrier beaches (Shipman, 2008). Types of embayments include barrier estuaries, barrier lagoons, closed lagoons and marshes, and open coastal inlets. There are 422 embayments (179 barrier estuaries, 142 barrier lagoons, 101 closed lagoons and marshes, and 157 open coastal inlets) that currently cover 90.8 km^2 of the Puget Sound shoreline (Simenstad et al., 2011).

[20] Puget Sound in this case is defined broadly to include the Strait of Juan de Fuca, Hood Canal and the San Juan Archipelago. See the Geographic Boundaries section of the Fact Book for more information.

c. **Beaches:** Beaches include coastal bluff-backed beaches and barrier beaches (Shipman, 2008). About equal numbers of bluff-backed and barrier beaches total 1,788 beach segments (Simenstad et al., 2011).

d. **Rocky coasts:** Rocky coasts of the northern Puget Sound include pocket beaches and plunging and platform shorelines (Shipman, 2008). There are 2,783 segments of these complex shorelines (364 plunging, 1,409 platform, and 1,010 pocket beaches) (Simenstad et al., 2011).

3. What has historically changed since the development of the Puget Sound shorelines:

   a. Since historic surveys from the mid- to late-1800s, three deltas have virtually disappeared as natural ecosystems, and the total length of river deltas in Puget Sound has declined by 47%. In total, more than 232 km^2 of natural deltas have vanished, almost 56% of their historic presence (Simenstad et al., 2011)—equivalent to 2.5X the area of Lake Washington. The various tidal wetland ecosystems that once composed these massive deltas have been lost to different degrees; see below.

   b. Even the area of small embayment estuaries have diminished by 69 km^2, or 67% of the historical 102 km^2 of small estuaries that once occurred along the shores of Puget Sound—a loss still 1.2 greater than the area of Lake Washington. The length of embayments has also declined: barrier estuaries have declined by 44%, barrier lagoons by 46%, closed lagoons and marshes by 48%, and open coastal inlets by 45% (Simenstad et al., 2011).

   c. The length of bluff-backed beaches in Puget Sound has decreased by 8% and the length of barrier beaches has declined by 12% since the mid- to late-1800s (Simenstad et al., 2011).

   d. The shoreline lengths of the complex rocky shorelines have also diminished to some degree, by 9.5% in the case of pocket beaches, 9.3% in the case of plunging rocky and 10.4% of rocky platforms (Simenstad et al., 2011).

Tidal wetlands of deltas and embayments

4. There are four main types of tidal wetlands in the estuaries of Puget Sound: mud flats, emergent marshes, scrub-shrub (willow and other woody vegetation) tidal wetlands, and tidal freshwater swamps (the once great tidal swamps, dominated by Sitka spruce, that once occurred across the region) (Simenstad et al., 2011). These tidal wetlands are important to the health of estuaries. They provide shelter and food for salmon and other fish, help protect the shoreline from storms and large waves, and filter runoff from the land (Martínez et al., 2007).

5. Tidal wetlands in Puget Sound have diminished by 301 km^2 since the mid- to late-1800s from 518 km^2 to 217 km^2 (Simenstad et al., 2011)—a decline 3.4X the area of Lake Washington or the size of 56,303 football fields.

    a. **Mud flats:** In the mid- to late-1800s, there was 166 km^2 of mud flats in Puget Sound. Since then, the area of mud flat has declined by 24% to an area of only 126 km^2 (Simenstad et al., 2011).

    b. **Emergent marshes:** Historically, there was a total of 161 km^2 of emergent marsh in Puget Sound: 86 km^2 in deltas and 75 km^2 in non-deltas. Currently, there are only 46 km^2 of emergent marsh in deltas and 32 km^2 in non-deltas—a 46% decline in deltaic emergent marsh and a 58% decline in non-deltas (Simenstad et al., 2011).

    c. **Scrub-shrub tidal wetlands:** Historically, there was a total of 64 km^2 of scrub-shrub wetlands in Puget Sound: 55 km^2 in deltas and 9 km^2 in non-deltas. Currently, there is less than 1 km^2 of scrub-shrub in deltas and less than 1 km^2 in non-deltas – declines of 99% and 92%, respectively (Simenstad et al., 2011).

    d. **Tidal freshwater swamps:** Historically, there was a total of 126 km^2 of tidally influenced freshwater swamps in Puget Sound: 108 km^2 in deltas and 18 km^2 in non-deltas. Currently, there are only 11 km^2 of tidal freshwater swamps in deltas and less than 1 km^2 in non-deltas—declines of 90% and 95%, respectively (Simenstad et al,. 2011).

Human modifications

6. Humans have modified coastal estuaries in many ways, including building dams, constructing shoreline armoring, and filling wetlands and intertidal flats for agriculture and housing.

    a. Changes to the Puget Sound watershed influence the health of coastal estuaries by altering groundwater runoff and erosion of sediment. Watershed changes include the development of industry and the construction of towns and cities, but also logging of forests for agriculture. Only 84% of the Puget Sound watershed has natural land cover, while the remaining 16% is considered developed (Simenstad et al., 2011).

    b. As of 2006, there were 436 dams in the Puget Sound watershed (Simenstad et al., 2011). Dams alter the water flow of rivers and trap sediment, which affect deltas and embayments at the mouths of these rivers and streams. For example, there was nearly 19 million cubic meters of sediment trapped behind the Elwha and Glines Canyon Dams on the Elwha River (Duda et al., 2011) – enough sediment to fill a football field to the height of the Space Needle more than 19 times.

c. The amount of artificial shoreline has increased by 3,443% since the mid- to late-1800s (Simenstad et al., 2001). For example, shoreline armoring – such as bulkheads and riprap – has been constructed on an average 27% of the Puget Sound shoreline, but as high as 63% of the central Puget Sound shoreline (Simenstad et al., 2011).

d. A total area of 40 km^2 historically natural shoreline has been covered with fill – enough to cover 7,475 football fields (Simenstad et al., 2011).

e. Breakwaters and jetties cover 37 km^2 of historically natural shoreline (Simenstad et al., 2011).

Protection and restoration

7. Between 2006 and 2014, the Estuary and Salmon Restoration Program assisted with 55 restoration and protection projects throughout Puget Sound. There were 17 projects in beach systems, 16 in embayment systems, and 22 in river delta systems (ESRP, 2015).

8. Between 2013 and 2015, the Puget Sound Acquisition and Restoration (PSAR) program funded projects to restore and protect 2,024 estuary and nearshore acres, 1,682 floodplain acres, and 189 river and stream miles (Puget Sound Partnership, 2015).

9. Floodplains by Design: In 2013, the Washington State Legislature provided $50 million in grants for floodplain management projects, of which $33 million was provided to "nine specified multi-benefit floodplain projects in the Puget Sound basin that were early examples of the Floodplains by Design concept." (Ecology, 2015).

10. A few examples of tidal wetland restoration in river deltas:

    a. In the Nisqually River delta, 3.64 hectares (ha) of tidal wetland was restored in 1996, 8.50 ha in 2002, 40.47 ha in 2006, and 308.37 ha in 2009 (Nisqually Delta Restoration, 2011).

    b. In the Stillaguamish River delta, 150 ha of tidal wetland was restored in 2012 (Nature Conservancy, 2015).

    c. In the Snohomish River estuary, there are 17 restoration project sites that have been completed or are in the planning stages (Tulalip Tribes, 2015).

References

Duda, J.J., Warrick, J.A., and Margirl, C.S., eds. (2011). Elwha River dam removal – Rebirth of a river: U.S. Geological Survey Fact Sheet 2011-3097, 4 p.

Ecology, Washington Department of. (2015). Department of Ecology website. Retrieved from: http://www.ecy.wa.gov/programs/sea/floods/CompetitiveGrants.html

ESRP. (2015). Estuary and Salmon Restoration Program. Retrieved from: http://www.rco.wa.gov/grants/esrp.shtml

Martínez, M.L., Intralawan, A., Vázque, G., Pérez-Maqueo, O., Sutton, P., Landgrave, R. (2007). The coasts of our world: ecological, economic and social importance. *Ecological Economics*, *63*, 254-272.

Nature Conservancy. (2015). Washington: Restoring a river mouth at Port Susan Bay. Retrieved from: http://www.nature.org/ourinitiatives/regions/northamerica/unitedstates/washington/washington-restoring-a-river-mouth-at-port-susan-bay.xml

Nisqually Delta Restoration. (2011). About the Nisqually Delta Restoration Project. Retrieved from: http://www.nisquallydeltarestoration.org/about.php

Puget Sound Partnership (2015). Puget Sound Acquisition and Restoration Fund fact sheet. Retrieved from: http://www.psp.wa.gov/PSAR.php.

Shipman, H. (2008). A Geomorphic Classification of Puget Sound Nearshore Landforms. Puget Sound Nearshore Partnership Report No. 2008-01. Published by Seattle District, U.S. Army Corps of Engineers, Seattle, Washington.

Simenstad, C.A., Ramirez, M., Burke, J., Logsdon, M., Shipman, H., Tanner, C., Toft, J., Craig, B., Davis, C., Fung, J., Bloch, P., Fresh, K., Campbell, S., Myers, D., Iverson, E., Bailey, A., Schlenger, P., Kiblinger, C., Myre, P., Gerstel, W., and MacLennan, A. (2011). Historical change of Puget Sound shorelines: Puget Sound Nearshore Ecosystem Restoration Project Change Analysis. Puget Sound Nearshore Ecosystem Restoration Project Report No. 2011-01. Published by Washington Department of Fish and Wildlife, Olympia, Washington, and US Army Corps of Engineers, Seattle, Washington.

Tulalip Tribes. (2015). Qwuloolt Estuary: Restoration Plan – Snohomish Estuary Restoration. Retrieved from: http://www.qwuloolt.org/RestorationPlan/SnohomishEstuary

Nearshore environments

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This document focuses on the physical and geological conditions in the nearshore environment of Puget Sound. The nearshore environment extends from the head of tide and the upper edge of coastal bluffs seaward to the offshore limit of the photic zone (Shipman 2008). The boundaries described in this section represent the broader definition of the Puget Sound watershed, including the Strait of Juan de Fuca or the San Juan Islands.

> *Puget Sound covers approximately 8,000 km² (2 million acres) and has 4,020 kilometers (2,500 miles) of shoreline (Gelfenbaum et al., 2006). It receives runoff from a 36,000 km² (8.3 million acres) watershed that includes 16 major rivers (Fresh et al., 2011; Cereghino et al., 2012).*

The Puget Sound Nearshore Ecosystem Restoration Project (PSNERP), a major collaborative effort, examined the extent and condition of several categories of *shoreform* (Shipman, 2008; Fresh et al., 2011) in the Puget Sound nearshore environment: 1) rocky platform and pocket beaches; 2) two beach types: bluff-backed beaches and barrier beaches; 3) four embayment types: barrier estuaries, barrier lagoons, closed lagoons/marshes, and open coastal inlets; and 4) large river deltas.

This report focuses on the value, extent, and condition of beach and embayment shoreforms. Large river deltas are discussed in a separate report. Overall, Puget Sound's shoreforms have experienced a large degree of alteration since the mid-19th century, the baseline for comparison.

1. The nearshore environment of Puget Sound provides habitat for 211 fish species, 100 species of sea birds, and 13 marine mammals (Cereghino et al., 2012).
    a. It includes critical habitats such as coastal forests, spawning beaches for forage fish (such as surf smelt), eelgrass beds, and salt marshes, all of which shape the health of salmon populations (Johannessen & MacLennan, 2007).
2. The shoreline of Puget Sound has become shorter and simpler since the first surveys in the last half of the 19th Century, and the vast majority of the changes are due to human alterations (Fresh et al., 2011).
    a. The net decline in shoreline length over all of the Sound has been 694 km or about 15% of the historical length of the shoreline (Fresh et al., 2011; Simenstad et al., 2011; Schlenger et al., 2011).
    b. More than 1,000 km of natural shoreline were lost and 368 km of artificial shoreline were added (Fresh et al., 2011).
3. Forty percent of the shoreline of Puget Sound has been altered by (Fresh et al., 2011) one or more of the following "stressors:" Armoring, nearshore fill, tidal barriers, marinas,

breakwaters/jetties, overwater structures, roads within 25 m of the shoreline, active & inactive railroads within 25 m of the shoreline.

   a. Only 31.3% of the length of Puget Sound's shoreline has not been modified (i.e., none of the stressors occurs) (Fresh et al., 2011).

   b. Negligible historically, artificial shoreline now represents about 9.5% of the shoreline (Fresh et al., 2011).

4. Armoring is clearly the most frequently occurring stressor, observed in along 74–78% of shoreline segments studied (Fresh et al., 2011), followed by nearshore fill (62%) and overwater structures (30%) (Schlenger et al., 2011).

   a. Armoring occurs along 27% of the length of the shoreline (1070 of 3969 km) (Schlenger et al., 2011).

   b. The percent of armored shoreline varies considerably (10 to 63 percent) across the sub-basins in the study area (Schlenger et al., 2011).

5. An estimated 34.6% of shorelines lack natural vegetation (Simenstad et al., 2011).

   a. Riparian vegetation overhanging the intertidal zone occurs along only 440 miles of the shoreline of Puget Sound (Clancy et al., 2009).

   b. Loss of overhanging vegetation can alter the microclimate of beaches for incubating eggs of intertidal spawning fish (Rice, 2006).

   c. Loss of vegetation reduces the supply of terrestrial insects falling into nearshore waters, an important food source for migrating juvenile salmonids (Brennan & Culverwell, 2004).

6. Fragmentation of nearshore marine habitat by frequent separate smaller anthropogenic shoreline alterations can reduce biological productivity beyond the effects of fewer but larger alterations (Gaydos et al., 2009).

7. The South Central Puget Sound sub-basin is the most impacted sub-basin in the Puget Sound Basin, with 51% of the nearshore zone area developed (Schlenger et al., 2011).

   a. Only 1% of the shoreline segments in this sub-basin had not been modified (Fresh et al., 2011).

   b. The Hood Canal sub-basin is the least impacted, with 10 percent of the nearshore zone area developed (Schlenger et al., 2011).

8. Projections suggest that approximately 19 % of nearshore segments studied in Puget Sound will become more degraded in the future (Schlenger et al., 2011). The segments forecast to degrade comprise 20 % of the shoreline length.

9. Together, bluff-backed and beaches compose the dominant nearshore shoreform, accounting for 49.6% of Puget Sound's shoreline (Fresh et al., 2011).

    a. Bluff-backed beaches cover the greatest shoreline length in Puget Sound historically forming 38.5% (1,529 km) of Puget Sound's shoreline (Fresh et al., 2011; Schlenger et al., 2011).

    b. A total of 77.6% of all beaches in Puget Sound are currently bluff-backed beaches (Fresh et al., 2011).

    c. Barrier beaches are the fourth ranking shoreform, accounting for 440 km (11.1%) of the shoreline (Fresh et al., 2011; Schlenger et al., 2011).

    d. Over time, there has been a decline in length of bluff-backed beach and barrier beach of 128 km (*8.4%)* and 60 km *(13.6%)*, respectively (Fresh et al., 2011).

10. Erosion along bluff-backed beaches is both a blessing and a curse. Erosion of portions of bluff-backed beaches called "feeder bluffs" supplies an estimated 90% of the sediment for maintaining beaches and associated nearshore habitats (Downing, 1983; Johannessen & MacLennan, 2007; Simenstad et al., 2011; Schlenger et al., 2011). However, bluff erosion can cause considerable damage to homes and other infrastructure.

11. Barrier beaches often provide the protective berm that supports coastal embayment shoreforms such as barrier estuaries and lagoons. This shoreform type also includes spits, tombolos, and other depositional features (Johannessen & MacLennan, 2007; Fresh et al., 2011).

12. Beach erosion rates in the Northern Sound are on the order of 2–10 cm yr^{-1} (Johannessen & MacLennan, 2007). Erosion rates farther south are apparently on the order of a few centimeters a year, or less, in most areas.

    a. Almost 1,000 km of coastal bluff are affected by shallow land sliding (Finlayson, 2006). Bluff retreat rates on these sites range from 3 cm yr^{-1} to 150 cm yr^{-1}. Estimates of the total length of unstable shoreline range by county from 3% to more than 50%, with an average of 31%.

    b. Bluffs are likely to retreat more rapidly in the future due to sea-level rise, increased precipitation, storminess (wave energy) and storm frequency, and higher groundwater levels (Johannessen & MacLennan, 2007).

13. A total of 33.4% of bluff-backed beaches and 27.2% of barrier beaches have been at least partly armored (Fresh et al., 2011; Schlenger, et al., 2011).

    a. Only 25% of all bluff-backed beaches are completely unarmored (Fresh et al., 2011).

   b. Armoring is correlated with beach narrowing and reduced shade and drift log abundance because of increased sediment transport (Johannessen & MacLennan, 2007; Fresh et al., 2011). Fine-grain sediment is mobilized preferentially, decreasing the volume of beach sediment and leaving only the coarse material behind. This erosion can reduce the potential upper intertidal fine gravel and sand spawning areas for surf smelt and sand lance, forage fish for Pacific salmon.

14. The embayment shoreforms ('embayment' refers to bays and bay-like formations) have suffered the most significant declines in numbers of all natural Puget Sound shoreform segments (Schlenger et al., 2011).

    a. 305 embayment shoreforms have been lost or transitioned to an artificial shoreform, from 884 under historical conditions to 579 currently, a 35% reduction (Fresh et al., 2011; Schlenger et al., 2011).

15. Embayment shoreforms in Puget Sound have also lost significant shoreline length.

    a. From an embayment shoreline length of about 1,100 km (23.2% of total shoreline), only about 600 km (15.0%) exist currently, a decline of nearly 46% (Fresh et al., 2011; Schlenger et al., 2011). This reduction in length occurred nearly evenly among all embayment shoreform types.

    b. Armoring is the main modification to embayment shoreforms, with 18% of the shoreline length of embayments armored (Fresh et al., 2011). Many of these changes are due to fill, tidal barriers, or roads that, in addition to removing natural shoreform features, tend to straighten and simplify the shoreline (Schlenger et al., 2011).

16. Embayments provide high value nearshore habitat for juvenile salmon (Schlenger et al., 2011).

    a. The sheltered condition that embayments provide can make them suitable for native shellfish, eelgrass and kelp beds, and shorebirds.

    b. Coastal inlets often contain creek deltas, with extensive and complex wetlands providing some of the ecosystem services found in river deltas, and are critical habitat for juvenile Pacific Salmon (Cereghino et al., 2012).

References

Brennan, J.S., and H. Culverwell. 2004 Marine Riparian: An Assessment of Riparian Functions in Marine Ecosystems. Published by Washington Sea Grant Program Copyright 2005, UW Board of Regents, Seattle, WA. 34 p. Available at https://wsg.washington.edu/wordpress/wp-content/uploads/Marine-Riparian-Function-Assessment.pdf

Cereghino, P., J. Toft, C. Simenstad, E. Iverson, S. Campbell, C. Behrens, J. Burke. 2012. Strategies for nearshore protection and restoration in Puget Sound. Puget Sound Nearshore Report No. 2012-01. Published by Washington Department of Fish and Wildlife, Olympia, Washington, and the U.S. Army Corps of Engineers, Seattle, Washington. Available at www.pugetsoundnearshore.org

Clancy, M., I. Logan, J. Lowe, J. Johannessen, A. MacLennan, F.B. Van Cleve, J. Dillon, B. Lyons, R. Carman, P. Cereghino, B. Barnard, C. Tanner, D. Myers, R. Clark, J. White, C. A. Simenstad, M. Gilmer, and N. Chin. 2009. Management Measures for Protecting the Puget Sound Nearshore. Puget Sound Nearshore Ecosystem Restoration Project Report No. 2009-01. Published by Washington Department of Fish and Wildlife, Olympia, Washington. Available at www.pugetsoundnearshore.org

Downing, J. 1983. The Coast of Puget Sound: Its Processes and Development. University of Washington Press, Seattle, 126 p.

Finlayson, D. 2006. The geomorphology of Puget Sound beaches. Puget Sound Nearshore Partnership Report No. 2006-02. Published by Washington Sea Grant Program, University of Washington, Seattle, Washington. Available at http://pugetsoundnearshore.org

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. Available at www.pugetsoundnearshore.org

Gaydos, J., L. Dierauf, G. Kirby, D. Brosnan, K. Gilardi, G. Davis. 2009. Top 10 Principles for Designing Healthy Coastal Ecosystems Like the Salish Sea. EcoHealth Conservation Medicine: Human Health: Ecosystem Sustainability 5:209 DOI: 10.1007/s10393-009-0209-1.

Gelfenbaum, G., T. Mumford, J. Brennan, H. Case, M. Dethier, K. Fresh, F. Goetz, M. van Heeswijk, T.M., Leschine, M. Logsdon, D. Myers, J. Newton, H. Shipman, C.A. Simenstad, C. Tanner, and D. Woodson, 2006. Coastal Habitats in Puget Sound: A research plan in support of the Puget Sound Nearshore Partnership. Puget Sound Nearshore Partnership Report No. 2006-1. Published by the U.S. Geological Survey, Seattle, Washington. Available at http://pugetsoundnearshore.org

Johannessen, J. and A. MacLennan. 2007. Beaches and Bluffs of Puget Sound. Puget Sound Nearshore Partnership Report No. 2007-04. Published by Seattle District, U.S. Army Corps of Engineers, Seattle, Washington. Available at www.pugetsoundnearshore.org

Rice, C.A. 2006. Effects of shoreline modification on a northern Puget Sound beach: microclimate and embryo mortality in surf smelt (*Hypomesus pretiosus*). Estuaries and Coasts 29:63–71.

Ruckelshaus, M. H and M. M. McClure. 2007. Sound Science: Synthesizing ecological and socioeconomic information about the Puget Sound ecosystem. 2007. Prepared in cooperation with the Sound Science collaborative team. U.S. Dept. of Commerce, National Oceanic & Atmospheric Administration (NMFS), Northwest Fisheries Science Center. Seattle, Washington. Available at http://blog.pugetsoundinstitute.org/wp-content/uploads/2011/12/SoundScience2007.pdf

Schlenger, P., A. MacLennan, E. Iverson, K. Fresh, C. Tanner, B. Lyons, S. Todd, R. Carman, D. Myers, S. Campbell, and A. Wick. 2011. Strategic Needs Assessment: Analysis of Nearshore Ecosystem Process Degradation in Puget Sound. Prepared for the Puget Sound Nearshore Ecosystem Restoration Project. Technical Report 2011-02. Available at www.pugetsoundnearshore.org

Shipman, H. 2008. A Geomorphic Classification of Puget Sound Nearshore Landforms. Puget Sound Nearshore Partnership Report No. 2008-01. Published by Seattle District, U.S. Army Corps of Engineers, Seattle, Washington. Available at www.pugetsoundnearshore.org.

Simenstad, C.A., M. Ramirez, J. Burke, M. Logsdon, H. Shipman, C. Tanner, J. Toft, B. Craig, C. Davis, J. Fung, P. Bloch, K. Fresh, S. Campbell, D. Myers, E. Iverson, A. Bailey, P. Schlenger, C. Kiblinger, P. Myre, W. Gerstel, and A. MacLennan. 2011. Historical Change of Puget Sound Shorelines: Puget Sound Nearshore Ecosystem Project Change Analysis. Puget Sound Nearshore Report No. 2011-01. Published by Washington Department of Fish and Wildlife, Olympia, Washington, and U.S. Army Corps of Engineers, Seattle, Washington. Available at www.pugetsoundnearshore.org.

Terrestrial and freshwater habitat

How important is land cover conversion as a stressor? And how has land cover changed in the Puget Sound watershed?

Essay by: Nick Georgiadis, University of Washington Puget Sound Institute

The 2014 Puget Sound Pressures Assessment

Ecosystem recovery should be, and often is, informed by the best available science. Typically, the source of the best available information is peer-reviewed scientific literature. However, questions often arise and major decisions must be made for which there is no vetted guidance in the scientific literature, and no time to study the issue directly. For example, among the first questions asked by recovery practitioners about an ecosystem like Puget Sound are: *Of the many human pressures on the ecosystem, which present the greatest threats?* And *On which pressures should recovery effort be focused?* Typically, answers are not to be found in technical journals, rather, they reside inside the crania of specialists and experts who are familiar with diverse components of the ecosystem. The process of carefully asking the right questions of experts, and classifying their informed answers, is known as 'expert elicitation'. The trick is to draw opinions as objectively as possible, from as many experts as possible, and synthesize their responses as systematically as possible. While the products may not be as well-supported as, say, the results of an incisive experiment, they are infinitely superior to abject guesses, and serve very well, if by default, as the best available information.

Expert elicitation was recently used to list and rank human actions and effects that are injurious to the Puget Sound ecosystem, often referred to as "stressors". Details of the exercise are intricate and lengthy, but it was thorough: in the end, 61 experts rated the impact of a total of 47 stressors on a total of 60 "endpoints" – the species and habitats that humans value the most, and aspire to conserve or restore. The assessment yielded scores quantifying how severely each stressor affects each endpoint. These scores were summed to yield overall rankings of stressor impact, and of endpoint vulnerability.

Results were published online in a report entitled *The 2014 Puget Sound Pressures Assessment* (PSPA; McManus et al., 2014), and were revealing about the relative impacts of stressors on terrestrial, freshwater, and marine environments.

Land cover conversion featured prominently among stressors with the greatest potential impacts across all environments:

- Conversion of land cover for natural resource production
- Non-point source conventional water pollutants
- Conversion of land cover for transportation & utilities
- Shoreline hardening
- Non-point source, persistent toxic chemicals in aquatic systems

Endpoints with greatest intrinsic vulnerability included:

- Cutthroat trout
- Salmon species: coho, Chinook, chum, pink, and kokanee
- Aquatic vertebrates relying on freshwater streams

Much to the relief of recovery professionals, the existing 'Vital Signs', selected in 2011 to serve as indicators of the general health of Puget Sound, are well represented among high-ranking stressors and endpoints in this assessment. Salmonids feature prominently among endpoints because they inhabit both marine and freshwater environments, and are therefore exposed to stressors in both. Similarly, conversion of land cover ranks highly among stressors because it includes not only agriculture and timber production, but also aquaculture (e.g. of oysters) in marine environments.

The colossal effort expended on salmon recovery, and on monitoring salmon numbers, breeding, harvest, and movements, is well known. The efforts to quantify changes in (terrestrial) land cover are not so well known, and deserve further mention here.

Estimates of land cover change

The only way to measure changes in land cover over large regions is to compare satellite images taken of the same area at different points in time, and identify 'pixels' that signify human-caused conversions, typically from natural vegetation to development (roads, buildings, pavement). Three studies are described here:

1. Alberti et al. (2004) assessed land cover change between 1991 and 1999 in Central Puget Sound, using Landsat (Thematic Mapper and Enhanced Thematic Mapper) imagery to distinguish seven classes: 75% impervious, 15-75% impervious, forest, grass, clear cut, bare soil, and water. Results showed that over 8 years (1991-98) urban growth produced an overall 0.84% increase in paved urban area per year, and a 0.98% increase in mixed urban areas per year. Forest cover declined by 1.03% per year over the same period.

2. Recently, Bartz et al. (2015) also used annual land cover maps created from Landsat images over 22 years (1986 to 2008) to evaluate trends in developed land cover (50-100% impervious) in areas adjacent to five types of habitat utilized by Chinook salmon (*O. tshawytscha*) in the Puget Sound region. Increases in developed land cover adjacent to each of the habitat types were small, but consistently measurable (Table 1).

Table 1

	% increase in developed cover per year
Nearshore	0.09
Estuary	0.06
Mainstem	0.14
Tributary	0.25
Floodplain	0.22
Basin	0.46

For each habitat type, the increasing trend changed during the time series. In nearshore, mainstem, and floodplain areas, the rate of increase in developed land cover slowed in the latter portion of the time series. In estuary and tributary areas the rate increased. Watersheds that

were already highly developed in 1986 tended to have higher rates of development than initially less developed watersheds. Overall, results suggested that developed land cover in areas adjacent to Puget Sound salmon habitat has increased only slightly since 1986 and that the rate of change has slowed near some key habitat types, although this has occurred within the context of a degraded baseline condition. Despite an increase in human population size in the Puget Sound region of more than 1,000,000 people from 1990 to 2010 (>30% increase), developed land cover in all habitat areas increased by considerably less than 1 percentage point during approximately the same time frame.

3. Pierce (2011) has done the most sophisticated analyses, using high-resolution (1m) imagery, new software, and prodigious computing power to detect changes in land cover from 2006 to 2009 in three WRIAs of the Puget Sound region: lower Skagit (WRIA 3), Snohomish (WRIA 7), and Kitsap (WRIA 15).

   Results showed that rates of change with visible indications of permanent conversion were similar in the three areas (Table 2).

Table 2

	WRIA 3	WRIA 7	WRIA 15
Permanent Change Locations (# of polygons)	658	1534	1433
Permanent Change Area (acres)	1182	2307	1449
Annual Rate of Change (% of total WRIA area)	0.08%	0.06%	0.11%

Comparing results from these studies is problematic because they differ in approach, data source, area, scale, and time period. While methods to detect and measure land cover change are clearly advancing in scope and sophistication, this has drawbacks, in that when methods change, it is difficult to monitor long-term trends. Ideally, observed land cover changes could be linked to data relating to issue of development permits, and thereby help to enforce Growth Management Act and Shoreline Management Plans. However, this is evidently a distant goal.

References

Alberti, M, Weeks, R., and Coe, S. (2004). Urban Land-Cover Change Analysis in Central Puget Sound. *Photogrammetric Engineering & Remote Sensing*, 70 (9), 1043–1052.

Bartz, K.K., Ford, M.J., Beechie, T.J., Fresh, K.L., Pess, G.R., Kennedy, R.E., et al. (2015) Trends in Developed Land Cover Adjacent to Habitat for Threatened Salmon in Puget Sound, Washington, U.S.A.. *PLoS ONE 10*(4): e0124415. doi:10.1371/ journal.pone.0124415.

McManus, E., Jenni, K., Clancy, M., Ghalambor, K., Logan, I., Langdon, J., Redman, S., Labiosa, W., Currens, K., Quinn, T., and Burke, J. (2014). *The 2014 Puget Sound Pressures Assessment*. Puget Sound Partnership Publication. Tacoma, WA.

Pierce, K. (2011) Final Report on High Resolution Change Detection Project. Unpublished.

Species and food webs

An overview

Essay by: Eric Wagner

The concept of the food web is one of the oldest in modern ecology, dating from Charles Elton's landmark 1927 book, *Animal Ecology*. Elton was interested in those fundamental but perhaps overlooked processes that have the power to shape entire communities. One such process was getting food. "Animals are not always struggling for existence," he wrote, "but when they do begin, they spend the greater part of their lives eating." How an animal caught its food was not important. What mattered was the way energy moved from one level of organisms to the next—from, as Elton saw it, a plant, to an herbivore, to a carnivore.

For Elton, those schematics were "food-chains"; all the food chains in a given community constituted its "food-cycle". Over time, the metaphor evolved from a chain, with its reliance on single linkages, into its more modern iteration, the web. This better reflects the many roles a single organism can play, or the fact that the relationships between different trophic levels and functional groups are not necessarily linear. So, too, do scientists draw food webs in a number of ways, depending on the scale of what they are trying to show, or the nature of the interactions between species. Within the Salish Sea, for instance, there can be terrestrial and aquatic food webs; or, to parse more finely, freshwater and marine food webs; or to parse more finely still, a soft-bottomed nearshore food web, a pelagic (open marine waters) food web, and so on.

The Salish Sea is rich in life, home to thousands of species of marine invertebrates, hundreds of species of plants, more than 200 species of fish, nearly 200 species of seabirds, and more than 30 species of mammals. All of them are part of at least one food web. They may be top-level predators, like seabirds or most of the marine mammals. They can be mid-level consumers, like juvenile fish, shorebirds, or sea stars, acting as links between the food web's lower and upper levels. There are herbivores and detritivores near the base, which graze either on plants or other non-living organic matter. And there are the primary producers—the phytoplankton, algae, and vascular plants—that form the very base of the food web.

All food webs are dynamic. Changes in the abundance of almost any species can cause strong ripples as the remaining organisms reshuffle themselves. Along the west coast of North America, one of the most famous examples of a so-called trophic cascade is that of the sea otter; or, more accurately, its absence. Sea otters are top-level predators in kelp forest food webs. Among other things, they prey on sea urchins, helping to control their numbers. When trappers hunted sea otters to near extinction from the mid-18th through the early 20th centuries— sea otters were completely extirpated from the state of Washington until their reintroduction in 1972—populations of urchins suddenly thrived, as they now had unfettered access to their preferred food, kelp. Heavily consumed, the kelp suffered as a result. But it wasn't just kelp that paid the price for the absent sea otters: all the species that depended on kelp for shelter or protection

were affected, too. More recently, the widespread loss of sea stars has left scientists watching to see how the rocky intertidal food web will reassemble itself, suddenly deprived of a keystone species.

All throughout the Salish Sea, food webs are in a near constant state of flux, whether due to local or regional conditions, seasonal changes, or large-scale perturbations, the potential consequences of which often remain unknown. As scientists study ocean acidification, for example, they have begun to try to predict where in the marine food web it will have the greatest impacts. The lowering of pH is felt most keenly by species that build shells or other internal structures from calcium, such as mollusks, crustaceans, and echinoderms. Of these, mollusks have so far received the most popular attention. But ecosystem-based models show that changes to crustacean abundance—most especially copepods, a kind of zooplankton—will most likely have the strongest impact on overall food web structure.

The collection of facts presented in this section, on the nearshore and pelagic food webs, as well as information on some of the region's most charismatic top-level consumers, reflect the latest knowledge on species and processes vital to the health of the Salish Sea ecosystem. They also highlight critical knowledge gaps that future research will fill. All of which will help the organism that sits at the apex of almost every food webs, and whose effects are felt throughout: the people who depend on all the resources the Salish Sea has to offer.

Species

Section author: Joe Gaydos, SeaDoc Society; University of California, Davis

Species of concern in the Salish Sea

The following list is drawn from a 2014 paper written by Joe Gaydos and Jacqlynn Zier of the SeaDoc Society that discusses the increase in species of concern in the Salish Sea. As of November 15, 2013, there were 119 species at risk in the Salish Sea, almost twice the number of species at risk when the indicator was first established in 2002. The paper was presented at the April 30 - May 2, 2014 Salish Sea Ecosystem Conference in Seattle, WA (Gaydos and Zier, 2014).

- American Avocet (*Recurvirostra americana*)
- American Bittern (*Botaurus lentiginosus*)
- American Golden-Plover (*Pluvialis dominica*)
- American Kestrel (*Falco sparverius*)
- American Peregrine Falcon (*Falco peregrinus anatum*)
- American Shad (*Alosa sapidissima*)
- American White Pelican (*Pelecanus erythrorhynchos*)
- Ancient Murrelet (*Synthliboramphus antiquus*)
- Baird's Beaked Whale (*Berardius bairdii*)
- Bald Eagle (*Haliaeetus leucocephalus*)
- Band-tailed Pigeon (*Patagioenas fasciata*)
- Basking Shark (*Cetorhinus maximus*)
- Belted Kingfisher (*Megaceryle alcyon*)
- Black Rockfish (*Sebastes melanops*)
- Black-footed Albatross (*Phoebastria nigripes*)
- Bluntnose Sixgill Shark (*Hexanchus griseus*)
- Bocaccio (*Sebastes paucispinis*)
- Brandt's Cormorant (*Phalacrocorax penicillatus*)
- Brant (*Branta bernicla*)
- Brown Bear (*Ursus arctos*)
- Brown Pelican (*Pelecanus occidentalis*)
- Brown Rockfish (*Sebastes auriculatus*)
- Buff-breasted Sandpiper (*Tryngites subruficollis*)
- Bull Trout (*Salvelinus confluentus*)

- Buller's Shearwater
  (*Puffinus bulleri*)
- Cackling Goose
  (*Branta hutchinsii*)
- California Gull
  (*Larus californicus*)
- Canary Rockfish
  (*Sebastes pinniger*)
- Caspian Tern
  (*Hydroprogne caspia*)
- Cassin's Auklet
  (*Ptychoramphus aleuticus*)
- China Rockfish
  (*Sebastes nebulosus*)
- Chinook Salmon - Puget Sound
  (*Oncorhynchus tshawytscha pop. 15*)
- Chum Salmon
  (*Oncorhynchus keta*)
- Chum Salmon - Hood Canal Summer Run
  (*Oncorhynchus keta pop. 2*)
- Clark's Grebe
  (*Aechmophorus clarkii*)
- Coastal Cutthroat Trout
  (*Oncorhynchus clarkii clarkii*)
- Coho Salmon - Interior Fraser Population
  (*Oncorhynchus kisutch pop. 7*)
- Coho Salmon - Puget Sound/Strait of Georgia
  (*Oncorhynchus kisutch pop. 5*)
- Common Loon
  (*Gavia immer*)
- Common Murre
  (*Uria aalge*)
- Copper Rockfish
  (*Sebastes caurinus*)
- Cuvier's Beaked Whale
  (*Ziphius cavirostris*)
- Darkblotched Rockfish
  (*Sebastes crameri*)
- Double-crested Cormorant
  (*Phalacrocorax auritus*)
- Dusky Canada Goose
  (*Branta canadensis occidentalis*)
- Eulachon
  (*Thaleichthys pacificus*)
- Fin Whale
  (*Balaenoptera physalus*)
- Flesh-footed Shearwater
  (*Puffinus carneipes*)
- Forster's Tern
  (*Sterna forsteri*)
- Gray Whale
  (*Eschrichtius robustus*)
- Great Blue Heron
  (*Ardea herodias*)
- Green Heron
  (*Butorides virescens*)
- Green Sea Turtle
  (*Chelonia mydas*)
- Green Sturgeon
  (*Acipenser medirostris*)
- Greenstriped Rockfish
  (*Sebastes elongatus*)
- Gyrfalcon
  (*Falco rusticolus*)
- Harbor Porpoise
  (*Phocoena phocoena*)
- Horned Grebe
  (*Podiceps auritus*)
- Horned Puffin
  (*Fratercula corniculata*)

- Hudsonian Godwit
  (*Limosa haemastica*)
- Humpback Whale
  (*Megaptera novaeangliae*)
- Killdeer
  (*Charadrius vociferus*)
- Killer Whale
  (*Orcinus orca*)
- Killer Whale - Northeast Pacific Offshore Population
  (*Orcinus orca pop. 2*)
- Killer Whale - Northeast Pacific Southern Resident Population
  (*Orcinus orca pop. 5*)
- Killer Whale - Northeast Pacific Transient Population
  (*Orcinus orca pop. 3*)
- Leatherback Sea Turtle
  (*Dermochelys coriacea pop. 1*)
- Long-billed Curlew
  (*Numenius americanus*)
- Long-tailed Duck
  (*Clangula hyemalis*)
- Marbled Murrelet
  (*Brachyramphus marmoratus*)
- North Pacific Spiny Dogfish
  (*Squalus suckleyi*)
- Northern Elephant Seal
  (*Mirounga angustirostris*)
- Northern Fulmar
  (*Fulmarus glacialis*)
- Northern Fur Seal
  (*Callorhinus ursinus*)
- Northern Sea Otter
  (*Enhydra lutris kenyoni*)
- Olympia Oyster
  (*Ostrea conchaphila*)
- Pacific Cod
  (*Gadus macrocephalus*)
- Pacific Hake
  (*Merluccius productus*)
- Pacific Herring
  (*Clupea pallasii*)
- Pacific Ocean Perch
  (*Sebastes alutus*)
- Pacific Sardine
  (*Sardinops sagax*)
- Pacific White-sided Dolphin
  (*Lagenorhynchus obliquidens*)
- Peale's Peregrine Falcon
  (*Falco peregrinus pealei*)
- Pelagic Cormorant
  (*Phalacrocorax pelagicus*)
- Pink Salmon
  (*Oncorhynchus gorbuscha*)
- Pink-footed Shearwater
  (*Puffinus creatopus*)
- Pinto Abalone
  (*Haliotis kamtschatkana*)
- Purple Martin
  (*Progne subis*)
- Quillback Rockfish
  (*Sebastes maliger*)
- Red Knot
  (*Calidris canutus*)
- Red-necked Phalarope
  (*Phalaropus lobatus*)
- Redstripe Rockfish
  (*Sebastes proriger*)
- River Lamprey
  (*Lampetra ayresii*)

- Rough-legged Hawk
  (*Buteo lagopus*)
- Rougheye Rockfish
  (*Sebastes aleutianus*)
- Sandhill Crane
  (*Grus canadensis*)
- Short-billed Dowitcher
  (*Limnodromus griseus*)
- Short-eared Owl
  (*Asio flammeus*)
- Shortspine Thornyhead
  (*Sebastolobus alascanus*)
- Snowy Owl
  (*Bubo scandiacus*)
- Sockeye Salmon - Cultus Lake
  (*Oncorhynchus nerka pop. 7*)
- Sockeye Salmon - Sakinaw Lake
  (*Oncorhynchus nerka pop. 8*)
- Steelhead - Puget Sound
  (*Oncorhynchus mykiss pop. 37*)
- Steller Sea Lion
  (*Eumetopias jubatus*)
- Surf Scoter
  (*Melanitta perspicillata*)
- Tiger Rockfish
  (*Sebastes nigrocinctus*)
- Tufted Puffin
  (*Fratercula cirrhata*)
- Tundra Swan
  (*Cygnus columbianus*)
- Walleye Pollock
  (*Theragra chalcogramma*)
- Wandering Tattler
  (*Tringa incana*)
- Western Grebe
  (*Aechmophorus occidentalis*)
- White Sturgeon - Lower Fraser River Population
  (*Acipenser transmontanus pop. 4*)
- White Sturgeon - Middle Fraser River
  (*Acipenser transmontanus pop. 6*)
- White Sturgeon - Nechako River
  (*Acipenser transmontanus pop. 3*)
- White Sturgeon - Upper Fraser River Population
  (*Acipenser transmontanus pop. 5*)
- Widow Rockfish
  (*Sebastes entomelas*)
- Yellow-billed Loon
  (*Gavia adamsii*)
- Yelloweye Rockfish
  (*Sebastes ruberrimus*)
- Yellowtail Rockfish
  (*Sebastes flavidus*)

Birds and mammals

Salish Sea-reliant mammals

Thirty-eight (38) species of mammals depend on the Salish Sea. Of the 38 species of mammals that have been documented using the Salish Sea marine ecosystem, 30 are highly dependent, 4 are moderately dependent, and 4 have a low dependence on the marine or intertidal habitat and marine derived food when present (Gaydos and Pearson, 2011; Coe and Gaydos, 2013).[21]

Salish Sea-reliant birds

One hundred and seventy-two (172) bird species depend on the Salish Sea (i.e. have been recorded using the Salish Sea marine ecosystem more than 5 times). Of those, 73 are highly dependent, 74 are moderately dependent, and 25 have low dependence on marine or intertidal habitat when present. Similarly, 73 species are highly dependent, 62 species are moderately dependent, and 37 species have a low dependence on marine-derived food. Seventy-two (72) species are both highly dependent on intertidal or marine habitat as well as on marine derived food (Gaydos and Pearson, 2011).

Threatened bird species

Four jurisdictions have the ability to list animals in the Salish Sea: the US and Canadian Federal Governments, the Province of British Columbia and the State of Washington. When last evaluated (Gaydos and Zier, 2014), 32% (55 of 172) of bird species that rely on the Salish Sea were listed as threatened, endangered, or were candidates for listing by one or more jurisdictions.

Marine bird declines

Within the Salish Sea, wintering marine bird populations have declined since the mid 1990s. A recent risk analysis revealed that of the 39 most common bird species that overwinter in the Salish Sea, species that dive and eat schooling forage or bait were 16x more likely to be in decline, suggesting a decrease in the quantity or quality of forage fish in the Salish Sea (Vilchis et al., 2014).

Killer whales[22] [23]

Three ecotypes of killer whales (*Orcinus orca*) can be found in the Salish Sea. These distinct population segments or designatable units are classified as fish eating Residents (both the Northern and Southern Resident Populations occur in the Salish Sea), marine mammal eating

[21] Gaydos and Pearson (2011) list 37 species of mammals. The 38th species, a Ribbon seal (Histriophoca fasciata), was documented in the Salish Sea in 2012. Like the other pinnipeds, it is highly dependent on marine resources.

[22] The Puget Sound Partnership Vital Signs tracks Southern Resident Killer Whales.

[23] The common names killer whale and orca are used interchangeably for Orcina orca.

Transients (West Coast Transients), and fish eaters that specialize in sharks called Offshore Killer Whales (Ford et al., 1998; Ford et al, 2011).

- **Differences:** The better understood Resident and Transient killer whale ecotypes differ by genetics (Hoelzel et al., 2002), diet (Baird and Dill, 1995; Ford et al., 1998), behavior (Baird, 2000), vocal repertoire (Ford 1990) and morphology (Baird and Stacey 1988).

- **Noise:** In the presences of high underwater noise levels, killer whales speak louder and slower, increasing their call amplitude and duration (Foote et al., 2004; Holt et al., 2008).

- **Diet:** Southern Resident killer whales are fish eaters that specialize in salmon (Oncorhynchus spp.), predominantly Chinook salmon (O. tshawytscha) during the summer and early fall (Ford and Ellis 2006; Ford et al., 2010; Hanson et al., 2010) and prey availability is a potential limiting factor in the recovery of this population. Estimated Chinook prey requirements for individual southern residents depends on fish caloric content, the length and sex of the whale, and female whale's pregnancy or lactation status (Williams et al., 2011). Estimates suggest that the 2009 population of Southern Residents (numbering 87 individuals) could consume 12–23% of available Fraser River Chinook between May and September (Williams et al., 2011). If the population reached 155 animals by 2029 energetic requirements could be 75% higher (Williams et al., 2011).

- **PCBs:** In both Resident and Transient killer whales from the Salish Sea, PCB accumulation is strongly related to age, sex, and ecotype with marine mammal-eating transients having higher levels of PCBs than residents (Ross et al., 2000). PCB levels in the majority of Residents and Transients surpass those found to be immuno-toxic and endocrine disrupting in harbor seals (Ross et al., 2000; Krahn et al., 2007) and PCB concentrations are 2.5-3.7 higher in Southern Residents than Northern Residents (Hickie et al., 2007).

Harbor seals

Harbor seals (*Phoca vitulina*), the most common pinniped in the Salish Sea, eat seasonally and regionally abundant fish species and have been documented to eat over 45 species of fish and 4 species of cephalopods in the Salish Sea (Lance et al., 2012).

Marbled Murrelets

The Marbled Murrelet (*Brachyramphus marmoratus*) is an iconic seabird that nests in old growth forest and forages in marine waters. In Washington State's half of the Salish Sea, the breeding (summer) Marbled Murrelet population has declined 7.4% annually between 2001 and 2010 (Miller et al., 2012).

Deep Divers

Compared to large estuaries like the Chesapeake Bay, the Salish Sea is deep thanks the Pleistocene glaciations. It is also home to numerous species of air-breathing birds and mammals that are able to take advantage of its depth, thanks to their phenomenal diving ability. For example, the Common murre (Uria aalge) can dive to 180 m (590.6 ft; Piatt and Nettleship, 1985), Harbor porpoise (Phocoena phocoena) can dive 226 m (741.5 ft; Schreer and Kovacs, 1997), the Harbor seal (Phoca vitulina) can dive to 508 m (1,666.7 ft; Hastings et al., 2004), and the Northern Elephant seal can dive to 1,735m (5692.3 ft; Robinson et al., 2012).

Fishes

(See also: Pelagic and nearshore food webs)

The Salish Sea supports 253 observed fish species (Pietsch & Orr, 2015).

Pacific herring and forage fish

In the last 40 years Pacific herring and surf smelt abundance has decreased 99% in Central and South Puget Sound (Greene et al., 2015). Jellyfish are 9 times more abundant than they were 40 years ago in some Puget Sound basins (Greene et al., 2015). Jellyfish can make up to 90% of the catch in Puget Sound surface trawls, and are most abundant in central and south basins (Rice et al., 2012). Jellyfish compete with adult forage fishes while consuming larval and juvenile stages of fish (Purcell & Arai, 2001).

Long-lived fishes

The Salish Sea is home to numerous long-lived fishes (fish living to 30 or more years). For example, Rougheye rockfish (Sebastes aleutianus) can live to be 205 years old, Yelloweye rockfish (Sebastes ruberrimus) can live to be 118 years old, and Spiny dogfish (Squalus sucklei) can live to be 100 years old (Beamish et al., 2006).

Salmonids

The watersheds and nearshore habitats of Puget Sound currently support 8 species of salmon, trout, and charr (NOAA 2007), four of which are listed as Threatened under the Endangered Species Act (ESA). These are Chinook salmon (*Oncorhynchus tshawytscha*), chum salmon (*O. keta*), bull trout (*Salvelinus confluentus*) and steelhead (*O. mykiss*).

Other species

Detailed accounts of other charismatic Puget Sound species are available on the Encyclopedia of Puget Sound at: http://www.eopugetsound.org/science-review/section-2-species-and-food-webs. See:

1. Bivalves
2. Pinto abalone
3. Dungeness crabs
4. Jellyfish
5. Forage fishes
6. Bentho-Pelagic fish
7. Rockfish
8. Salmonids
9. Marine birds
10. Bald eagles
11. Harbor seals
12. Killer whales

References

Baird, R. W. and L. M. Dill. 1996. Ecological and social determinants of group size in transient killer whales. Behavioral Ecology 7:408–416.

Baird, R. W. and P. J. Stacey. 1988. Variation in saddle patch pigmentation in populations of killer whales (*Orcinus orca*) from British Columbia, Alaska, and Washington State. Canadian Journal of Zoology 66:2582–2585.

Baird, R. W., 2000. The killer whale-foraging specializations and group hunting. In: Mann J, Connor R, Tyack P, Whitehead H, editors. Cetacean societies: field studies in behavior. Chicago, IL: University of Chicago Press. p. 125–153.

Beamish, R. J., G. A. McFarlane and A. Benson. 2006. Longevity overfishing. Progress in Oceanography 68:289-302.

Coe, W. H. and J. K. Gaydos 2013. Ribbon Seals in the Salish Sea? Encyclopedia of Puget Sound. Available at: http://www.eopugetsound.org/articles/ribbon-seals-salish-sea

Foote, A. D., R. W. Osborne, and R. A. Hoelzel. 2004. Whale-call response to masking boat noise. Nature 428: 910.

Ford, J. K. B. 1990.Vocal traditions among resident killer whales (Orcinus orca) in coastal waters of British Columbia. Canadian Journal of Zoology 69:1454–1483.

Ford, J. K. B., G. M. Ellis L. G. Barrett-Lennard, A. B. Morton, R. S. Palm and K. C. Balcomb III. 1998. Dietary specialization in two sympatric populations of killer whales (Orcinus orca) in coastal British Columbia and adjacent waters. Canadian Journal of Zoology 76: 1456-1471.

Ford, J. K. B. and G. M. Ellis. 2006. Selective foraging by fish-eating killer whales (*Orcinus orca*) in British Columbia, Marine Ecology Progress Series 316:185-199.

Ford, J. K. B., G. M. Ellis, P. F. Olesiuk, and K. C. Balcomb. 2010. Linking killer whale survival and prey abundance: food limitation in the ocean's apex predator? Biology Letters 6:139-142.

Ford, J. K. B., G. M. Ellis, C. O. Matkin, M. H. Wetklo, L. G. Barrett-Lennard and R. E. Withler. 2011 Shark predation and tooth wear in a population of northeastern Pacific killer whales. Aquatic Biology 11: 213-224.

Gaydos, J. K., and S. Pearson. 2011. Bird and Mammals that Depend on the Salish Sea: a compilation. Northwestern Naturalist 92: 79-89.

Gaydos, J. K. and J. Zier. 2014. Species of Concern within the Salish Sea nearly double between 2002 and 2013. Proceedings of the Salish Sea Conference, Seattle, WA, April 2014.

Greene, C., Kuehne, L., Rice. C, Fresh, K., & Pentilla, D. (2015). Forty years of change in forage fish and jellyfish abundance across greater Puget Sound, Washington (USA): anthropogenic and climate associations. Marine Ecology Progress Series, 525, 153-170.

Hanson M.B., R. W. Baird, J. K. B. Ford, J. Hempelmann-Halos, D. M. Van Doornik, J. R. Candy, C. K. Emmons, G. S. Schorr, B. Gisborne, K. L. Ayres, S. K. Wasser, K. C. Balcomb, K. Balcomb-Bartok, J. G. Sneva and M. J. Ford. 2010. Species and stock identification of prey consumed by endangered southern resident killer whales in their summer range. Endangered Species Research 11:69–82.

Hastings, K. K., K. J. Frost, M. A. Simpkins, G. W. Pendleton, U. G. Swain, and R. J. Small. 2004. Regional differences in diving behavior of harbor seals in the Gulf of Alaska. Canadian Journal of Zoology 82:1755-1773.

Hickie, B. E., P. S. Ross, R. W. MacDonald, and J. K. B. Ford. 2007. Killer whales (*Orcinus orca*) face protracted health risks associated with lifetime exposure to PCBs. Environmental Science and Technology 41:6613-6619.

Hoelzel, A. R., A. Nataoli, M. E. Dalheim, C. Olavarria, R. W. Baird, and N. A. Black. 2002. Low worldwide genetic diversity in the killer whale (*Orcinus orca*): implications for demographic history. Proceedings of the Royal Society, London 269:1467–1473.

Holt, M. M., D. P. Noren, V. Veirs, C. K. Emmons, and S. Veirs. 2008. Speaking up: killer whales (*Orcinus orca*) increase their call amplitude in response to vessel noise. Journal of the Acoustical Society of America 125 DOI: 10.1121/1.3040028

Krahn, M. M., M. B. Hanson, R. W. Baird, R. H. Boyer, D. G. Burrows, C. K. Emmons, J. K. B. Ford, L. L. Jones, D. P. Noren, P. S. Ross, G. S. Schorr, and T. K. Collier. 2007. Persistent organic pollutants and stable isotopes in biopsy samples (2004/2006) from Southern Resident killer whales. Marine Pollution Bulletin 54:1903-1911.

Lance, M., C. Wan-Ying, S. J. Jeffries, S. F. Pearson, and A. Acevedo-Gutierrez. 2012. Harbor seal diet in northern Puget Sound: implications for the recovery of depressed fish stocks. Marine Ecology Progress Series 464:257-271.

Miller, S. L., M. G. Raphael, G. A. Falxa, C. Strong, J. Baldwin, T. Bloxton, B. M. Galleher, M. Lance, D. Lynch, S. F. Pearson, C. J. Ralph, and R. D. Young. Recent population decline of the Marbled Murrelet in the Pacific Northwest. The Condor 114:771-781.

Piatt, J. F. and D. N. Nettleship. 1985. Diving depths of four alcids. The Auk 102:293-297.

Pietsch, T.W., and J.T. Orr (2015). Fishes of the Salish Sea: a compilation and distributional analysis. NOAA Professional Paper NMFS 18, 106 p. doi:10.7755/PP.18.

Rice, C., Duda, J., Greene, C. & Karr, J (2012). Geographic Patterns of Fishes and Jellyfish in Puget Sound Surface Waters, Marine and Coastal Fisheries: Dynamics, Management, and Ecosystem Science, 4(1), 117-128, DOI:10.1080/19425120.2012.680403.

Robinson, P. W., D. P. Costa, D. E. Crocker, J. P. Gallo-Reynoso, C. D. Champagne, M. A. Fowler, C. Goetsch, K. T. Goetz, J. L. Hassrick, L. A. Huckstadt, C. E. Kuhn, J. L. Maresh, S. M. Maxwell, B. I, McDonald, S. H. Peterson, S. E. Simmons, N. M. Teutschel, S. Villegas-Amtmann, and K. Yoda. 2012. Foraging behavior and success of a mesopelagic predator in the Northeast Pacific Ocean: Insights from a data-rich species, the Northern Elephant Seal. PLOS ONE 7:5 e36728.

Ross, P. S., G. M. Ellis, M. G. Ikonomou, L. G. Barrett-Lennard, and R. F. Addison. 2000 High PCB concentrations in free-ranging Pacific killer whales, Orcinus orca: effects of age, sex and dietary preference. Marine Pollution Bulletin 40:504-515.

Schreer, J. F. and K. M. Kovacs. 1997. Allometry of diving capcity in air-breathing vertebrates. Canadian Journal of Zoology 75:339-358.

Thompson, R. E. 1994. Physical Oceanography of the Strait of Georgia-Puget Sound-Juan de Fuca Strait System. Pp. 36-92. In Wilson, R. C. H., R. J. Beamish, F. Aitkens and J. Bell (Eds.). Proceedings of the BC Washington Symposium on the Marine Environment, January 13 -14, 1994. Canadian Technical Report on Fisheries and Aquatic Sciences 1948.

Vilchis, I. L., C. Kreuder Johnson, J. R. Evenson, S. F. Pearson, K. Barry, P. Davidson, M. Raphael and J. K. Gaydos. 2014. Assessing ecological correlates of marine bird declines to inform marine conservation. Conservation Biology. DOI: 10.1111/cobi.12378

Williams, R., M. Krkosek, E. Ashe, T. . Branch, S. Clark, P. S. Hammond, E. Hoyt, D. P. Noren, D. Rosen and A. Winship. 2011. Competing conservation objectives for predators and prey: Estimating killer whale prey requirements for Chinook salmon. PLOS One 6:11 e26738

Food webs

The nearshore food web

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Summary

The Puget Sound food web relies on two distinct food web pathways; a phytoplankton-based "grazer" community that directly consumes living organic matter, and a detritus-based community that consumes dying or decaying organic materials that are first transformed by microbes (Seliskar and Gallagher 1983). This fact sheet describes the detritus-based food webs of Puget Sound, with an emphasis on the sources that contribute to the base of the food web, how landscape change has affected detritus availability, and the types of organisms that ultimately depend on detritus for their energy needs. For the most part, detritus-based food webs are associated with benthic (sedimentary seafloor) ecosystems, with the source of energy emanating from rooted vascular plants and their epiphytes, benthic-attached macroalgae (i.e. kelp), or benthic microalgae. This distinguishes the detrital food web from pelagic systems wherein the main source of food at the base of the food web is produced in the water column by phytoplankton.

Sources of detritus and landscape change

1. Sources of detritus supporting Puget Sound food webs include: 1) terrestrial input from watersheds, 2) estuarine wetlands (including tidal freshwater swamps, scrub-shrub tidal wetlands, and emergent marshes, 3) seagrass beds and associated epiphytes, 4) benthic microalgae, 5) marine macroalgae (i.e. kelp), and marine riparian vegetation (Seliskar & Gallagher 1983). Together, these ecosystems produce the biomass equivalent of at least 15,000 school buses each year (with school buses estimated to weigh 10 metric tons).

    Approximate biomass contributions to Puget Sound's detrital pool based on areal coverage (Simenstad et al., 2011) and annual primary productivity estimates (Fact 4):

    a. Eelgrass: 79,360 metric tons (22610 ha eelgrass, Christiaen et al., 2015). This is equivalent to 7936 school buses (at 10mt each).

    b. Kelps & macroalgae: No areal estimates are available for Puget Sound, but along the WA west coast and Strait of Juan de Fuca floating species encompass an estimated 1500 ha (Mumford & Berry, 2014). This is equivalent to 500-22000 metric tons of biomass generated per year. Within Puget Sound, floating kelp occurs along 11% of the shoreline and understory kelp occurs along 31% of the shoreline (ShoreZone Inventory). So, kelps on just the outer coast produce enough material to equal 2,200

school buses. This doesn't include the shorelines within Puget Sound or its sub-basins, which together cover nearly 8000 km.

c. Mudflats (benthic microalgae): 31.3 metric tons (mt). Mudflats, which we think are barren zones, actually produce 3 school buses worth of organic material per year.

d. Emergent marshes (estuarine mixing zone): 62.7 mt. 6.2 school buses.

e. Scrub-shrub tidal wetlands: 36.3 mt. 3.6 school buses.

f. Tidal freshwater swamps: 16.3 mt. 1.6 school buses.

g. Marine riparian vegetation: Unknown

h. Terrestrial/Riverine organic matter: Cumulative measure unknown. The total organic carbon exported Skagit and Snohomish alone contribute 18000-56000 mt/yr (Mullholland & Watts, 1982). 1800-5600 buses.

2. Primary productivity is exceptionally high for these ecosystems (range: 350 – 1800 g C m^2/yr; Thom, 1990; Ewing, 1986), rivaling that of tropical rainforests, which are often thought to be the most productive ecosystems in the world (2200 g C m^2/yr). The other source of food energy for Puget Sound food webs comes from water column production by phytoplankton (planktonic algae), which exhibit comparatively lower productivity rates than marsh ecosystems (465 g C m^2/yr Winter et al., 1975).

   Primary productivity estimates for detrital sources contributing to Puget Sound are strong for:

   a. Eelgrass ecosystems: 351 g C/m^2/yr (Thom, 1990). 50% of annual primary production due to epiphytic algae, 2% to *Z. japonica*, and 48% to *Z. marina* (Padilla Bay). This compares to 303 g C/m^2/yr in Grays Harbor (Thom, 1984).

   b. Emergent marsh ecosystems: 443-878 g C/m^2/yr (Ewing, 1986).

   c. Brackish wetlands: 1115-1742 g C/m^2/yr (Ewing, 1986), 1629 g C/m^2/yr (Disraeli & Fonda, 1978), 1390 g C/m^2/yr (Burg et al., 1976), 1355 g C/m^2/yr (Levings & Moody, 1976).

   Primary productivity estimates are poor or unavailable for Puget Sound/ Salish Sea for the following detrital sources:

   a. Benthic microalgae: 229 g C/m^2/yr in Hood Canal, WA (Simenstad & Wissmar, 1985). 50-250 g C/m^2/yr, measured in the temperate Ems-Dollard estuary, Denmark (Colign & de Jonge, 1984).

   b. Tidal freshwater marshes: 1530 g C/m^2/yr, mean value from North American review (Findlay et al., 1981).

c. Kelps and macroalgae: 350-1500 g C/m^2/yr, *Macrocystis pyrifera,* 600-1300 g C/m^2/yr for Laminaria in coastal California (Dayton, 1985). Macroalgae productivity strongly depends on dissolved inorganic nitrogen, which varies with coastal upwelling cycles associated with El Nino and La Nina events. No Puget Sound primary productivity rates were available.

d. Riverine inputs (limited data Puget Sound) and marine riparian vegetation: Nanaimo River = Dissolved organic carbon (DOC): 2000 g C/ m^2/yr, fine particulate organic carbon (FPOC): 56 g C/ m^2/yr (Naiman & Sibert, 1978), similar to marsh ecosystems. Skagit River 3.8 g C/m^3/yr Much of this material is thought to be refractory, and therefore unavailable to consumers (Canuel et al., 2009; Mueller-Solger et al., 2002).

3. While phytoplankton becomes available to Puget Sound food webs via punctuated seasonal blooms in the spring and fall (Winter et al., 1975), detritus is available continually throughout the year because it breaks down slowly, with decomposition ranging between 8-112 weeks (Brinson et al., 1978).

   Vascular marsh plants decay at a rate of approximately 0.3%/yr (Findlay et al., 1990), although decomposition depends on temperature, aerobic conditions, microbial and detritus feeder community composition, hydroperiod (moisture), and the lability of the species decomposing (Brinson et al., 1981). Microbial conditioning of detrital material enhances the nitrogen content, and hence, the nutritional quality of the material for consumers (Sosik & Simenstad, 2013).

4. Sound-wide degradation of these ecosystems represents a non-trivial reduction of the amount of detritus entering Puget Sound food webs. Most critically for detritus-based food webs, the total area of wetlands has declined dramatically in most river deltas, with the greatest losses in South Central Puget Sound and the Whidbey sub-basins. In the 16 major estuarine deltas feeding into Puget Sound, 25% of unvegetated mudflats, 45% of marshes within estuarine mixing zones, 98% of brackish marshes, and 90% of tidal freshwater wetlands have been lost (Simenstad et al., 2011). This represents over 275 metric tons/yr of detrital materials that no longer reach Puget Sound food webs just due to alterations in the deltas of 16 river systems leading into Puget Sound. When non-delta ecosystems are included, the Sound is deprived of nearly 450 metric tons of detritus per year—equal to about 45 school buses.

   Calculations for the historical change in detrital biomass emanating from Puget Sound river deltas are based on primary production estimates for each source (see Fact 4) and the estimated historical change in the areal extent of each ecosystem type according to the PSNERP Historical Change Analysis of Puget Sound nearshore ecosystems (Simenstad et al., 2011).

   Estimated biomass lost due to historical change in landscape structure:

River Delta losses:

1. Mudflats: 9,500 $kg/m^2/yr$
2. Emergent marshes: 25,700 $kg/m^2/yr$
3. Scrub-shrub tidal wetlands: 90,280 $kg/m^2/yr$
4. Tidal freshwater swamps: 150,000 $kg/m^2/yr$

Non-Delta losses:

1. Mudflats: NA
2. Emergent marshes: 37037 $kg/m^2/yr$
3. Scrub-shrub tidal wetlands: 98,570 $kg/m^2/yr$
4. Tidal freshwater swamps: 38,250 $kg/m^2/yr$

5. Approximately 47% of annual marsh primary production is exported from marsh ecosystems to estuarine food webs as detritus (Sherwood et al., 1990), feeding benthic infauna such as clams and mussels (Howe & Simenstad, 2012), gammarid amphipods, and polychaete annelid worms (Jones et al., 1990). The remainder accretes in marsh sediments or feeds marsh detritivores (Sherwood et al., 1990).

6. In Puget Sound, over 27% of total shoreline length is armored by some type of structure, although many regions, such as Central Puget Sound (60%), exhibit much higher percentages (Simenstad et al., 2011).

   The Puget Sound Nearshore Ecosystem Restoration Project "conducted a comprehensive and spatially-explicit analysis of net changes to nearshore ecosystems of Puget Sound – its beaches, estuaries, and deltas- since its earliest industrial development" (Simenstad et al., 2011). Present (2000-2006) shoreline structure was quantitatively compared to the earliest land surveys of the General Land Office and US Coast and Geodetic Survey (1850-1890s).

   Shoreline armoring is approaching 100% in the Skagit, Stillaguamish, and Snohomish river deltas, has reached 100% in the Duwamish and Puyallup deltas, encompasses the entire eastern shore of Bellingham and Samish Bays, and stretches across 75% of the Nisqually delta. Shoreline length has been reduced by greater than 50% in the Nooksack and Samish deltas, and over 50% of the aquatic zone in Birch bay has been covered by fill. Tidal barriers are prominent in the Quilcene, Hamma hamma, Duckabush, Dosewallips, and Skokomish river deltas.

7. Shoreline armoring reduces detritus availability to beach organisms by 66-76%, and disrupts ecosystem connectivity between detritus-generating ecosystems and marine food webs (Heerhartz et al., 2014). Armoring also changes the composition of wrack to exclude

terrestrial sources. Beach wrack available to beach detritivores is composed of ~60% marine algae, 24% terrestrial plant materials, and 13% eelgrass.

8. Shoreline armoring reduces talitrid (beach hopper) abundance (Sobocinski et al., 2010), which is an important food source for shore crabs (*Hemigrapsus nudus*) (Lewis et al., 2007), birds and other animals (Toweil, 1974; Vermeer, 1982).

9. There are many types of detritivores in estuarine and marine ecosystems. Suspension feeders, such as mussels, littleneck clams, barnacles and oysters, filter food suspended in the water as it passes by. By contrast, benthic-deposit feeders engulf sediments, digesting the bioavailable portions. Benthic-deposit feeders include several types of clams, polychaete worms, gastropods, sea cucumbers, crabs and sand dollars. Grazers also depend on benthic-associated food production, but are not classified as detritivores. Grazers consume (as a group) a combination of fresh macroalgae, epiphytic algae, and fresh detritus. Grazers include such organisms as snails, limpits, sea urchins, and chitons (Encyclopedia of Puget Sound, Herbivores and detritiores in Puget Sound).

10. The benthic and nearshore communities of Puget Sound rely strongly on detritus for food web support, especially near river mouths, tidal marshes, eelgrass and kelp beds. Suspension-feeding mussels, for example, obtain between 11-88% of their nutrition from detrital sources, depending on the season (Hoffnagle et al., 1979; Tallis, 2009; Howe & Simenstad, 2014), and a variety of estuarine and nearshore invertebrates ultimately derive their nutrition from sources other than phytoplankton (Simenstad & Wissmar, 1985).

    The Salish Sea's intertidal food webs echo those studied across the world. From Amchitka, AK (Duggins et al., 1989), San Francisco Bay, CA (Howe & Simenstad 2011, 2011), and the tip of South Africa (Bustamante et al., 1995), strongly relying on detritus to fuel community metabolism.

11. Detrital food webs support keystone predators, such as the Ochre seastar (*Pisaster ochraceus*) which plays a key role in regulating community diversity in Puget Sound's rocky intertidal habitats (Paine, 1980). *P. ochraceus* feeds preferentially on barnacles (proportion of diet = 10-54%) and mussels (~20%). Detritus comprises 11-88% of the diet of both prey species (Tallis, 2009).

    Pisaster ochraceus populations have dramatically declined in Puget Sound as a result of seastar wasting disease. The cause of the disease has yet to be unequivocally identified, but emerging research points to a viral infection of densovirus (Hewson et al., 2014), perhaps augmented by higher than normal water temperatures (Bates et al., 2009). The loss of this keystone predatory species indicates that nearshore food webs are dynamic in space and time, and we expect extensive restructuring of rocky intertidal communities as a result its removal via densovirus (Paine, 1980).

12. Juvenile chum salmon exploit detritus-based food webs by feeding selectively on harpacticoid copepods, for which the detrital carbon uptake exceeds algal carbon uptake by 9-10 fold (Sibert et al., 1977). This commercially valuable fisheries resource is usually considered planktivorous, but during the first critical weeks of estuarine life, chum rely on a detritus-based, benthically derived food web.

13. Stable isotope evidence suggests 12-35% of carbon assimilated by chum fry emanates from the terrestrial environment; the rest is derived from detrital macroalgae in the marine environment (Romanuk & Levings, 2005). Similarly, Chinook fry depend on terrestrial detrital pathways for 10-40% of their nutritional needs, and juvenile pink salmon depend on terrestrial detritus for 12-35% of their dietary needs. Chinook are primarily tied to detritus-based food webs by feeding on emergent insect communities (Shreffler et al., 1992), with some supplementation from epibenthic suspension feeding crustaceans, such as *Corophium spp*. (Shreffler et al., 1992).

14. Dominant estuarine/nearshore fish dependent upon detritus-based food web pathways include: (Seliskar & Gallagher, 1983).

    a. Anadromous species

        i. Chinook fry and smolts (*Oncorhynchus tshawytscha*)

        ii. Chum fry (*Oncorhynchus keta*)

        iii. Pink fry (*Oncorhynchus kisutch*)

        iv. Sockeye smolts (*Oncorhynchus nerka*)

        v. Longfin smelt (*Spirinchus thaleichthys*)

    b. Marine species

        i. Northern anchovy (*Engraulis mordax*)

        ii. Shiner perch (*Cymatogaster aggregata*)

        iii. Staghorn sculpin (*Leptocottus armatus*)

        iv. Starry flounder (*Platichthys stellatus*)

        v. Surf smelt (*Hypomesus pretiosus*)

        vi. English sole juveniles (*Parophrys vetulus*) (80-94% detritus based; Howe & Simenstad, 2015).

    c. Freshwater species

        i. Peamouth chub (*Mylocheilus caurinus*)

ii. Prickly sculpin (*Cottus asper*)

iii. Threespine stickleback (*Gasterosteus aculeatus*)

15. Major food sources for fish in tidal marsh ecosystems include:

    a. Amphipods (especially *Americorophium spp.*)

    b. Harpacticoid copepods

    c. Emergent insects (adults, pupae, and larvae; *Dolichopodidae, Chironomidae, Ceratopogonidae,* and *Ephydridae*)

    d. Terrestrial insects (*Hemiptera*)

    e. Mysid shrimp (*Neomysis mercedis*)

    f. Isopods (*Gnorimosphaeroma oregonensis*)

    g. Flatfish larvae

    h. Cumaceans

    i. Oligochaetes

    j. Polychaetes

    k. Decapod larvae (crabs and shrimp)

*Epibenthic crustaceans are particularly important contributors to fish diets. (Seliskar & Gallagher, 1983; Levy et al., 1979; Northcote et al., 1979; Northcote et al., 1981; David et al., 2014)

16. Restoration efforts that have restored tidal flow to estuarine wetland ecoystems (i.e. Nisqually, Skagit, and Skokomish) via dike removals or breaches have rapidly restored ecological attributes associated with detritus-based food webs, including ecosystem capacity to support higher densities of organisms, and ecosystem connectivity in terms of sources of detritus (David et al., 2014; Howe & Simenstad, 2014; Greene and Beamer, 2011).

17. The importance of detritus based food web pathways differs among ecosystem types. Six primary (75-100% of total index of relative importance) direct pathways have been identified between detritus and upper trophic levels in rocky intertidal habitats. Five primary pathways have been identified in cobble littoral habitats, four primary pathways for exposed gravel-cobble habitats, and five for protected sand-eelgrass ecosystems, and four for protected mud/eelgrass systems (Simenstad et al., 1979).

18. Detritus-based food webs link terrestrial, estuarine, and marine ecosystems through energy flow (Romanuk and Levings 2005, Tallis 2009, Howe & Simenstad 2015). Detrital food webs in the estuary of large river systems reflect an integrated “bouillabaisse” of many types of

detritus across space, while detrital food webs associated with small river systems or bays show strong associations with the detritus of immediately available vegetation (Howe 2012).

19. Confining rivers between levees restricts connectivity between rivers, riparian zones, floodplains and marsh ecosystems, thereby reducing the interface where organic matter exchange occurs (Amoros and Bournette 2002, Winemiller 2003. River channelization also focuses river discharge into a forceful jet-like plume, rather than a dispersive fan of smaller, less forceful river channels (Syvitski 2005). In the case of the Skagit River, higher river flow velocities caused by levee confinement exports detritus beyond the immediate estuarine system, functionally separating detrital marsh resources from benthic-deposit feeding organisms, such as clams. Clams on the Skagit delta derive only 30% of their diets from marsh detritus, while clams located across from the river plume on Whidbey Island derived 60% of their diets from marsh-produced detritus (Howe 2012).

References

Greene, C.M., and Beamer, E.M. 2012. Monitoring population responses to estuary restoration by Skagit River Chinook salmon. Intensively Monitored Watershed Project. Annual Report 2011. Fish Ecology Division, Northwest Fisheries Science Center and Skagit River System Cooperative.

David, A.T., Ellings C.M., I Woo, I., Simenstad, C.A., Takekawa, J.Y., Turner, K.L., smith, A.L., and Takekawa, J.E. 2014. Foraging and growth potential of juvenile Chinook salmon after tidal restoration of a large river delta. Transactions of the American Fisheries Society 143(6): 1515-1529.

Seliskar, D.M., and Gallagher, J.L. 1983. The ecology of tidal marshes of the Pacific Northwest coast: A community profile. National Coastal Ecosystems Team, Division of biological Services, Fish and Wildlife Service, US Department of the Interior. FWS/OBS-82/32.

Northcote, T.G., Johnston, N.T., and Tsumura, K. 1979. Feeding relationships and food web structure of lower Fraser River fishes. Tech. Rep. 16. University of British Columbia, Westwater Research Centre, Vancouver, B.C. 73. pp.

Levy, D.A., Northcote, T.G., and Birch, G.J. 1979. Juvenile salmon utilization of tidal channels in the Fraser River Estuary, British Columbia. Techn. Rep. 23. University of British Columbia, Westwater Research Centre, Vancouver B.C. 70 p.

Sobocinski, K.L., Cordell, J.R., and Simenstad, C.A. 2010. Effects of shoreline modifications on supratidal macroinvertebrate fauna on Puget Sound, Washington beaches. Estuaries and Coasts. 33: 699-711.

Heerhartz, S.M., Dethier, M.N., Toft, J.D., Cordell, J.R., and Ogston, A.S. 2014. Effects of shoreline armoring on beach wrack subsidies to the nearshore ecotone in and estuarine fjord. Estuaries and Coasts. 34: 1256-1268.

Tallis, H. 2009. Kelp and rivers subsidize rocky intertidal communities in the Pacific Northwest (USA). Marine Ecology Progress Series. 389: 85-96.

Sosik, E.A., and Simenstad, C.A. 2013. Isotopic evidence and consequences of the role of microbes in macroalgae detritus-based food webs. Marine Ecology Progress Series. 494: 107-119.

Winter, D.F., Banse, K., and Anderson, G.C. 1975. The dynamics of phytoplankton blooms in Puget Sound, a fjord in the northwestern United States. Marine Biology. 29: 139-176.

Vermeer, K. 1982. Comparison of the diet of the glacuous-winged gull on the east and west coasts of Vancouver Island. The Murrelet 63: 80-85.

Toweil, D.E. 1974. Winter food habits of river otters in Western Oregon. Journal of Wildlife Management, 38: 107-111.

Lewis, T.L., Mews, M., Jelinksi, D.E., and Zimmer, R. 2007. Detrital subsidy to the supratidal zone provides feeding habitat for intertidal crabs. Estuaries and Coasts. 30: 451-458.

Simenstad, C.A., Ramirez, M., Burke, J., Logsdon, M., Shipman, H., Tanner, C., Toft, J., Craig, B., Davis, C., Fung, J., Bloch, P., Fresh, K., Campbell, S., Myers, D., Iverson, E., Bailey, A., Schlenger, P., Kiblinger, C., Myre, P., Gerstel, W., and MacLennan, A. 2011. Historical change of Puget Sound shorelines: Puget Sound Nearshore Ecosystem Restoration Project Change Analysis. Puget Sound Nearshore Ecosystem Restoration Project Report No. 2011-01. Published by Washington Department of Fish and Wildlife, Olympia, Washington, and US Army Corps o Engineers, Seattle, Washington.

Brinson, M.M., Lugo, A.E., and Brown, S. 1981. Primary productivity, decomposition and consumer activity in freshwater wetlands. Annual Review of Ecology and Systematics. 12: 123-161.

Christiaen, B., Dowty, P., Ferrier, L., Berry, H., Hannam, M., and Gaeckle, J. 2015. Puget Sound Submerged Vegetation Monitoring Program. 2010-2013 Report. Puget Sound Ecosystem Montoring Program. Washington State Department of Natural Resources.

Berry, H.D., Mumford, T.M., and Dowty, P. 2005. Using historical data to estimate changes in floating kelp (Nereocystis leutkeana and Macrocystis integrifolia) in Puget Sound, Washington. Puget Sound Georgia Basin Research Conference. Nearshore Habitat Program, Washington Department of Natural Resources, Olympia, WA.

Thom, R.M. 1990. Spatial and temporal patterns in plant standing stock and primary productin in a temperate seagrass system. Botanica Marina. 33: 497-510.

Ewing, K. 1986. Plant growth and productivity along complex gradients in a Pacific Northwest brackish intertidal marsh. Estuaries. 9 (1): 49-62.

Disraeli, D.J. and Fonda, R.W. 1978. Gradient analysis of the vegetation in a brackish marsh in Bellingham Bay, Washington. Canadian Journal of Botany. 57 (5): 465-475.

Burg, M.E., Rosenberg, E., and Tripp, D.R. 1976. Vegetation associations and primary productivity of the Nisqually salt marsh on southern Puget sound, Washington, p. 104-109. In, S.G. Herman and A. M. Wiedemann (eds.), Contributions to the Natural History of the Southern Puget Sound REgion, WAshington. Evergreen State College, Olympia.

Levings, C.D. and Moody, A.I. 1976. Studies of intertidal vascular plants, especially sedge (Carex lyngbyei) on the disrupted Squamish Estuary, British Columbia. Fish. Mar. Serv. Tech. Rep. 606. West Vancouver.

Simenstad, C.A. and Wissmar, R.C. 1985. d13C evidence of the origins and fates of organic carbon in estuarine and nearshore food webs. Marine Ecology Progress Series. 22: 141-152.

Coligne, F., and de Jong, V.N. 1984. Primary production of microphytobenthos in the Ems-Dollard Estuary. Marine Ecology Progress Series. 14: 185-196.

Findlay, S., Howe, K., and Austin, H.K. 1990. Comparison of detritus dynamics in two tidal freshwater wetlands. Ecology. 71 (1): 288-295.

Dayton, P.K. 1985. Ecology of kelp communities. Annual Review of Ecology and Systematics. 16: 215-245.

Jones, K.K., Simenstad, C.A., Higley, D.A., and Bottom, D.L. 1990. Community structure, distribution, and standing stock of benthos, epibenthos, and plankton in the Columbia River Estuary. Progress in Oceanography. 25: 211-242.

Sherwood, C.R., Jay, D.A., Harvey, R.B., Hamilton, P., and Simenstad, C.A. 1990. Historical changes in the Columbia River Estuary. Progress in Oceanography. 25: 299-352.

Hoffnagle, J. , Ashley, R., Cherrick B., Gant, M., Hall, R., Magwire, C., Martin, M., Schrag, J., Stunz, L., Vanderzanden, K., and Van Ness, B. 1979. A comparative study of salt marshes in the Coos Bay Estuary. A National Science Foundation Student Originated Study. University of Oregon, Eugene. 334 p.

Howe, E.R., and Simenstad, C.A. 2014. Using isotopic measures of connectivity and ecosystem capacity to compare restoring and natural marshes in the Skokomish River estuary, WA, USA. Estuaries and Coasts.

Duggins, D.O., Simenstad, C.A., and Estes, J.A. 1989. Magnification of secondary production by kelp detritus in coastal marine ecosystems. Science. 245: 170-173.

Howe, E.R., and Simenstad, C.A. 2011. Isotopic determination of food web origins in restoring and ancient estuarine wetlands of the San Francsico Bay and Delta. Estuaries and Coasts. 34: 597-617.

Bustamante, R. H., Branch, G.M, and Eekhout, S.1995. Maintenance of an exceptional intertidal grazer biomass in South Africa: subsidy by subtidal kelps. Ecology. 76: 2314-2329.

Thom, R.M., and Albright, R.G. 1990. Dynamics of benthic vegetation standing-stock, irradiance, and water properties in central Puget Sound. Marine Biology. 104: 129-141.

Emmett, R., Llanso, R., Newton, J., Thom, R., Hornberger, M., Morgan, C., Levings, C., Copping, A., and Fishman, P. 2000. Geographic signatures of North American west coast estuaries. Estuaries. 23 (6): 765-792.

Borum, J., and Sand-Jensen, K. 1996. Is total primary production in shallow coastal marine waters stimulated by nitrogen loading? Oikos. 76 (2)L 406-410.

Naiman, R.J., and Sibert, J.R. 1978. Transport of nutrients and carbon from the Nanaimo River to its estuary. Limnology and Oceanography. 23 (6): 1183-1193.

Galloway, A.E., Lowe, A.T., Sosik, E.A., Yeung, J.S., and Duggins, D.O. 2013. Fatty acid and stable isotope biomarkers suggest microbe-induced differences in benthic food webs and between depths. Limnology and Oceanography. 58 (4): 1451-1462.

US Geological Survey. 2006. Surface-water quality in rivers and drainage basins discharging to the southern part of Hood Canal. Scientific Investigations Report 2006-5073. Available at: http://pubs.usgs.gov/sir/2006/5073/section4.html

Khangaonkar, T, Sackmann, B., Long, W., Mohamedali, T., and Roberts, M. 2012. Puget Sound Dissolved oxygen modeling study: Development of an intermediate scale water quality model. Pacific Northwest National Laboratory, for Washington State Department of Ecology. PNNL-20384.

Paine, R.T. 1980. Food webs: Linkage, interaction strength, and community infrastructure. Journal of Animal Ecology. 49(3), 666-685.

Hewson, I., Button, J.B., Gudenkauf, B.M., Miner, B., Newton, A.L., Gaydos, J.K., Wynne, J., Groves, C.L., Hendler, G., Murray, M., Fradkin, S., Breitbart, M., Fahsbender, E., Lafferty, K.D., Kilpatrick, A.M., Miner, C.M., Raimondi, P., Lahner, L., Friedman, C.F., Daniels, S., Haulena, M., Marliave, J., Burge, C.A., Eisenlord, M.E., and Harvell, C.D. 2014. Densovirus associated with sea-star wasting disease and mass mortality. Proceedings of the National Academy of Sciences of the United States of America. 111 (48), 17278-17283.

Bates, A.E., Hilton, B.J., and Harley, C.D.G. 2009. Effects of temperature, season and locality on wasting disease in the keystore predatory sea star Pisaster ochraceus. Diseases of Aquatic Organisms. 86: 245-251.

Romanuk, T.N., and Levings, C.D. 2005. Stable isotope analysis of trophic position and terrestrial versus marine carbon sources for juvenile Pacific salmonids in nearshore marine habitats. Fisheries Management and Ecology. 12 (2), 113-121.

Shreffler, D.K., Simenstad, C.A., and Thom, R.M 1992. Foraging by juvenile salmon in a restored estuarine wetland. Estuaries. 15 (2), 204-213

Simenstad, CA, Miller, BS, Nyblade, C.F., Thornburgh, K., and Bledsoe, L.J. 1979. Food web relationships of northern Puget Sound and the Strait of Juan de Fuca. A synthesis of available knowledge. Fisheries Research Institute. Marine Ecosystems Analysis Puget Sound Project. Office of Environmental Engineering and Technology, U.S. Environmental Protection Agency, EPA No D6-E693-EN

Howe, E.R. and Simenstad, C.A. 2015. Using stable isotopes to discern mechanisms of connectivity in estuarine detritus-based food webs. Marine Ecology Progress Series. 518: 13-29.

Howe, E.R. 2012. Detrital shadows: Evaluating landscape and species effects of detritus-based food web connectivity in Pacific Northwest estuaries. Ph.D. Dissertation. School of Aquatic and Fishery Sciences. University of Washington, Seattle, WA.

Mulholland, P.J. and Watts, J.A. 1982. Transport of organic carbon to oceans by the rivers in North America. A synthesis of existing data. Tellus 34, 176-186.

Mueller-Solger, A., Jassby, A.D., Muller-Navarra, D.C. 2002. Nutritional quality of food resources for zooplankton (Daphnia) in a tidal freshwater system (Sacramento-San Joaquin River Delta). Limnology and Oceanography 47: 1468-1476.

Canuel, E.A., Lerberg, E.J., Dickhut, R.M., Kuehl, S.A., Bianchi, T.S., and Wakeham, S.G. 2009. Changes in sediment and organic carbon accumulation in a highly-disturbed ecosystem: The Sacramento-San Joaquin River Delta (California, USA). Marine Pollution Bulletin 59: 154-163.

Amoros, C., and Bournette, G. 2002. Connectivity and biocomplexity in waterbodies of riverine floodplains. Freshwater Biology 47: 761-776.

Winemiller, K.O. 2003. Floodplain river food webs: generalizations and implications for fisheries management. In: Proceedings of the second international symposium on the management of large rivers for fisheries (Volume II). Food and Agriculture Organization of the United Nations. Division: Fisheries Group. ISSN: 1020-6221. http://www.fao.org/3/a-ad526e/ad526e0l.htm

Syvitski, J.A., Kettner, A., Correggiari, A., and Nelson, B. 2005. Distributary channels and their impact on sediment dispersal. Marine Geology. 222: 75-64.

The pelagic (open water) food web

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Summary

There is not just one Puget Sound food web. Terrestrial, freshwater, and marine habitats and species are connected in complex webs of interaction driven by water flow, proximity, and animal movement. The marine environment is further divided up into unique nearshore, soft-bottom, rocky and open water habitats, all of which contain unique species but are also connected to each other, by shared prey resources, or common predators, or animal movement. The Puget Sound is strongly influenced by bottom-up forcing, meaning that the animals in Puget Sound are sensitive to changes at the bottom of the food web (Harvey et al., 2010). The Puget Sound supports more than 250 fish species (Pietsch & Orr, 2015), 38 marine mammal species (Gaydos & Pearson 2011), 172 bird species (Gaydos & Pearson 2011), and a highly diverse community of invertebrate species (Harvey et al., 2010). The marine habitat of Puget Sound can be divided up into nearshore, benthic (associated with the sea floor), and pelagic (open water) habitats. This section focuses on the pelagic habitat within the Puget Sound (http://www.eopugetsound.org/articles/habitats-puget-sound-watershed).

Cross-system

1. The animals and plants in the pelagic zone together represent an estimated 25-30% of the total biomass in the Puget Sound marine ecosystem; the rest is contained in bottom-associated plants and animals (Harvey et al., 2010).

2. There are 252 fish species in the Salish Sea ecosystem (Pietsch & Orr, 2015, Pietsch pers. Comm. 6/10/2015).

3. Over 50% of the biomass in Puget Sound is estimated to be in benthic invertebrates: bottom-dwelling animals like geoducks, clams, mussels, crabs, octopuses, sea stars, and the small crustaceans that are the standard fare for most seabirds and fish in the Sound (Harvey et al., 2010).

Zooplankton

4. Zooplankton, tiny marine crustaceans, are a critical link between primary producers, or plants and algae that trap energy from the sun, and larger species like fish, mammals and birds. Many of the most important species in Puget Sound rely upon zooplankton, including salmon, forage fish like herring, surf perch, and sand lance, hake, Pollock, and shrimp (Harvey et al., 2010). Yet, no comprehensive zooplankton monitoring program exists in Puget Sound. Each Puget Sound basin has its own unique zooplankton and bacteria community (Moore et al., 2014). Copepods are typically the most dominant zooplankton type in Puget Sound (Keister & Tuttle, 2013).

Phytoplankton

5. The spring bloom, which is the peak of primary production during the year, happens in Central Puget Sound in late April/May of each year, and is dominated by diatoms (Moore et al., 2014). The spring bloom is followed by a peak in zooplankton grazing in June (Moore et al., 2014). Diatoms are the most abundant and diverse group of primary producers in Puget Sound (Moore et al., 2014).

6. Toxins in Puget Sound shellfish, and associated beach closures, have been increasing in frequency and magnitude since the 1950s (Trainer et al., 2003).

Forage fish

7. Forage fish, including Pacific herring, are preferred prey for over 30 mammals, birds, fish and invertebrate species, including Chinook salmon, harbor seals, lingcod, and rockfish (Duffy et al., 2010; Harvey et al., 2010; Lance et al., 2012).

8. In the last 40 years Pacific herring and surf smelt abundance has decreased 99% in Central and South Puget Sound (Greene et al., 2015). Jellyfish are 9 times more abundant than they were 40 years ago in some Puget Sound basins (Greene et al., 2015). Jellyfish can make up to 90% of the catch in Puget Sound surface trawls, and are most abundant in central and south basins (Rice et al., 2012). Jellyfish compete with adult forage fishes while consuming larval and juvenile stages of fish (Purcell & Arai, 2001).

9. Pacific sand lance and three-spine stickleback, two forage fish species, have increased in Puget Sound in the last 40 years (Greene et al., 2015).

10. In Puget Sound more than 200 miles of shoreline are utilized as spawning beaches for surf smelt and more than 140 miles of shoreline are utilized as spawning beaches for sand lance (U.S. Geological Survey, 2015)

Other Fish

11. A number of formerly abundant bottomfish in Puget Sound – walleye pollock, Pacific cod, Pacific hake – were depleted by heavy fishing in the 1970s and 1980s and have not recovered, though fishing has been restricted for decades (Gustafson et al., 2000). These species are very common in the diets of harbor seals and sea lions (Lance, et al., 2012, Harvey et al., 2010), which populations have been steadily increasing over that same time period (Jeffries et al., 2003).

12. The most common sharks in Puget Sound are the bluntnose six-gill shark (Hexanchus griseus), the Pacific spiny dogfish (Squalus acanthias) and the spotted ratfish (Hydrolagus colliei) (Griffing et al., 2014).

13. The Puget Sound has 28 species of rockfish (Sebastes spp.) (Palsson et al., 2009). Rockfish are known to be some of the longest lived fish of Puget Sound. Maximum ages

for several species are greater than 50 years. The rougheye rockfish can live up to 205 years (Palsson et al., 2009).

14. As of 2009 there are 30 marine/estuarine invasive species in Puget Sound: 5 plants, 3 macro algae, and 22 invertebrates. Fifteen of these species are known to occur or are established in Puget Sound (Eissinger, 2009).

Other organisms

15. Harbor seals vary their diet by location and season: during the winter and spring months seals in the north favor Pacific herring (Clupea pallasii), Pacific sand lance (Amodytes hexapterus), Northern anchovy (Engraulis mordax) and walleye pollock (Theragra chalcogramma), while in summer and fall months they eat primarily salmon (Lance et al., 2012).

16. The endangered Southern Resident Killer Whale (SRKW) observed most commonly in Puget Sound feeds overwhelmingly on Chinook salmon (Ford et al., 1998).

17. The most common Puget Sound squid, Pacific squid, average eight inches in length from mantle to tentacle tip (WDFW, 2015). The much larger Humboldt squid (Dosidicus gigas) – 7 feet long and 100 lbs. – is occasionally observed in Puget Sound (WDFW, 2015).

18. Giant Pacific octopuses (Enteroctopus dofleini), the largest species of octopus in the world (Conrath and Conners, 2014), are major benthic predators in Puget Sound (Scheel and Anderson, 2012). Their preferred prey seems to be cancer crabs (Cancer productus) (Scheel and Anderson, 2012). The largest giant Pacific octopus on record was said to weigh close to 600 pounds (Morris et al., 1980).However, more typical weights for this species range from 50 to 100 pounds (NOAA Fisheries, 2015b; High, 1976).

References

Conrath, C., & Conners, M. (2014). Aspects of the reproductive biology of the north Pacific giant octopus (Enteroctopus dolfleini) in the Gulf of Alaska. Fisheries Bulletin, 112, 253-260. Doi:10.7755/FB.112.4.2.

Duffy, E., Beauchamp, D., Sweeting, R., & Beamish, R. (2010). Ontogenetic diet shifts of juvenile Chinook salmon in nearshore and offshore habitats of Puget Sound. Trans. Amer. Fish. Soc., 139: 803-823.

Eissinger, M. (2009). Marine Invasive Species Identification Guide: for the Puget Sound Area. Puget Sound Marine Invasive Species Volunteer Monitoring Program (MISM). 38p.

Essington, T. E. Dodd, K., & Quinn, T. (2013). Shifts in the estuarine demersal fish community after a fishery closure in Puget Sound, Washington. Fisheries Bulletin, 111, 205-217.

Ford, J., Ellis, G., Barret-Lennard, L., Morton, A., Palm, R. & Balcomb III, K. (1998). Dietary specialization in two sympatric populations of killer whales (Orcinus orca) in coastal British Columbia and adjacent waters. Canadian Journal of Zoology, 76(8), 1456-1471.

Gaydos, J. K., & S. Pearson. (2011). Bird and Mammals that Depend on the Salish Sea: a compilation. Northwestern Naturalist 92: 79-89.

Greene, C., Kuehne, L., Rice. C, Fresh, K., & Pentilla, D. (2015). Forty years of change in forage fish and jellyfish abundance across greater Puget Sound, Washington (USA): anthropogenic and climate associations. Marine Ecology Progress Series, 525, 153-170.

Griffing, D., Larson, S., Hollander, J., Carpenter, T., Christiansen, J., & Doss, C. (2014). Observations on Abundance of Bluntnose Sixgill Sharks, Hexanchus griseus, in an Urban Waterway in Puget Sound, 2003-2005. PloS ONE, 9(1): e87081. doi:10.1371/journal.pone.0087081.

Gustafson, R. G., Lenarz, W. H., McCain, B. B., Schmitt, C. C., Grant, W. S., Builder, T. L., & Methot, R. D. (2000). Status review of Pacific hake, Pacific cod, and walleye pollock from Puget Sound, Washington. U.S. Dept. Commer., NOAA Tech. Memo. NMFS-NWFSC-44, 275p.

Harvey, C., Bartz, K., Davies, J., Francis, T., Good, T., Guerry, A., Hanson, B., Holsman, K., Miller, J., Plummer, M., Reum, J., Rhodes, L., Rice, C., Samhouri, J., Williams, G., Yoder, N., Levin, P., & Ruckelshaus, M. (2010). A mass-balance model for evaluating food web structure and community-scale indicators in the central basin of Puget Sound. U.S. Dept. Commer., NOAA Tech. Memo. NMFS-NWFSC-106, 180 p.

High, William H. (1976). The Giant Pacific Octopus. MFR Paper, National Marine Fisheries Service, NOAA. Retrieved September 25, 2015 from http://spo.nmfs.noaa.gov/mfr389/mfr3893.pdf.

Jeffries, S., Huber, H., Calambokidis, J., & Laake, J. (2003). Trends and status of harbor seals in Washington State: 1978-1999. Journal of Wildlife Management 67(1):208-219.

Keister, J. & Tuttle, L. (2013). Effects of bottom-layer hypoxia on spatial distributions and community structure of mesozooplankton in a sub-estuary of Puget Sound, Washington, U.S.A. Limnology and Oceanograph, 58(2), 667-680.

Lance, M., Chang, W., Jefferies, S., Pearson, S. & Acevedo-Gutierrez, A. (2012). Harbor seal diet in northern Puget Sound: implications for the recovery of depressed fish stocks. Marine Ecology Progress Series, 464, 257-271. Doi: 10.3354/meps09880.

Moore, S., Stark, K., Bos, J., Williams, P., Newton, J., & Dzinbal, K. (Eds). (2014). PSEMP Marine Waters Workgroup. Puget Sound marine waters: 2013 overview. Retrieved May 20, 2015, from http://www.psp.wa.gov/downloads/psemp/PSmarinewaters_2013_overview.pdf.

Morris, R., Abbott, D., & Haderlie, E. (1980). Intertidal invertebrates of California. Stanford University Press, Stanford, CA.

NOAA Fisheries. (2015). California sea lion. Office of Protected Resources. Retrieved June 22, 2015, from http://www.nmfs.noaa.gov/pr/species/mammals/pinnipeds/californiasealion.htm

NOAA Fisheries. (2015b). The Elusive Giant Pacific Octopus. Retrieved September 25, 2015 from http://www.afsc.noaa.gov/species/octopus.php.

Palsson, W., Tsou, T-S., Bargmann, G., Buckley, R., West, J., Mills, M., Cheng Y. & Pacunski, R. (2009). The biology and assessment of rockfishes in Puget Sound. Fish Management Division, Fish Program Washington Department of Fish and Wildlife. 208p.

Pietsch and Orr, In Press. Pietsch pers. Comm. June 10th, 2015.

Purcell, J. E., & Arai, M. N. (2001). Interactions of pelagic cnidarians and ctenophores with fish: a review. Hydrobiologia 451: 27-44.

Rice, C., Duda, J., Greene, C. & Karr, J (2012). Geographic Patterns of Fishes and Jellyfish in Puget Sound Surface Waters, Marine and Coastal Fisheries: Dynamics, Management, and Ecosystem Science, 4(1), 117-128, DOI:10.1080/19425120.2012.680403.

Scheel, D. & Anderson, R. (2012). Variability in the diet specialization of Enteroctopus dofleini (Celphalopoda: Octopodidae) in the eastern Pacific examined from midden contents. American Malacological Bulletin, 30(2), 267-279. Doi: 10.4003/006.030.0206.

Trainer, V.L, Eberhart, B.-T.L., Wekell J.C., Adams, N.G., Hanson, L., Cox, F., & Dowell. J. (2003). Paralytic shellfish toxins in Puget Sound, Washington State. J. Shellfish Res. 22, 213-223.

U.S. Geological Survey (USGS). (2015) Puget Sound forage fish. Retrieved June 23, 2015, from http://wfrc.usgs.gov/fieldstations/marrowstone/ps_forage.html.

WDFW. (2015). Washington Department of Fish and Wildlife, Squid. Retrieved June 23, 2015, from http://wdfw.wa.gov/fishing/shellfish/squid/.

Threats

Pressures assessment

Ranking injurious effects of humans on Puget Sound: A non-technical summary of the 2014 Puget Sound Pressures Assessment

Essay by: Nick Georgiadis, University of Washington Puget Sound Institute

A recovery strategy fashioned on expert opinion

In 2007 Gov. Gregoire challenged residents of the region to make Puget Sound "fishable, diggable, and swimmable" again, and charged recovery practitioners to define a "science-based, unified, and prioritized" recovery plan for the ecosystem. After 150 years of environmental decline on many fronts, planning the recovery of such a large and complex region could not be completed in a single step. There was no ready-made list of the most damaging effects, no obvious way to prioritize recovery targets, and no wholly objective way to order the actions needed to achieve them. The best, indeed only way to make and rank such lists is to assemble, as systematically as possible, the informed opinions of experts.

Box 1. A primer of recovery parlance

Human actions that are injurious to the ecosystem are called 'pressures' (for example, conversion of natural habitat to residential, commercial, and industrial uses). The direct effects of these actions, the means by which they exact change on the ecosystem, are called 'stressors' (for example, habitat conversion due to development; to forestall confusion, it is noted here that despite the title of the document, the assessment was done on stressors, not pressures). 'Endpoints' are key ecosystem components – species and habitats – that are impacted by stressors (for example, Chinook salmon, small high-gradient streams, and urban open space). They qualify by being especially valued, those that are being managed or recovered. Finally, the geographical areas within which the assessment applies are called 'assessment units'. In this case, the assessment was conducted at two geographic levels: within the entire Puget Sound region, and within each of 16 separate watersheds and 7 marine basins that together comprise the whole.

This 'expert elicitation' approach has been used in different ways to, for example, list and rate the human actions that are injurious to the Puget Sound ecosystem, identify suitable recovery targets and prioritize the actions needed to achieve them, design the research needed to fill gaps in understanding about ecosystem processes, gaps that raise uncertainty and hinder progress (see ref. 1-3). Such lists are not fixed for the rest of time. They must be amended as knowledge is gained, methods improve, progress is made, and priorities change. The latest addition to this set arises from a second assessment of the pressures wrought by humans on the Puget Sound ecosystem. The ensuing report is entitled *The 2014 Puget Sound Pressures Assessment* (see ref. 4). This article summarizes the goals, methods, and results of the assessment, as well as some implications for Puget Sound recovery.

Goals

Simply conceived, the assessment had dual goals. The first was to list human actions that are injurious to the ecosystem ('stressors'; see the primer of recovery parlance in Box 1), and rank them by their capacity to cause harm. The second was to list the most valued components of the ecosystem – key species and habitats, or 'endpoints' – and rank them by their relative vulnerability to be harmed.

How the assessment was done

Careful selection attempted to ensure that the three major ecosystem domains – freshwater, marine-nearshore, and terrestrial – were represented by both stressors and endpoints. When selection was completed, a total of 47 stressors and 60 endpoints had made the cut. This gave a large number of potential stressor-endpoint pairs (47 x 60 = 2,820) for which the effects of each of the former on each of the latter were to be assessed. Because all endpoints are not affected by all stressors – for instance, *headwater wetlands* are not much affected by *sea level rise* – this number was reduced to 1,372 pairs having plausible interactions. Experts were asked to only rate stressor-endpoint pairs about which they had confidence in forming an opinion, and to consider only *direct* effects of the stressor on the endpoint. Finally, for each pair, they were asked to rate three factors relating to these effects: 1) **functional impact**, the magnitude of change in condition of an endpoint when exposed to a stressor at high intensity; 2) the **time** it would take for an endpoint to recover after exposure to a stressor; and 3) the **resistance** of an endpoint, its capacity to stay the same after exposure to a stressor, a measure of its sensitivity. Rather than select a single rating category from a range of options for each factor, experts indicated their degree of confidence in ratings by expressing each opinion as a probability distribution across all categories. For example, a hypothetical rating by expert *x* for recovery time of endpoint *y* when exposed to stressor *z* might look like the probabilities listed at right. In this example the expert thought the most likely response time was over a period of years, possibly longer, and was less likely to be shorter. This novel rating approach allowed uncertainty to directly influence results (the theory underpinning this analytical approach is summarized in ref. 6).

Table 3

Rating Category for Recovery Time	Expert Rating
No Impact	0.00
Months	0.15
Years	0.50
Decades	0.35
Centuries	0.00
Irreversible	0.00

For a few stressor-endpoint pairs, no expert could be found to make an assessment, but in the end, 60 experts rated 1,087 stressor-endpoint pairs (by comparison, in the 2009 assessment, a few experts rated 26 pressure classes and 11 endpoints; 1). Most pairs (61%) were rated by more than one expert, and for these the mean rating was calculated to yield final IV scores.

Results: a plurality of rankings

The PSPA produces two primary quantities relating to the vulnerability of endpoints and the influence of stressors, called Intrinsic Vulnerability and Potential Impact.

Intrinsic Vulnerability (IV)

Intrinsic Vulnerability estimates how much a given stressor affects a specific endpoint under limiting assumptions: that the stressor is acting directly on the endpoint, that stressor expression is strong, and that management efforts are not affecting the stressor-endpoint interaction. Results can be presented as a rectangular table, with stressors listed down the left hand side, endpoints arrayed across the top, and the body of the table filled with IV scores for each stressor-endpoint pair that has been assessed.

An index of the overall impact of each stressor was derived as the sum of IV scores in each row of the table, a function how many endpoints each stressor affects, and how severely. Likewise, an index of endpoint vulnerabilities was derived as the sum of IV scores in each column, a function of the number of stressors affecting each endpoint, and how severely. Sorting these indices into descending order yielded rankings of stressors by their potential to harm, and endpoints by their vulnerability to be harmed.

Among the most vulnerable endpoints (highest IV scores) were *cutthroat trout*, various *salmon species*, *eelgrass*, and *lotic freshwater vertebrate communities*. Among the least vulnerable were *killer whales*, *alpine plant communities*, and both *managed and unmanaged forests*. A similar sorting of stressor indices revealed that *conversion of land cover for development* (residential, commercial, transportation and utilities), *large oil spills*, *sources of pollution* and *toxic chemicals in aquatic systems*, *shoreline hardening*, *altered stream flows from climate change*, and *terrestrial habitat fragmentation* were among the stressors with the most potential for harm. Among the stressors with least potential for harm were *species disturbance in marine, terrestrial and freshwater environments*, *bycatch*, *air pollution*, *changing precipitation amounts and patterns*, *dams as fish passage barriers*, *barriers to terrestrial animal movement including migration culverts* and *other fish passage barriers*.

In interpreting these results, it is important to remember that IV scores reflect only *direct* effects of stressors on endpoints. Thus killer whales emerged with a relatively low score, but their prey, salmon, had consistently high scores. Restoring salmon stocks should greatly improve prospects of killer whales.

Potential Impact (PI)

As the term intrinsic vulnerability (IV) implies, these results rank stressors and endpoints in the abstract, free of geographical or any other context. In reality, however, endpoint distributions and stressor intensities vary greatly across Puget Sound. It is for this reason that recovery strategies change locally across the region – for example, salmon recovery plans differ among major watersheds. To capture this local variation, IV scores for each stressor-endpoint pair were modified to yield a ‘Potential Impact’ (PI) score within *each* of the 16 major watersheds and 7 marine basins that together comprise the Puget Sound ecosystem (Figure 1). PI scores were derived by multiplying IV scores by 1 or 0, depending on whether a given endpoint was present or absent (respectively) in each assessment unit. This product was in turn multiplied by an estimate of ‘stressor intensity’ in each assessment unit, measured, where possible, from mapped (GIS) data. PI scores were averaged across endpoints, and across stressors, to yield indices of

Potential Impact within each assessment unit. These assessment unit scale results were further aggregated to produce a Puget Sound scale view.

For watersheds in Puget Sound, among the stressors with the most potential for harm were: *conversion of land cover* for all uses, *non-point source pollutants in aquatic systems*, *timber harvest*, *shoreline hardening*, and *terrestrial habitat fragmentation*. For marine basins, they were: *conversion of land cover for transportation & utilities and natural resource production, non-point source, persistent toxic chemicals in aquatic systems*, *shading of shallow water habitat*, *shoreline hardening*, *spread of disease and parasites to native species*, and *introduction, spread, or amplification of human pathogens*.

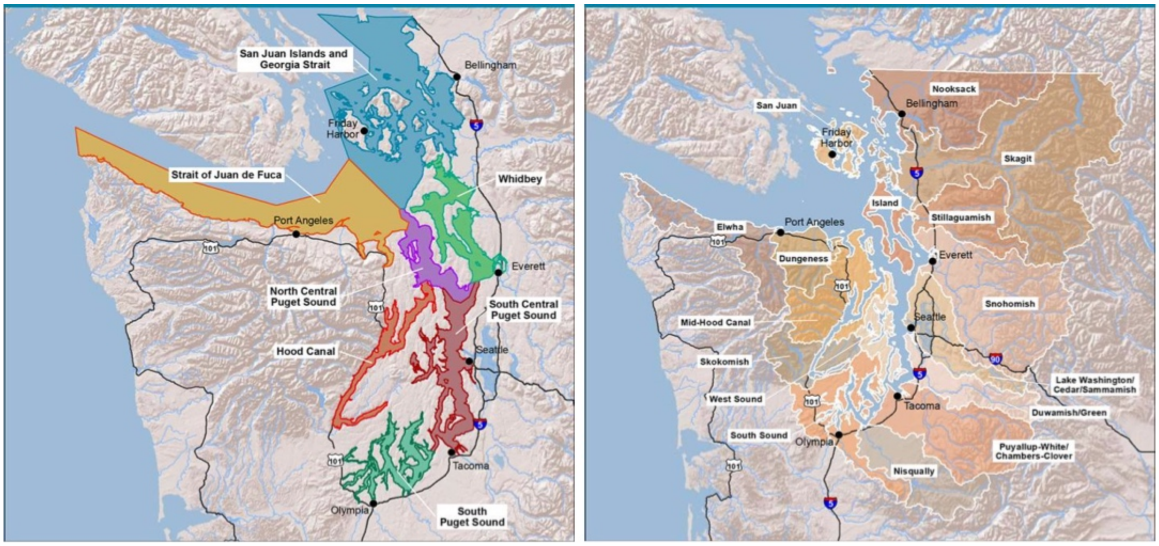


Figure 6. The 7 marine basins (left) and 16 watersheds (right) in which Potential Impacts were assessed. (Fig. 3 in ref. 4).

Among the most potentially impacted endpoints, were, for freshwater habitats: *cutthroat trout*, *coho* and *Chinook* salmon, *lotic freshwater vertebrate and invertebrate communities*, and *riparian vegetation*. For marine and nearshore habitats they were *eelgrass* and *kelp*, *chum* and *pink salmon*, *marine sessile filter feeders*, *rockfish* (adult), *embayments*, and *beaches*.

Rating the Pressures Assessment

This is by necessity a superficial summary of what was an intricate, exhaustive, in many ways novel, and ultimately successful attempt to rate and rank stressors and endpoints in Puget Sound. Those hoping for a single ranking of stressors (or endpoints) that could be applied universally across the region will be disappointed. Given the size and diversity of Puget Sound, theirs was a naïve hope in any case. In its final manifestation, several rankings emerged from the assessment, each with its own meaning and significance. For example, in addition to the two rankings mentioned above (IV and PI), there were different ways of calculating IV indices (mean vs. sum), and different ways of gauging overall stressor impact. This plurality of outputs is the reason that no 'definitive' ranking is included here, making an important point: anyone interested in applying the results should first read and understand the nuances of the main

report (see ref. 4), the logic described in the appendices (see ref. 5), and how the various outputs are intended to be applied (they will be rewarded – these docs are well written).

Some might ask how good an assessment can be that is based on tens of thousands of 'guesses'? They might further wonder what can scores derived from these guesses, scores that are accurate to two or more significant figures, actually mean? The respective answers are 'quite good', and 'quite a lot', for several reasons. First, these were *informed* guesses by professionals, many of whom have spent most of their careers on one or a few related topics. Imagine how much better this outcome was than, say, one in which the same stressor-endpoint pairs had been assigned *at random* to the same pool of experts for assessment, or indeed to the same number of randomly chosen non-specialists. Second, the authors took pains to assess and account subjective uncertainty, and performed sensitivity analyses that together boost confidence that results are meaningful. They caution that similar IV (or PI) indices probably do not distinguish stressors (or endpoints), but that widely disparate scores probably do. Finally, the results do seem intuitively plausible. For example, the fact that some stressors (e.g. *conversion of land cover for development*) scored highly in rankings derived in different ways, or for different habitats, does enhance confidence that these are among the most injurious (e.g. Figure). Similarly, by choosing to tackle say the 'top 10' stressors and endpoints on any ranked list, the chance is good that the most important are among them. Even so, it is worth repeating that, to apply the results effectively, one must grasp the complexities of this assessment, rather than take any single ranking at face value.

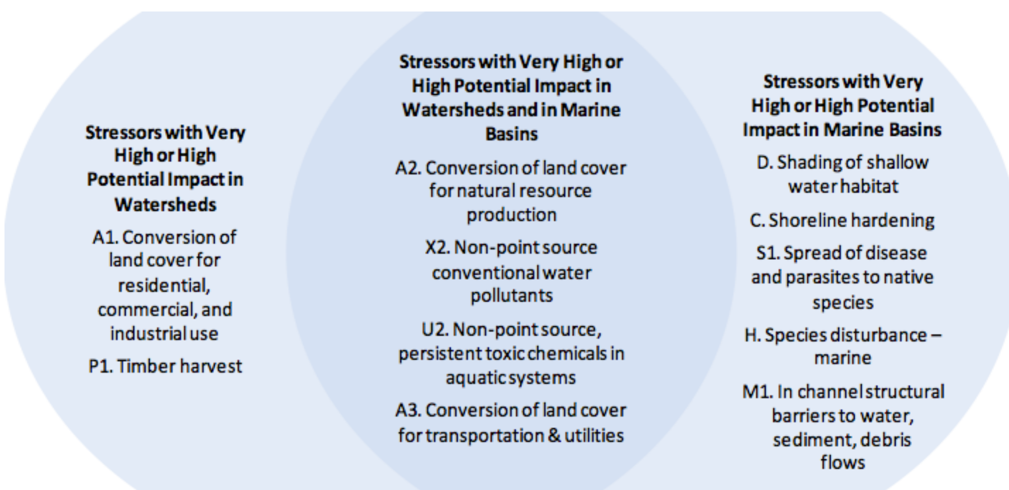


Figure 7. Stressors with Very High or High Potential Impact within many Assessment Units (Fig. 11 in ref. 4).

How is this assessment expected to make a difference?

The stated purpose of the PSPA is to help members of the Puget Sound science community and decision makers better understand the potential impact and relative intensity of stressors in the Puget Sound region, and to inform decisions about recovery strategies and priorities. It was *not* intended to replace existing local pressure assessments, or those that consider finer-scale data. However, it may complement or provide a starting point for locally focused efforts, where none currently exist. More specifically, the authors suggest how *Potential Impact* (PI) scores can be used in conjunction with *Intrinsic Vulnerability* (IV) scores to guide decisions and action in four contrasting scenarios (Fig. 7).

The PSPA is already beginning to influence recovery in several ways: PSP staff have discussed how results may be used by local implementers (LIOs), as supporting information for groups developing Implementation Strategies, in steelhead recovery planning, and in the next phases of Chinook monitoring and adaptive management (S. Redman, personal communication). Assessment results will also help sponsors prioritize decisions about recovery support.

This list of early applications is instructive in illustrating how the PSPA will make an impact: not by causing everyone to fall into lockstep with a single ranking, but by guiding many separate, independent and measured applications of results at appropriate scales. Propagation of that process over time and space will result in convergence of recovery effort and direction that would otherwise be hard to achieve.

The assessment provides a good example of how to proceed towards recovery under pervasive uncertainty. The team that performed this analysis deserves recognition as steely-eyed ecosystem recovery scientists. And the experts who contributed should feel rewarded for participating in a worthwhile effort. The work was funded by EPA. Work well done.

Intrinsic Vulnerability (IV) >>>		
	Higher IV/Lower PI **The potential for harm is high, but the stressor may be rare (infrequent) and/or the current stressor intensity may be relatively low** • These stressors should be priorities for action. • Consider potential opportunities to mitigate stressor before impacts are more fully felt.	**Higher IV/Higher PI** **Stressor has high potential for harm and likely affects many endpoints; current stressor intensity is relatively high** • These stressors should be priorities for action. • Where possible strategies should emphasize overall stressor reduction.
	Lower IV/Lower PI **The potential for harm is relatively low across endpoints and/or the stressor affects relatively fewer endpoints; the stressor is rare and/or the current stressor intensity is relatively low** • These stressors may have high potential for harm in certain places or for certain endpoints; IV results should be checked to identify any particularly vulnerable endpoints. • Consider targeted management strategies and/or de-emphasize depending on local context.	**Lower IV/Higher PI** **The potential for harm is relatively low across endpoints and/or the stressor affects relatively fewer endpoints, but stressor intensity likely is high.** • These stressors could be priorities for action. If stressor reduction is not possible, consider targeted management strategies to reduce or mitigate harmful stressor-endpoint relationships.
	Potential Impact (PI)>>>	

Figure 8. Suggestions as to how combinations of IV and PI scores may help to guide decision making (Fig. 13 in ref. 4).

References

Knauer, J., Neuman, E., St. John, D. 2009. Identification, Definition and Rating of Threats to the Recovery of Puget Sound. Technical Memorandum, Puget Sound Partnership.

The 2014/2015 Action Agenda for Puget Sound. 2014. Puget Sound Partnership.

Puget Sound Partnership. 2011. Priority Science for Restoring and Protecting Puget Sound: A Biennial Science Work Plan for 2011-2013.McManus, E., K. Jenni, M. Clancy, K. Ghalambor, I. Logan, J. Langdon, S. Redman, B. Labiosa, K. Currens, T. Quinn, J. Burke. 2014. *The 2014 Puget Sound Pressures Assessment*. Puget Sound Partnership Publication # _. Tacoma, WA

Puget Sound Partnership. 2014. *The 2014 Puget Sound Pressures Assessment: Appendices*. Puget Sound Partnership Publication # _. Tacoma, WA.

Labiosa, W., Landis, W, Quinn, T, Johnston, R., Currens, K, Redman, S., and Anderson, R. 2014. Puget Sound Pressures Assessment Methodology. Puget Sound Partnership Technical Report 2014-02.

Conclusion: New strategies for recovery

A healthy ecosystem supports human values

Essay by: Christopher Dunagan

The Puget Sound region is expected to grow by as many as 2 million residents over the next 25 years. Social scientists say we need to better understand how humans interact with Puget Sound—the good and the bad—if we want to understand how to protect it.

In the 1850s, lumberjacks brought their saws and axes to the Puget Sound region and began cutting down the massive fir and cedar trees that grew to the water's edge. Lumber was in high demand in Northern California, where a gold rush was fostering a population explosion. Schooners began moving lumber from the first sawmills in Puget Sound to San Francisco and other Pacific Coast ports.

It wasn't long before other newcomers opened up avenues of trade in fish, shellfish and minerals. Like lumber, barrels of fish and shellfish were welcomed in burgeoning markets along the West Coast.

Eventually, supplies of these naturally produced goods declined, but Puget Sound's natural resources remained a dominant economic force until modern times.

Today, economists, ecologists and social scientists are looking at the natural values of Puget Sound in a different way, studying and measuring the many economic and social benefits of living within an intact, functioning ecosystem.

In many cases, these benefits are measured in real dollars. Some argue that a healthy natural environment attracts the very labor force that helps maintain the strong and diverse economy of the Puget Sound region. A functioning ecosystem also brings with it inherent benefits like clean and inexpensive drinking water.

But some human values are not as easy to define. What is the importance of our enjoyment of nature, or the ability to continue cultural traditions like fishing? These are values that vary from person to person, and placing a monetary worth on things like mental health and outdoor activities comes with its own challenges.

Ecosystem services

While the idea that humans benefit from nature is not new, the concept of "ecosystem services" has been evolving since the 1970s, gaining increasing momentum in recent years. Ecologists, economists and sociologists are collaborating to identify how damage or improvement to the overall ecosystem ultimately affects human wellbeing and quality of life.

In 2003, the United Nations released a wide-ranging report called the "Millennium Ecosystem Assessment," which examined the worldwide decline in ecosystem services. It elaborated on this basic definition:

> *Ecosystem services are the benefits people obtain from ecosystems. These include:*
>
> - *Provisioning services, such as food and water;*
> - *Regulating services, such as regulation of floods, drought, land degradation and disease;*
> - *Supporting services, such as soil formation and nutrient cycling; and*
> - *Cultural services, such as recreational, spiritual, religious and nonmaterial benefits.*

In creating the Puget Sound Partnership in 2007, the Washington Legislature explicitly called for a "healthy human population" and "quality of human life" as major goals in the effort to protect and restore the Puget Sound ecosystem.

Other goals center around species, habitats, water supplies and the quality of water and sediments—"so that the waters in the region are safe for drinking, swimming, shellfish harvest and consumption, and other human uses and enjoyment, and are not harmful to the native marine mammals, fish, birds, and shellfish of the region."

Much of the work of the Partnership has been to encourage protection and restoration projects to maintain and improve habitats and ecological function. At the same time, the agency has encouraged people to minimize their ecological footprint.

The once-popular notion that nature is something separate and people should just leave it alone does not work in areas already altered by humans. Because the Puget Sound region faces the prospect of adding nearly 2 million people over the next 25 years, planners are beginning to recognize that humans must be considered an integral part of the ecosystem. The challenge is to find ecologically sound ways to fit new residents into the Puget Sound landscape.

One of the major approaches since the 1980s has been to concentrate new development within cities and existing communities. At the same time, planners have been working to maintain or restore ecological functions in rural areas, including operating farms and areas managed for timber production.

The Partnership has been tracking public perceptions and awareness, including people's emotional connections to Puget Sound. Making people aware of their effects on the environment and getting people to change their behaviors has been the goal of many partner-run public-

awareness campaigns, including the collaborative "Puget Sound Starts Here" that involves hundreds of regional government, nonprofit and business partners.

Protection strategies

The state's Growth Management Act and Shoreline Management Act call on local governments to take the lead in protecting the ecosystem as people build new homes and businesses. Local governments, in turn, are required to account for human impacts and to require environmental mitigation where damage cannot be avoided. Cities and counties vary in their level of protection and their efforts to make sure that developers follow land-use regulations.

Although habitat is still being lost to development, regulations are evolving to reduce the resulting damage. Local critical areas ordinances are designed to better protect wetlands, streams, floodplains, aquifer-recharge areas, erodible slopes and special wildlife habitats. Meanwhile, new stormwater rules call for greater infiltration, helping to maintain natural streamflows and reduce pollution.

City and county shoreline master programs are being updated to better protect shoreline habitat. Larger buffers are being imposed so that homes are built farther from vital nearshore areas. New shoreline armoring, such as the creation of bulkheads, is generally prohibited except where needed to protect houses from wave damage or flooding.

Where ecological damage cannot be avoided, mitigation projects may be required to enhance habitat and offset the damage.

Logging practices also are improving, thanks to evolving research and ongoing updates to Forest Practices Regulations. Teams of scientists continue to evaluate whether logging rules need to be strengthened to reduce habitat damage and protect specific fish and wildlife species.

With financial aid and guidance from local conservation districts, farmers are finding ways to improve habitat while maintaining their livelihood.

Tradeoffs

Maintaining ecosystem services can be viewed as a cost to some people but a benefit to others. Most of the new Forest Practices Rules, such as increased stream buffers, have led to decreased timber harvests on private forestland. Requirements to improve roads and stream crossings have increased costs for landowners. The resulting protections for water quality and fish and wildlife habitat do not directly improve the bottom line for most timber companies.

On the other hand, maintaining healthy forests with a goal of protecting water quality has proved beneficial. The city of Bremerton, for example, owns and protects the entire 3,000 acres that drains into Casad Reservoir, the city's primary water supply. Keeping people out of that forested watershed has allowed the city to avoid building a costly water-filtration system. That cost savings, along with income from limited logging, has kept Bremerton's water bills among the lowest in the state, while creating a large preserve for wildlife.

Unlike timber companies, the shellfish industry can be considered a direct beneficiary of efforts to clean up polluted waters, since the result has been a reopening of areas previously closed to commercial shellfish harvesting.

In some ways, the fishing industry is caught in the middle. While the industry would benefit from a healthy ecosystem with large runs of salmon and other fish, declining fish populations have led to fishing restrictions to protect the remaining stocks. Those actions have forced many fishers out of business. While habitat improvements are expected to help rebuild fish populations, successes so far have been limited. Some people argue that further fishing restrictions are necessary until the stocks recover.

All these issues—forests, fish and shellfish—are related to human values that go beyond business. Many Washington residents place a high value on visiting forests, fishing and gathering clams and oysters on public and private beaches. While the sale of outdoor equipment and fishing licenses provide direct economic benefits, the cultural values are not so easily quantified.

Cultural traditions

For Native Americans, cultural traditions that go back thousands of years are built upon a foundation of natural resources. Many customs and practices use native materials, such as specific plants and animals. The right to continue hunting. fishing and gathering shellfish was guaranteed in formal treaties with the U.S. government. While economic gains, such as the sale of salmon by tribal members, can be valued easily, that is not the case for customs and practices that rely on social connections and tribal heritage.

Other residents of Puget Sound also hold dear certain traditions, such as fathers teaching their children to fish. Hiking, camping, bird watching, taking photos of wildlife and many other outdoor activities have their own values, which are increased with healthy ecosystems. Even a family's tradition of returning again and again to a favorite outdoor location cannot be discounted, nor can the enjoyment of scientists involved in research used to improve the ecosystem.

As Puget Sound changes over time—improving in some areas and declining in others—the Puget Sound Partnership has been refining ways to measure the changes. New "vital signs" indicators have been approved for categories called "human health," and "human quality of life."

One measure of human health is the number of acres of shellfish beds that can be safely harvested in the Puget Sound region, a number that has been improving.

The more challenging quality-of-life indicators were recently revised into five categories:

- **Economic vitality,** which includes measurements of business vitality and employment in the natural resource industries,

- **Cultural well-being,** which involves asking people whether they are able to maintain their cultural practices associated with the natural environment,
- **Good governance,** which involves asking people whether they trust government leaders and feel they have an opportunity to influence decisions about natural resources.
- **Sense of place,** which involves asking people their feelings about the region, including their sense of stewardship, inspiration from nature and overall satisfaction.
- **Sound behavior,** which involves asking people about their behaviors with respect to the environment and whether they engage in activities to help the ecosystem.

A related, ongoing survey has been gauging the attitudes and values of individual Puget Sound residents, beginning with the first survey in 2008. Since the survey's inception, more than 60 percent of the population has held to the belief that cleaning up the waters of Puget Sound is an "urgent" priority.

References

Anderson, W. T. (1996, September/October). There's no going back to nature. *Mother Jones*.

Batker, David , Maya Kocian, Jennifer McFadden, Rowan Schmidt (2010). *Valuing The Puget Sound Basin: Revealing Our Best Investments*. Earth Economics, Tacoma, Washington.

Briceno, T., Schundler, G. (2015). *Economic Analysis of Outdoor Recreation in Washington State. Earth Economics*. Earth Economics, Tacoma, Washington.

Ecology, Washington State Department of (n.d.). *Wetlands and Critical Areas Ordinance Updates*. Retrieved June 15, 2015, from GMA and Local Wetlands Regulations: http://www.ecy.wa.gov/programs/sea/wetlands/gma/guidance.html

Ioana Milcu, Andra, Jan Hanspach, David Abson, Joern Fischer (n.d.). Cultural Ecosystem Services: A Literature Review and Prospects for Future Research. *Ecology and Society* .

Lelea, Sharachchandra, Oliver Springate-Baginskib, Roan Lakerveldc, Debal Debd, Prasad Dashe (2013). Ecosystem Services: Origins, Contributions, Pitfalls, and Alternatives. *Conservation and Society , 11* (4), 343-358.

Leschine, Thomas M., A. W. Petersen (2007). *Valuing Puget Sound's Valued Ecosystem Components*. Puget Sound Nearshore Partnership. Seattle, Washington: U.S. Army Corps of Engineers.

Menges, G. L. (n.d.). *American Indians of the Pacific Northwest Collection*. Retrieved June 15, 2015, from University of Washington Digital Collections: http://content.lib.washington.edu/aipnw/

Millenium Ecosystem Assessment. (2001). *Millennium Ecosystem Assessment Synthesis Reports*. United Nations. Washington, D.C.: Island Press

Office of Financial Management (n.d.). *Growth Management Act County Projections*. Retrieved June 15, 2015, from http://www.ofm.wa.gov/pop/gma/default.asp

Plummer, Mark L., Morgan Schneidler (2011). *Incorporating Human Well-being into Ecosystem-based Management in Puget Sound Science Update, April 2011 version*. Puget Sound Partnership, Tacoma, Washington.

Puget Sound Partnership. (2013). *State of the Sound Report, a Biennial Report on the Recovery of Puget Sound*. Tacoma, Washington.

Quinn, T. (2009). An Environmental and Historical Overview of the Puget Sound Ecosystem. *Puget Sound Shorelines and the Impacts of Armoring*. Washington State Department of Ecology, Toxic Cleanup Program.

Stiles, Kari . Kelly Biedenweg, Katharine F. Wellman, Leah Kintner, Dave Ward (2015). *Human Wellbeing Vital Signs and Indicators for Puget Sound Recovery: A Technical Memorandum for the Puget Sound Partnership*. Puget Sound Partnership.

Sturgeon, N. (2009). *Environmentalism in Popular Culture: Gender, Race, Sexuality, and the Politics of the Natural*. Tucson, Arizona: University of Arizona Press.

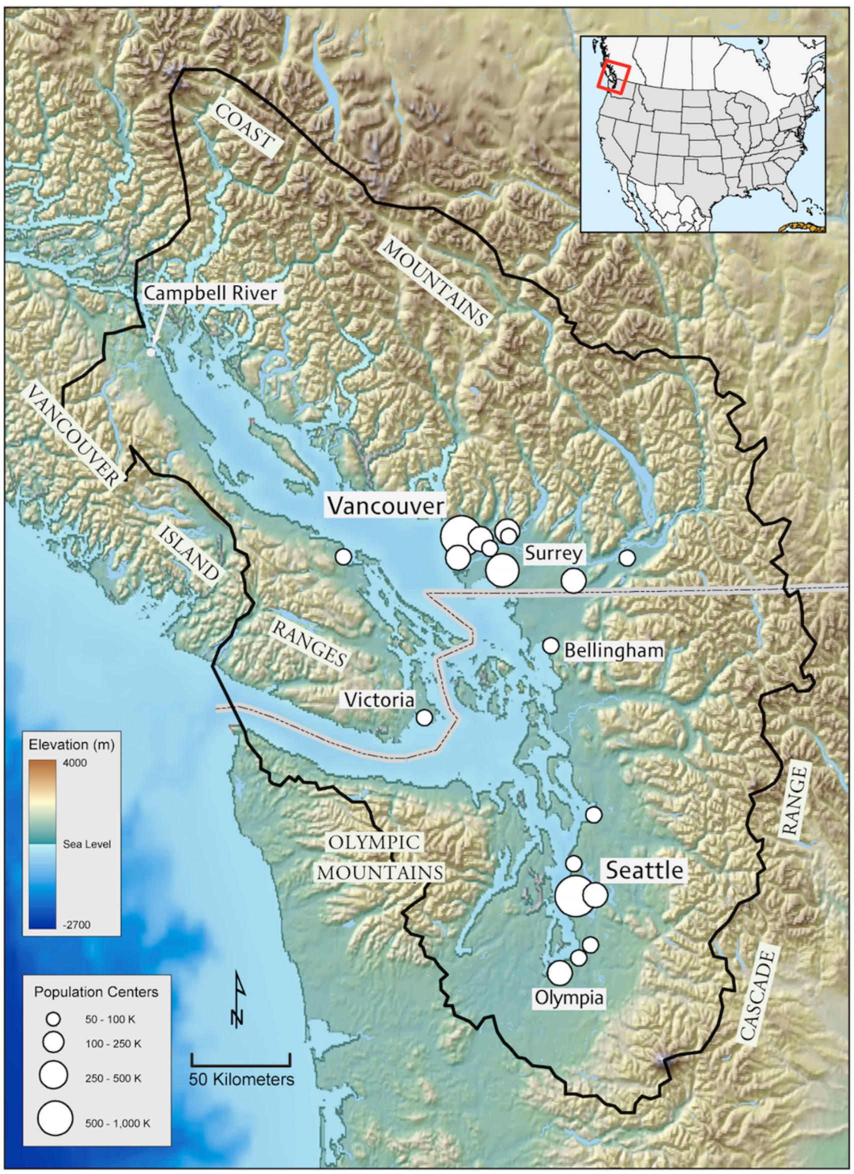
Appendix

Maps and GIS data

Section editor: Kris Symer, University of Washington Puget Sound Institute

SeaDoc Society Salish Sea ecosystem map

The Puget Sound Basin is only one half of a 17,000 sq. km. ecosystem, the Salish Sea. Efforts to restore Puget Sound or the Georgia Basin will fail if the U.S. and Canada do not improve cross-border collaboration. Map: N. Maher



Source: http://www.seadocsociety.org/salish-sea-ecosystem-map-page/

Map of the Salish Sea and surrounding basin

By Stefan Freelan, Western Washington University (2009).

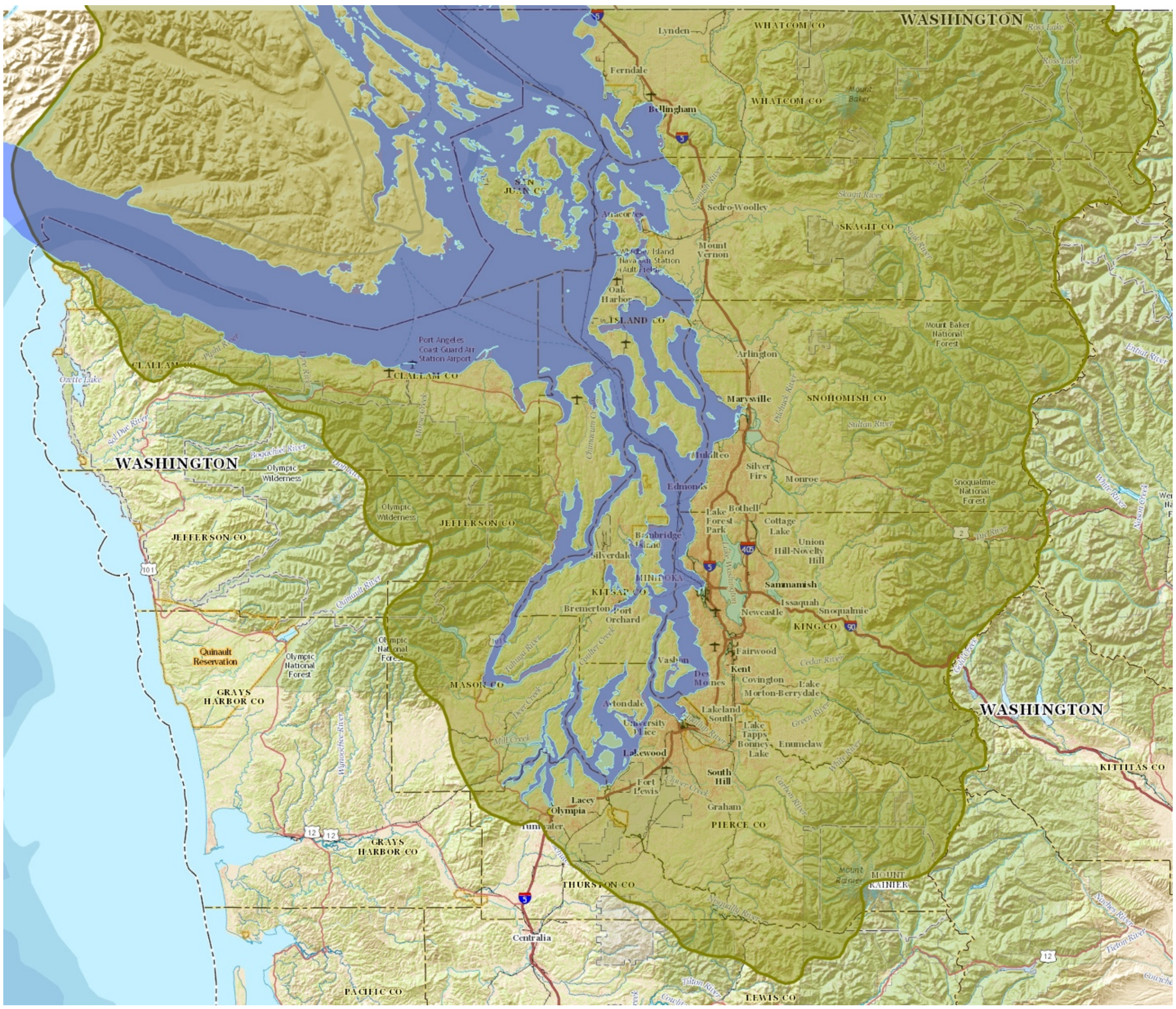
Source: http://staff.wwu.edu/stefan/salish_sea.shtml

Puget Sound counties

Twelve of Washington's 39 counties include Puget Sound waters:

- Clallam
- Island
- Jefferson
- King
- Kitsap
- Mason
- Pierce
- San Juan
- Skagit
- Snohomish
- Thurston
- Whatcom

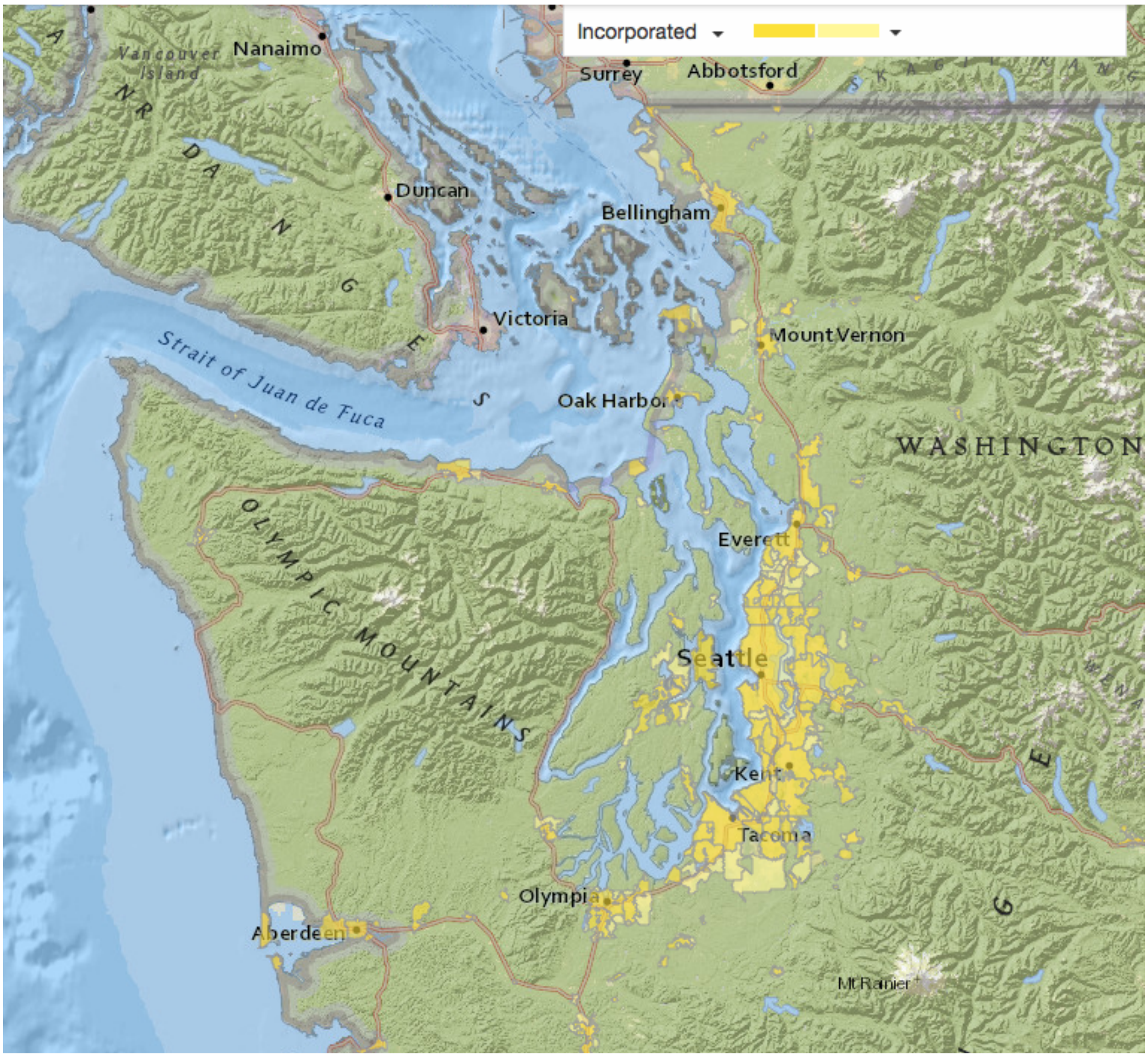
Portions of Lewis and Grays Harbor county are also contained in the surrounding watershed basin. Fourteen counties thus comprise the broader Puget Sound watershed basin. This is seen by overlaying Puget Sound watershed boundaries over a suitable basemap such as the USGS national map (at a scale showing county boundaries).



Source: http://www.eopugetsound.org/maps/salish-sea-basin-and-water-boundaries

City and urban growth area boundaries

Cities and Unincorporated Urban Growth Areas (UGA) as defined by the Growth Management Act. This dataset was compiled from county sources by the Washington State Department of Commerce and refined by Ecology. NOTE: This layer is current as of June 2013.



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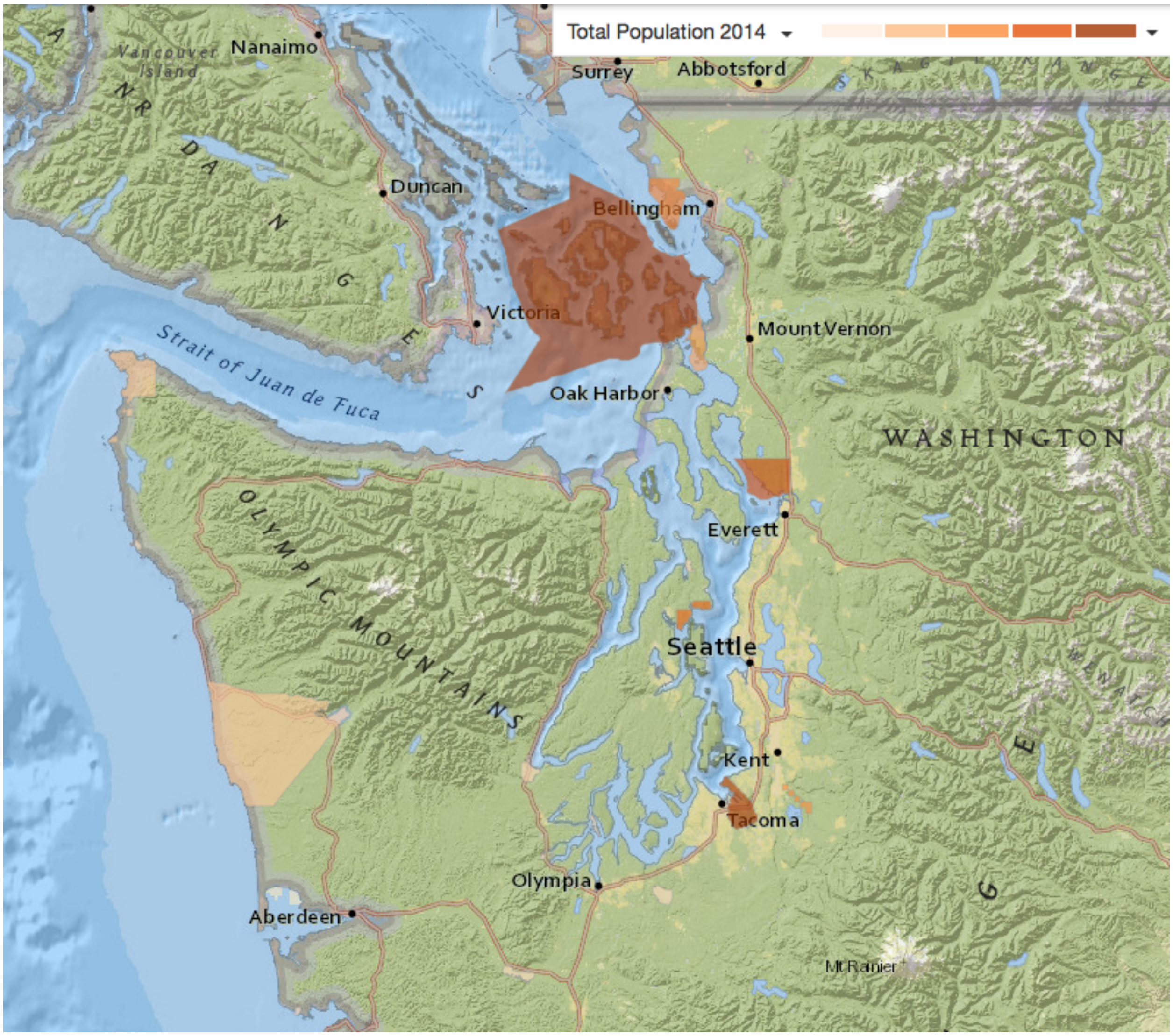
SAEP tribal areas

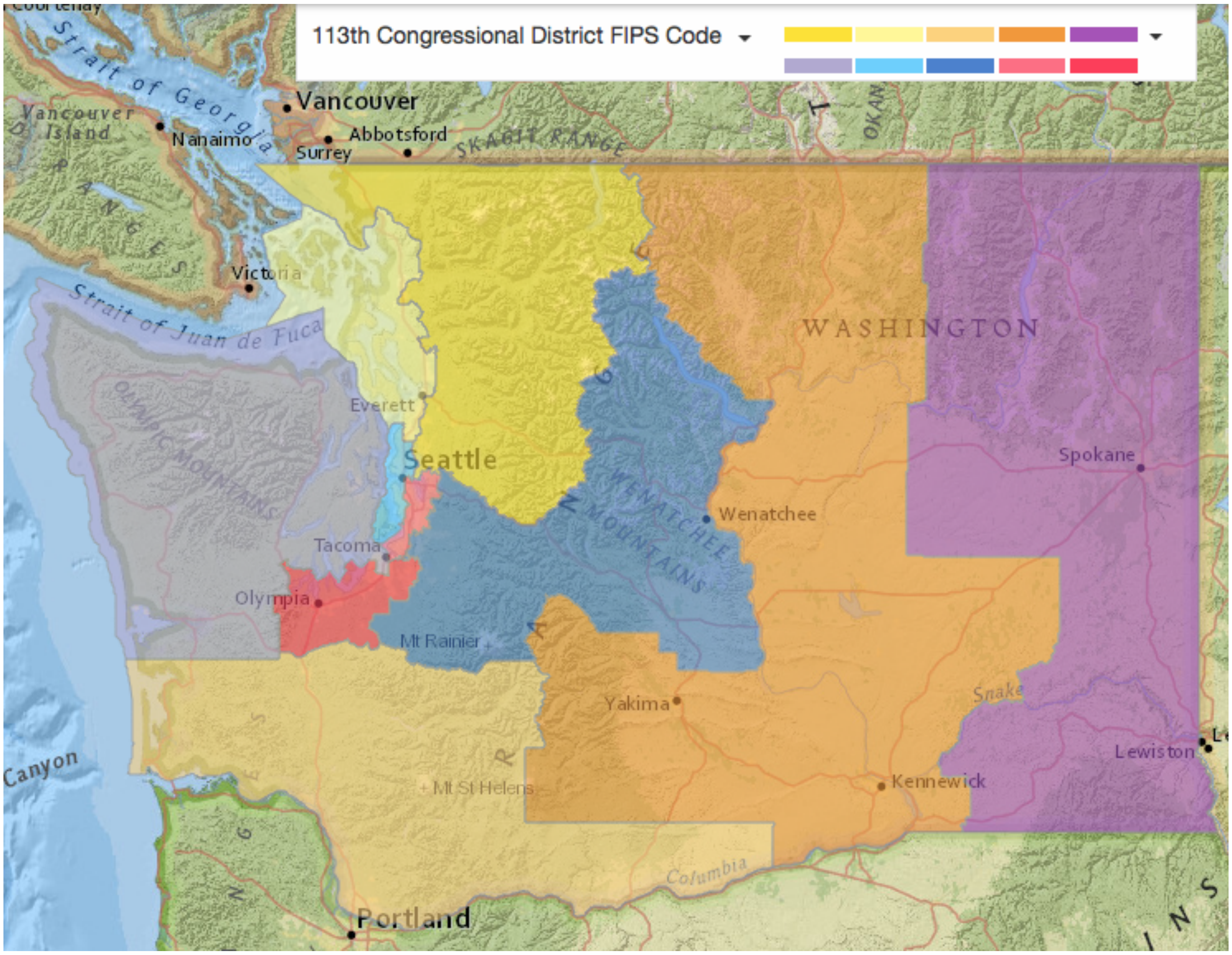
OFM Small Area Estimate Program (SAEP) population and housing estimates for Tribal Areas.



Source: http://geo.wa.gov/datasets/8955da39eaa443968108fbe7aed064bf_5?geometry=-127.791%2C48.158%2C-120.144%2C49.245&mapSize=map-normal&mappedField=POP2014&selectedTheme=8

SAEP congressional districts

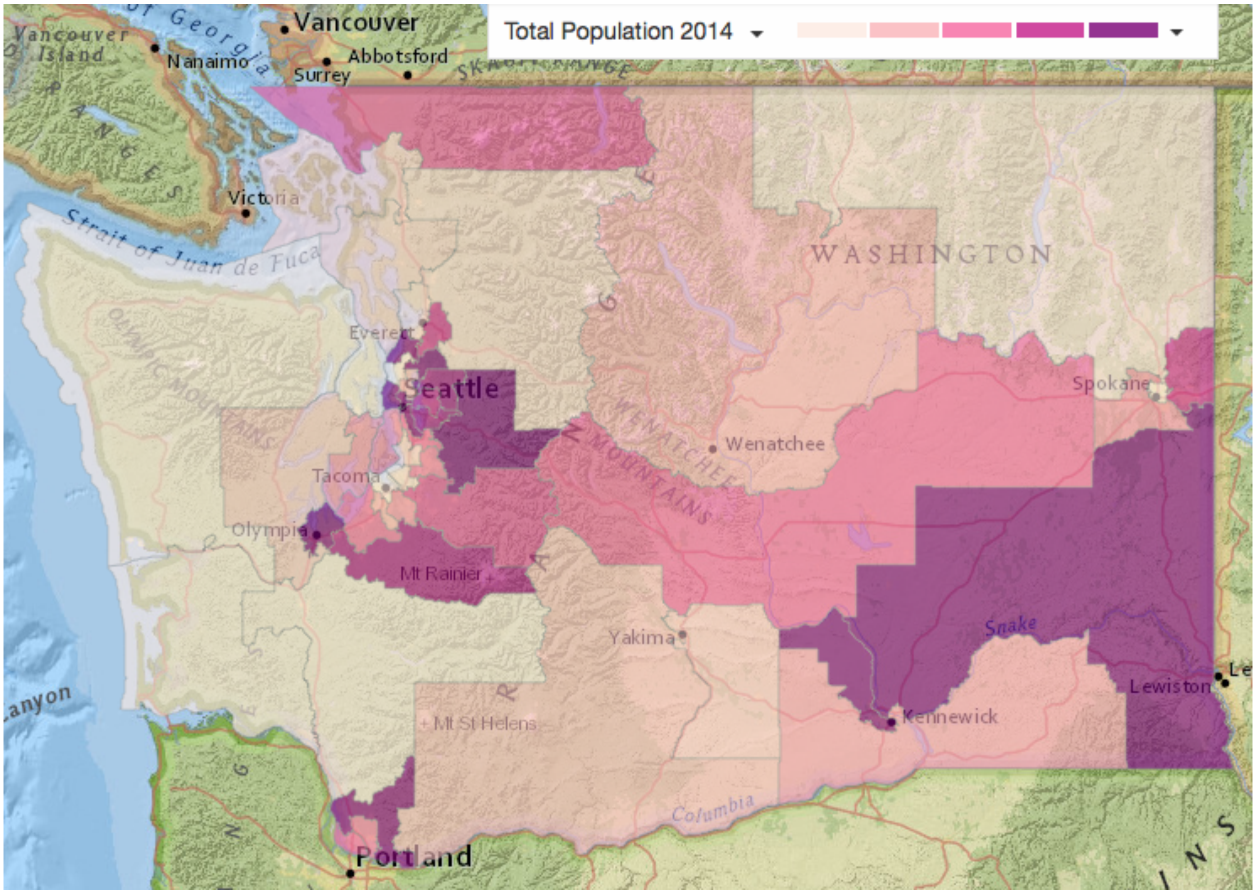
OFM Small Area Estimate Program (SAEP) population and housing estimates for Congressional Districts.



Source:
http://geo.wa.gov/datasets/8955da39eaa443968108fbe7aed064bf_2?filterByExtent=true&geometry=-131.253%2C47.517%2C-115.96%2C49.696&mapSize=map-normal&mappedField=CD113FP&selectedTheme=2

SAEP legislative districts

OFM Small Area Estimate Program (SAEP) population and housing estimates for Legislative Districts.

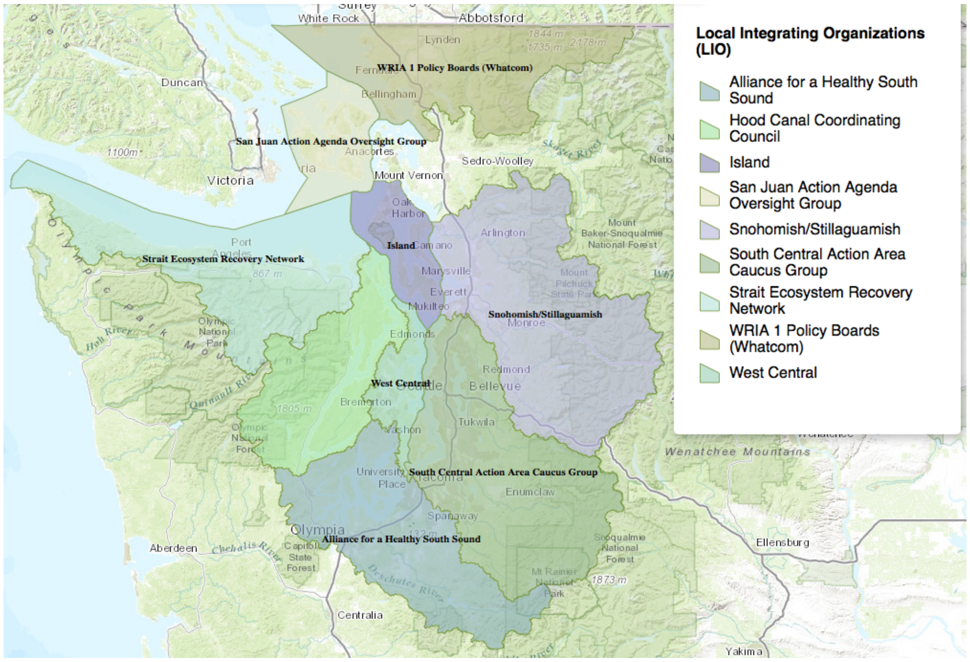


Source: http://geo.wa.gov/datasets/8955da39eaa443968108fbe7aed064bf_3?mapSize=map-normal&geometry=-137.252%2C45.019%2C-104.513%2C49.489&mappedField=POP2014&selectedTheme=18

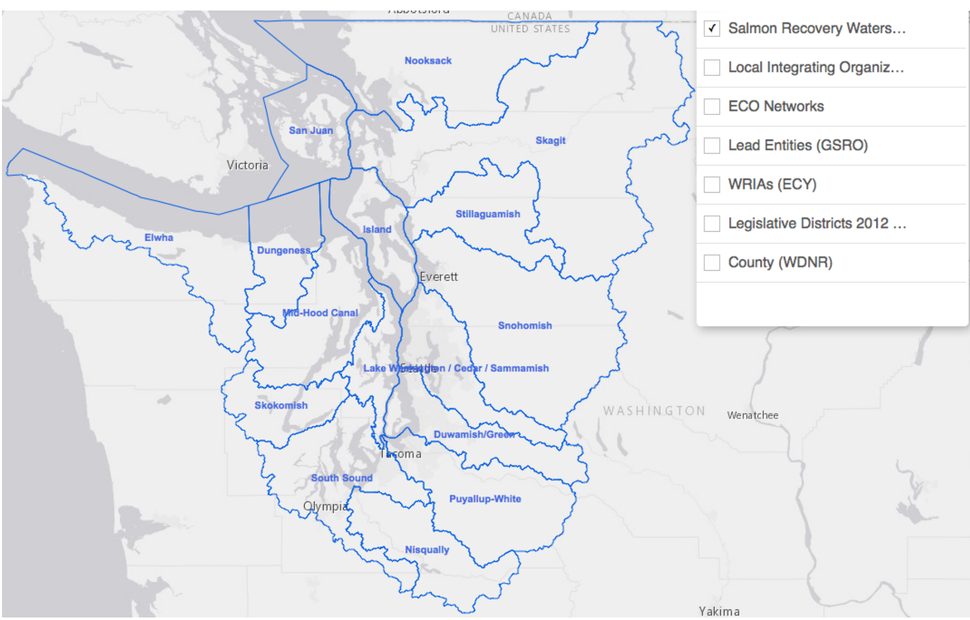
Puget Sound Partnership boundaries

Management Boundaries of Puget Sound Partnership and other relevant datasets such as county and WRIA boundaries.

Local integrating organizations (LIO)



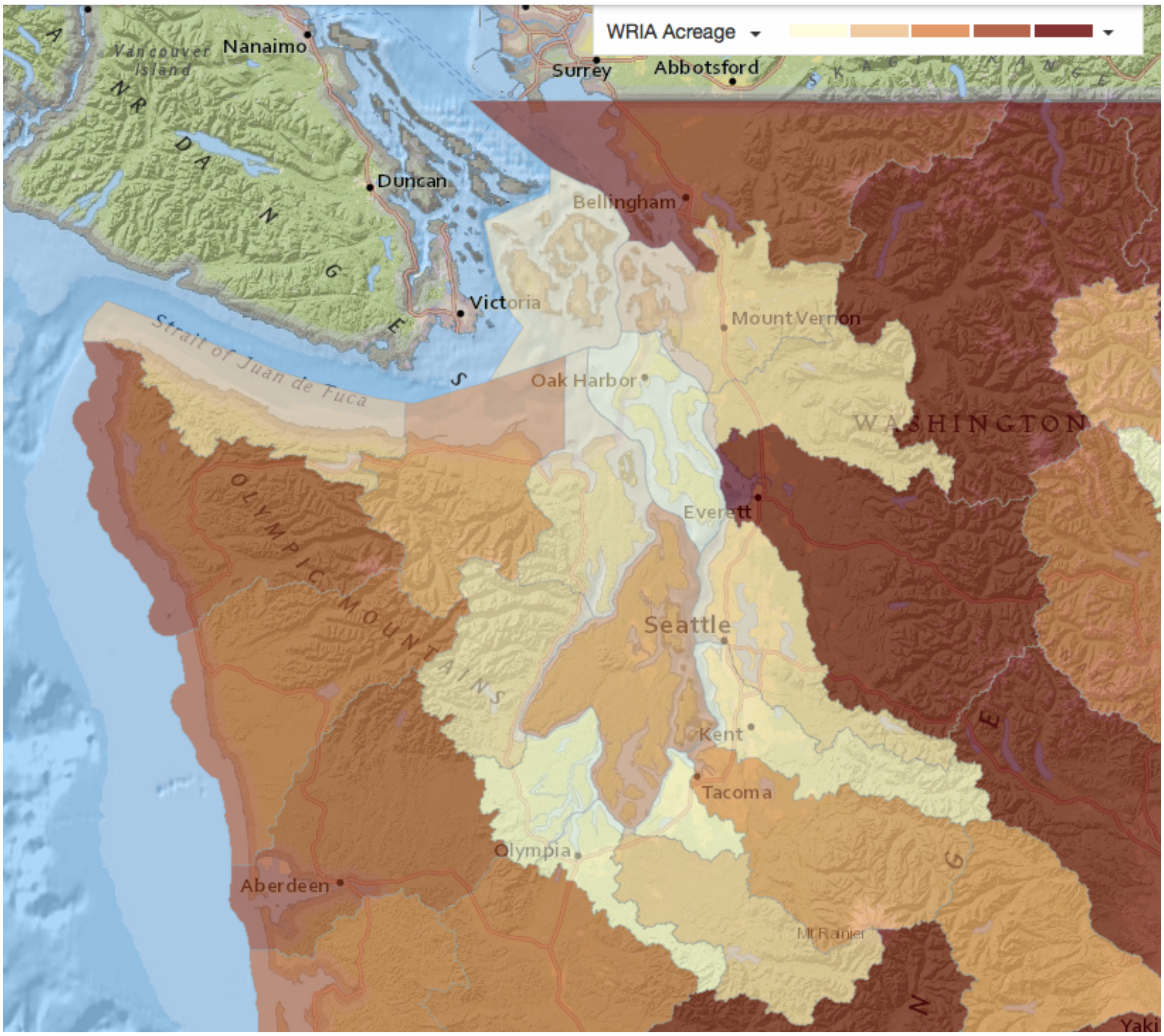
Salmon recovery watersheds



Source: http://wa-geoservices.maps.arcgis.com/apps/Viewer/index.html?appid=1ee39e6a3fb34bcaa770f6df333d36d0

Water Resource Inventory Areas (WRIA)

WRIAs were formalized under WAC 173-500-040 and authorized under the Water Resources Act of 1971, RCW 90.54. The Department of Ecology was given the responsibility for the development and management of these administrative and planning boundaries. These boundaries represent the administrative under pinning of this agency's business activities. The original WRIA boundary agreements and judgments were reached jointly by Washington's natural resource agencies (Ecology, Natural Resources, Fish and Wildlife) in 1970.



Source: http://geo.wa.gov/datasets/d3071915e69e45a3be63965f2305eeaa_0

Ecoregions

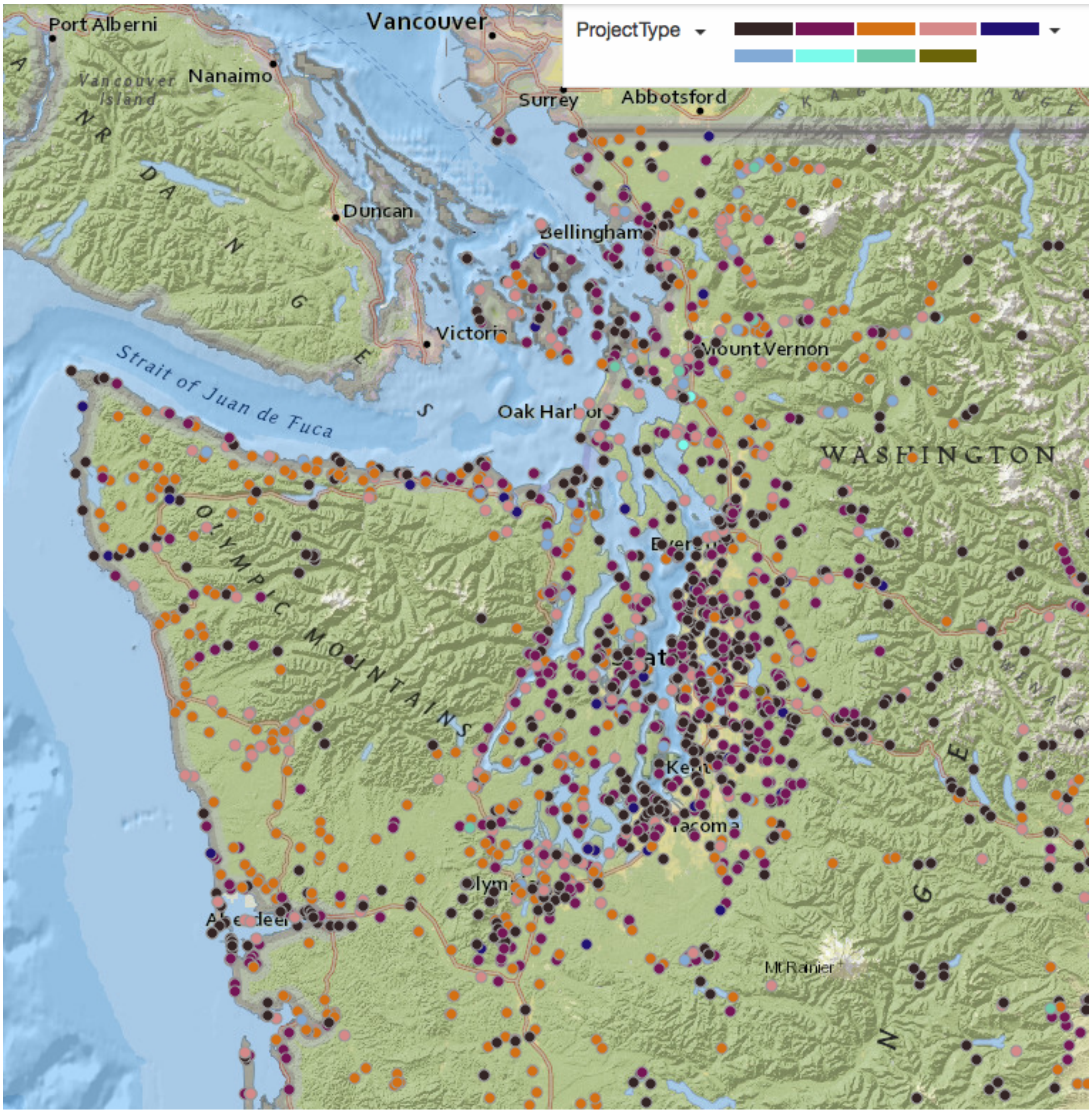
Ecoregions by state were extracted from the seamless national shapefile. Ecoregions denote areas of general similarity in ecosystems and in the type, quality, and quantity of environmental resources. They are designed to serve as a spatial framework for the research, assessment, management, and monitoring of ecosystems and ecosystem components. These general purpose regions are critical for structuring and implementing ecosystem management strategies across federal agencies, state agencies, and nongovernment organizations that are responsible for different types of resources within the same geographical areas. The approach used to compile this map is based on the premise that ecological regions can be identified through the analysis of patterns of biotic and abiotic phenomena, including geology, physiography, vegetation, climate, soils, land use, wildlife, and hydrology. The relative importance of each characteristic varies from one ecological region to another. A Roman numeral hierarchical scheme has been adopted for different levels for ecological regions. Level I is the coarsest level, dividing North America into 15 ecological regions. Level II divides the continent into 52 regions (Commission for Environmental Cooperation Working Group, 1997). At Level III, the continental United States contains 104 regions whereas the conterminous United States has 84 (U.S. Environmental Protection Agency, 2005). Level IV ecoregions are further subdivisions of Level III ecoregions. Methods used to define the ecoregions are explained in Omernik (1995, 2004), Omernik and others (2000), and Gallant and others (1989).

Source:
http://geo.wa.gov/datasets/8d812a11df584c208c156a5320fe6a4c_0?filterByExtent=true

Recreation and Conservation Office funded projects

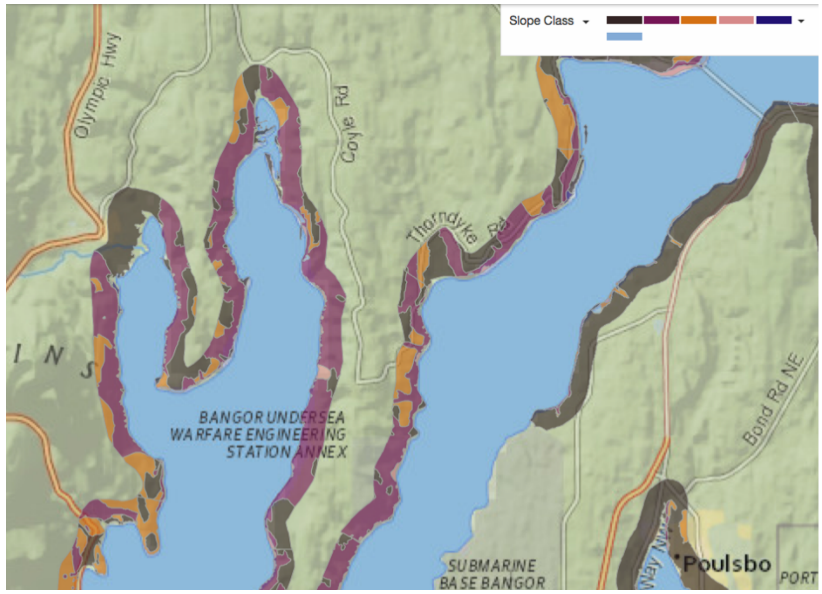
The WA RCO Funded Projects map and feature services have one layer showing all funded projects by program section. Project sites are labeled with project number and program named when zoomed in to 1:100,000 scale. Detailed project descriptions are hyperlinked.

The WA RCO Funded Projects data is intended for grant management planning and public information only. Project worksite locations are self-reported by project sponsors and may not have been located accurately nor verified by WA RCO staff.



Source: http://geo.wa.gov/datasets/c0d376088de64d2f960d1443dfbde670_0

Slope stability



The digital maps presented here were originally published as hard copy maps in the Coastal Zone Atlas of Washington between 1978 and 1980. Although the Atlas has been out of print for many years, the maps contain information that remain the basis for local planning decisions. After receiving multiple requests for electronic versions of portions of the Atlas, an effort was made to scan, georeference and digitize aspects of the Atlas, beginning with the slope stability maps. These maps indicate the relative stability of coastal slopes as interpreted by geologists based on aerial photographs, geological mapping, topography, and field observations. Such methods are standard, but may occasionally result in some unstable areas being overlooked and in some stable areas being incorrectly identified as unstable. Further inaccuracies are introduced to the data through the process of converting the published maps into digital format. Important land use or building decisions should always be based on detailed geotechnical investigations.

This mapping represents conditions observed in the early and mid-1970s. Shorelines and steep slopes are dynamic areas and many landslides have occurred since that time that are not reflected on these maps. Subsequent human activities may have increased or decreased the stability of some areas. These maps are intended to educate the public about Washington's shoreline and to guide regional land use decisions. These maps should not be used as a substitute for site-specific studies carried out by qualified geologists and engineers. The Department of Ecology assumes no liability for the data depicted on these maps.

Mapping of slope stability in the Coastal Zone Atlas only extends 2000 feet inland from the shoreline. Mapping was carried out only in those areas under direct state shoreline jurisdiction and therefore did not include federal military installations or Indian Reservations. The Coastal Zone Atlas was printed on a base map consisting of United States Geological Survey (USGS) 1:2400 topographic quadrangles, some of which were quite old. This information was provided for reference, but should not be used to determine current conditions, as many structures, roads, and other features have changed considerably.

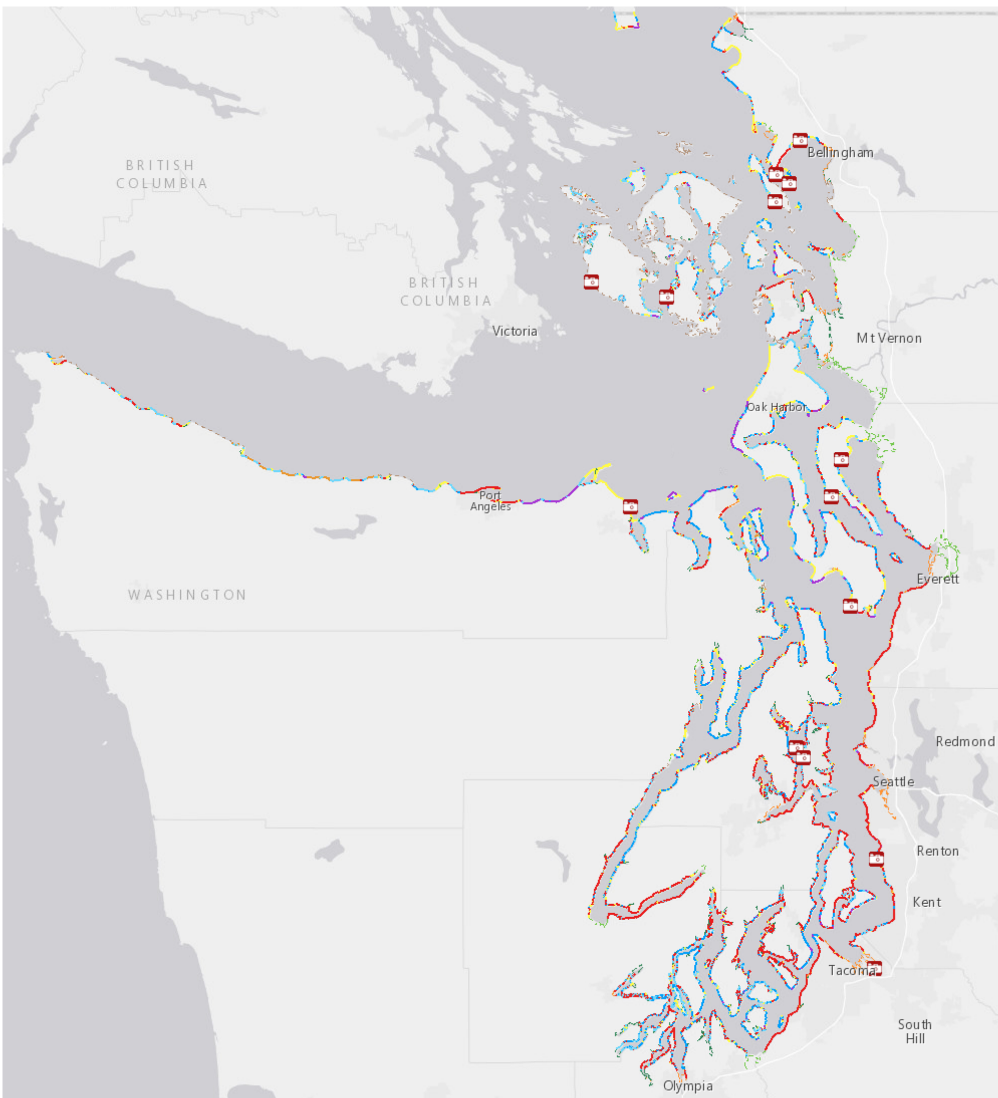
Source:
http://geo.wa.gov/datasets/618d401d4bc14212b9019503deab5467_0?selectedAttributes%5b%5d=SLP_CLASS&chartType=bar&geometry=-123.665%2C47.542%2C-121.908%2C47.819

Feeder bluffs and coastal landforms

There are many different ways to classify shorelines, but we've chosen a system that divides the coast up into the following landforms: Beaches (Bluffs and Spits), Rocky Shorelines, Large River Deltas, Small Lagoons and Estuaries, Artificial Shorelines.

The mapping was carried out as part of the Puget Sound Feeder Bluff project and is based on field observations, aerial photography, geologic and topographic maps, and other sources.

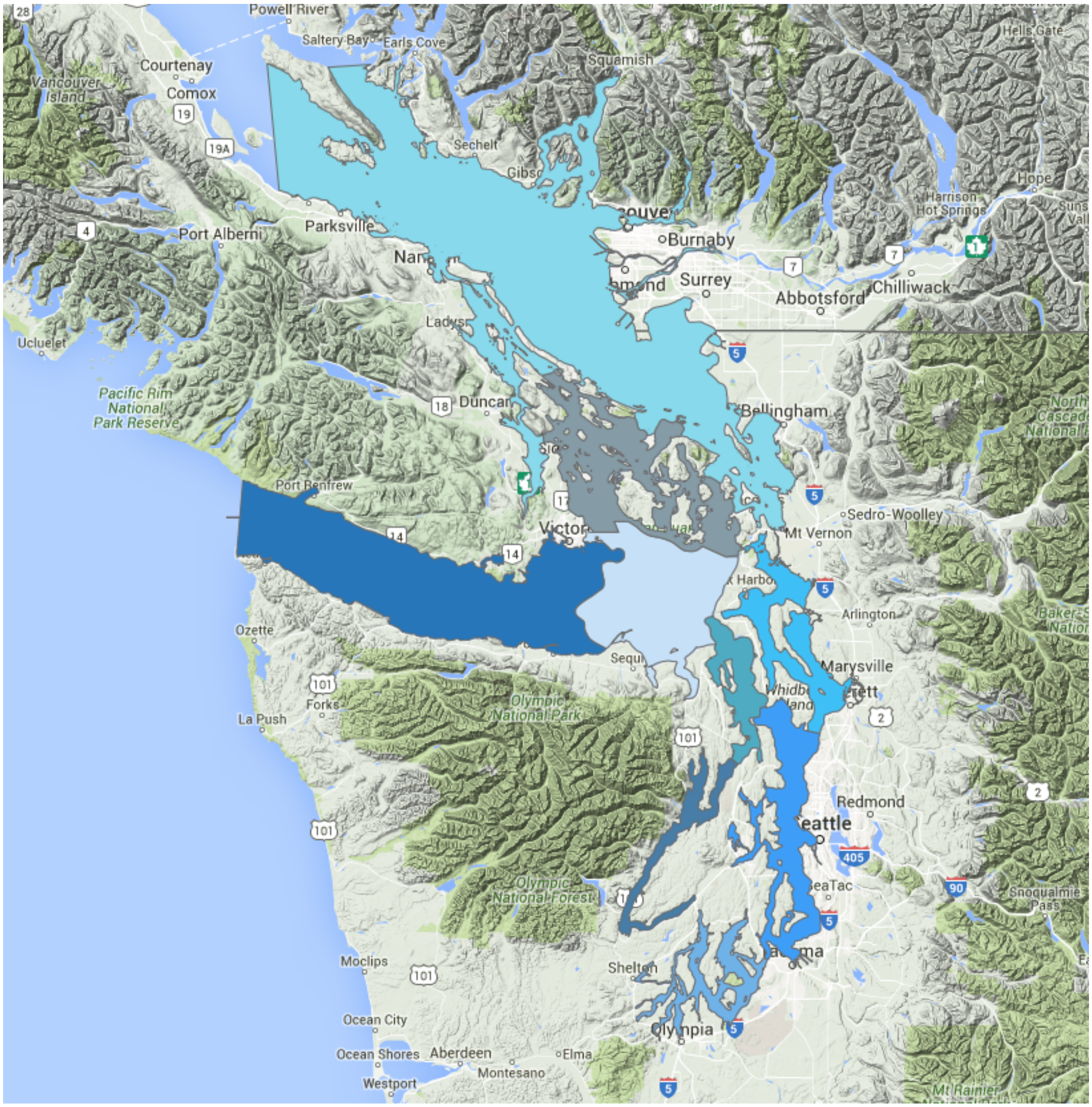
The classification used in these maps is based in part on work done by the Puget Sound Nearshore Ecosystem Restoration Project (PSNERP). Additional information on coastal landforms can be found at: Puget Sound Coastal Landforms



Source:
https://fortress.wa.gov/ecy/coastalatlas/storymaps/StoryMap.html?id=coastallandforms

Marine basins (biogeographic regions)

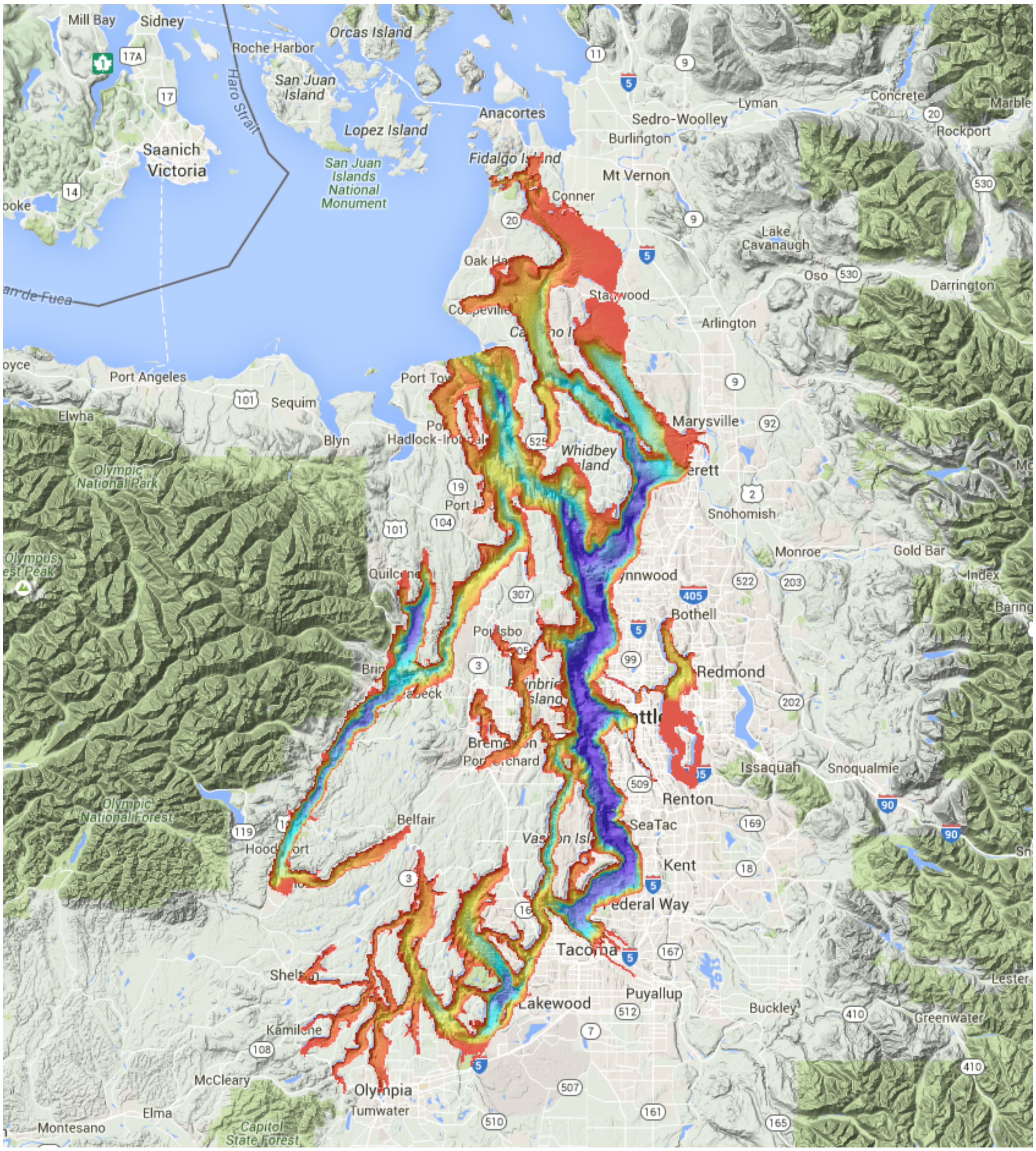
Puget Sound is divided into nine sub-basins which are defined primarily by oceanographic zones and sills (Ebbesmeyer et al.1984). These nine sub-regions are: West Strait of Juan de Fuca, East Strait of Juan de Fuca, San Juan Archipelago, Strait of Georgia, Whidbey Basin, Admiralty Inlet, Hood Canal, Central Puget Sound, and South Puget Sound.



Sources: http://www.dnr.wa.gov/publications/aqr_rsve_guidance.pdf and https://erma.noaa.gov/northwest/erma.html#/x=-123.44039&y=48.39419&z=8&layers=3+7531

Estuarine bathymetry

This 30-meter resolution bathymetric digital elevation model (DEM) shows underwater topography and sea floor depths. It was derived from source hydrographic survey soundings collected by NOAA dating from 1934 to 1982. The total range of soundings for the surveys used was 3.0 to -295.1 meters at mean low water.



Sources: https://data.noaa.gov/dataset/puget-sound-wa-p290-bathymetric-digital-elevation-model-30meter-resolution-derived-from-source- and https://erma.noaa.gov/northwest/erma.html#/x=-122.88283&y=47.93253&z=9&layers=3+7372