Sound Science:

Synthesizing Ecological and Socioeconomic Information about the Puget Sound Ecosystem

January 2007

A regional science collaboration

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Sound Science: Synthesizing Ecological and Socio-economic Information about the Puget Sound Ecosystem summarizes what we know about the greater Puget Sound ecosystem and what we think could happen in the future given present trajectories and trends. It provides a broadly agreed-to synthesis of the current scientific information about the Puget Sound ecosystem, including linkages among processes, species, habitats, and ecosystem services that benefit humans. We also have included analyses of the key issues facing Puget Sound in the future, the gaps in our scientific understanding, and the contribution that science can make in an informed discussion of solutions.

The development of the Sound Science document has been a collaborative process among scientists from a variety of disciplines and institutions throughout Puget Sound. The content reflects the wealth of knowledge in existing plans, research projects and personal expertise. The open dialogue and vigorous discussion about the interactions between components of the ecosystem, key threats to that system and critical science needs is almost as significant as the findings themselves. This document is the product of over 30 authors and almost 100 reviewers from federal, tribal, state, local, non-governmental, and academic institutions across the Puget Sound region. In total, hundreds of natural and social scientists have contributed either as co-authors, through extensive reviews, or by participating in workshops to debate and improve the information. We believe that the resulting content of the document thus reflects the collective views of the broad community of natural and social scientists familiar with Puget Sound.

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View the document online (under documents) at:
http://www.nwfsc.noaa.gov/research/shared/sound_science/index.cfm

Executive Summary

The Puget Sound Ecosystem: Enduring Beauty and Growing Distress

Puget Sound is famous for the abundant resources that flow from its stunning marine and terrestrial ecosystem. Diverse mountain ranges, forests, river deltas, rocky shorelines, and tideflats give way to an underwater landscape supporting interlocking webs of species ranging from mighty orcas to microscopic algae. Unique among developed estuaries in the United States, Puget Sound is a fjord-like system with huge variations in elevation and terrain both above and below sea level. This variable topography has given rise to diverse plant and animal communities adapted to a multitude of specialized habitats; however these species are also highly sensitive to human and natural disturbances in climate, precipitation, temperature, light availability, and nutrient input.

The beauty and economic promise of Puget Sound and the neighboring Georgia Basin to the north are expected to attract three million new human residents in the next 20 years. Despite the beautiful appearance of this ecosystem, a number of indicators show that the processes supporting our diverse species have been disrupted or impaired. The past and present pollution of Puget Sound has created a toxic legacy that continues to work its way through the food web, threatening the health of marine and freshwater species, and posing risks to humans as well. The underwater landforms and complex water circulation patterns within Puget Sound also work to minimize the flushing of many pollutants out to sea. Habitat loss and impairment are widespread throughout Puget Sound's rivers, shorelines and marine environments, and over 40 species are listed as threatened and endangered, or as candidates for listing. Several important studies are reported by the Puget Sound Action Team and other agencies that describe the indicators and trends of ecosystem decline in detail. (See, for example, the Puget Sound Update and the State of the Sound Report at www.psat.wa.gov.)

The Application of Ecosystem-Based Management for Puget Sound

National commissions evaluating the state of the oceans and coastal areas of the United States have indicated that a broader perspective is needed to treat the causes along with the symptoms of ecosystem decline. An ecosystem-based approach looks at the complex linkages within the physical and biological components of an ecosystem, and how social and economic choices by humans can change these processes. Only when the consequences of human actions and values are highlighted throughout the ecosystem can the entire range of tradeoffs be made apparent and considered when social and economic decisions are made. To ensure that the benefits and services we derive from the ecosystem, such as fish, timber, crops, water supply, recreation and waste treatment, can continue in the future, we must consider what our natural resource management actions will do to the underlying structure and function of the ecosystem itself. Input from Puget Sound's scientific community was obtained in the preparation of the Sound Science document to help inform natural resource policies in Puget Sound by characterizing the components of the ecosystem, the issues affecting the ecosystem in the future, and current gaps in scientific understanding.

Changing Ecological and Human Components of Puget Sound

This document defines the greater Puget Sound region as the lands and waters from the crests of the Cascade and Olympic mountains to the marine waters extending from the mouth of the Strait of Juan de Fuca east, including the San Juan Islands, and south to Olympia. Overlaying the complex geological structure of Puget Sound's mountains, rivers, and bathymetry are natural chemical and physical processes that shape the habitat for diverse marine and terrestrial species. Weather systems from the Pacific Ocean run into the Olympics and Cascades, creating variations in precipitation and temperature. The circulation of marine waters through bays and across underwater "sills" of Puget Sound affect the transfer of nutrients and contaminants between the ocean waters and estuary. The cycling of wood, water, nutrients and sediment between the terrestrial, freshwater and marine environments historically has supported interconnected communities of species in Puget Sound, that are characterized by intense competition for habitat, food and space.

Humans have long been beneficiaries of the services provided by the Puget Sound ecosystem, but in the past two centuries, humans have also caused large-scale change to ecosystem processes. Humans have eliminated or impaired habitat through the modification of watersheds, rivers, shorelines and marshes, harvested some species to critically low levels, intentionally or accidentally introduced non-native and invasive species, and deposited toxic chemicals and concentrated nutrients into fresh and marine waters. In recent decades, efforts to ameliorate these effects have been initiated, and examples of localized successes can be found in many parts of Puget Sound. Increasingly, however, scientists and policy makers in Puget Sound have become aware of the need to

evaluate human actions on a Sound-wide and ecosystem-wide basis and consider the long-term connections of these complex physical, chemical and inter-species processes when making natural resource management decisions.

The Future of Puget Sound

The fourth Section consists of a series of issue papers on the future of Puget Sound prepared by groups of scientists and presented in their own words. The paper on **Climate Change and Puget Sound** reveals compelling evidence of past, present and future changes for the region, including rising temperatures, alterations of seasonal river flow patterns, increases to winter runoff and flooding, reduced snowpack, and corresponding changes to the circulation patterns and biotic communities of the marine environment. In **The Future of Puget Sound Habitats**, scientists review the substantial changes to the Puget Sound ecosystem over the past 150 years. This analysis reveals that, unless different choices are made regarding land use and the disposal of contaminants, habitat quality, availability and diversity will decline and become more fragmented, thus reducing its value and function. **Species, Food Webs, and Human Impacts on Marine Ecosystems** provides several case studies of the ways in which human actions have had unintended and often unpredictable consequences to the food web. Three lessons are drawn from these examples—that food webs can change rapidly through natural processes, that these transformations are often surprising because complex linkages are often not fully revealed until connections have been disrupted, and that our ability to predict outcomes from any given action is severely limited without a good model of food webs.

Humans are an integral part of the Puget Sound ecosystem and three issue papers explore the impact of the ecosystem on humans and our ability to effect change. Changes in land cover and impacts to other species resulting from population growth are discussed in **Interactions between Natural and Human Systems in Puget Sound**. Conversely, **Puget Sound: Marine Ecosystems and Human Health** describes how growth and development may directly affect humans. Increasing trends of three types of contaminants are described: persistent toxic substances that bioaccumulate in upper level species such as marine mammals and humans, marine biotoxins from harmful algal blooms, and outbreaks of disease from the transmission of pathogens in water and shellfish. Finally, opportunities and tools for decision-makers to take a look at the myriad connections associated with a given action and to explore choices are discussed in Integrating the Sciences: **Natural and Social Science Support for Decision-Making**.

Key Findings

The Puget Sound ecosystem exhibits several indicators of degradation such as listed species, a disrupted food web, diminishing habitats, and persistent and toxic contaminants. Scientists stress the importance of concerted and immediate action that will allow the Puget Sound region to take advantage of opportunities to halt or reverse continued declines. Furthermore, preventative strategies are one of the most ecologically sound and cost effective solutions for the future. While change is an inherent feature of any ecosystem, the projected changes in climate, population growth, and the complexity of the Puget Sound ecosystem all point to the need for a broader outlook for ecosystem management.

Understanding interactions and linkages among species, habitats, and the processes that support them is critical to our ability to predict the ecosystem response to natural perturbations and management actions. An ecosystem-wide view of Puget Sound will improve our ability to choose cost-effective actions and predict long term results. The integration of information about human and natural systems is vital in analyzing alternative management approaches. Finally, connections between scientists and decision makers are considered to be crucial in achieving a broader perspective and sustainable strategy for the future of Puget Sound.

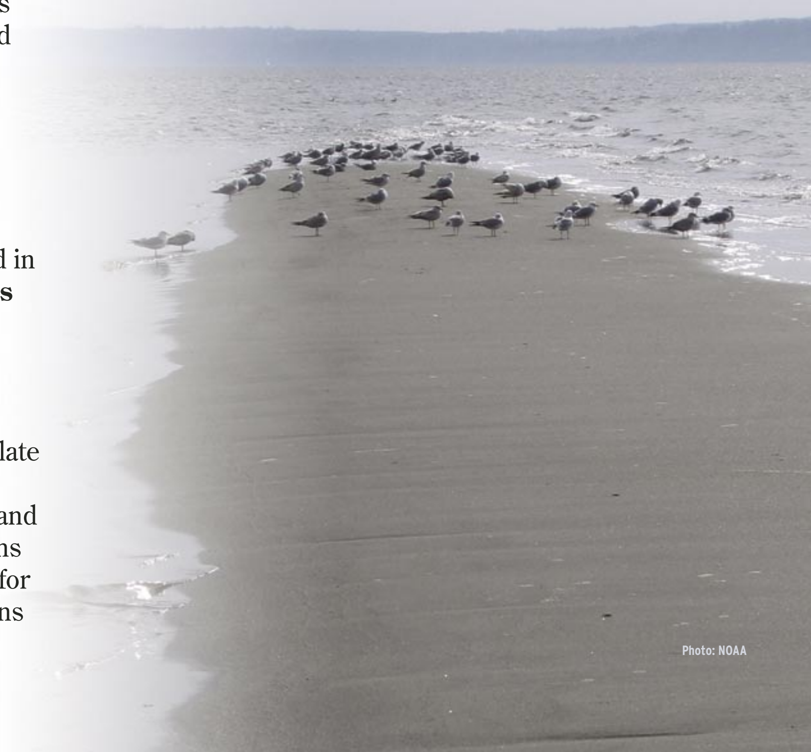

Photo: NOAA

Acknowledgments

This document reflects the collective knowledge of a broad community of scientists working in the Puget Sound region. Science and policy leaders from the following groups helped conceive of and develop this document from the earliest stages: King County Department of Natural Resources (KC DNR), NOAA Fisheries' Northwest Fisheries Science Center (NWFSC), Northwest Indian Fisheries Commission (NWIFC), Puget Sound Action Team (PSAT), The Nature Conservancy (TNC), University of Washington (UW), US Army Corps of Engineers (USACE), US Environmental Protection Agency (EPA), US Geological Survey (USGS), Washington State Department of Ecology (WA ECY), Washington Department of Fish and Wildlife (WDFW), and the Washington State Department of Natural Resources (WDNR).

Discussions with Jim Kramer (Shared Strategy and Puget Sound Partnership), Josh Baldi (WA ECY), David Dicks (Cascadia Law Group), Martha Neuman (Puget Sound Partnership), Anne Kinsinger (USGS), and Tim Smith (WDFW) helped to frame the policy context for this document in its early stages.

Many people helped substantially with the content of this document. Kurt Fresh (NWFSC), Jan Newton (UW), and Mark Plummer (NWFSC) provided abundant helpful input on content and overall scope of the document near its inception. A number of additional contributors from many agencies provided text and figures to early and later drafts of this document. These contributors include Angela Grout (KC DNR); Tom Good, Brad Hanson, and Dawn Noren (NWFSC); Sarah Brace (PSAT); Fred Goetz (USACE); Cynthia Barton, Guy Gelfenbaum, Marijke van Heeswijk, Mary Irvine, Robert Koeppen, Reg Reisenbichler, Frank Shipley, and Lyman Thorsteinson (USGS); and Megan Dethier, Allan Devol, Terrie Klinger, Dave Fluharty, and Mitsuhiro Kawase (UW). The information they provided at those preliminary stages was invaluable in ensuring that the breadth of Puget Sound information has been presented fully and accurately. The content of this document has evolved from those early stages through three peer-reviewed drafts and a science workshop in the spring of 2006, during which over 100 scientists provided in-depth comments and new material to enhance its accuracy and richness and offered critical contributions that informed the final Key Findings.

The Steering Committee—David Armstrong (UW), Tracy Collier (NWFSC), Andrea Copping (Pacific Northwest National Laboratory), Ken Currens (NWIFC), Rob Duff (Washington Department of Health), Brian Grantham (WA ECY), Lief Horwitz (USGS), Tom Mumford (WA DNR), Tim Quinn (WDFW), Michael Rylko (EPA), Mike Scuderi (USACE), Ron Shultz (PSAT), Randy Shuman (KC DNR), and Jacques White (TNC)—represented the views and scientific expertise of the signatories and shepherded the document through its final edits and fact-checking. They also provided final input and advice on the Key Findings Section.

The lead authors of the six Issue Papers—Nate Mantua, Tim Beechie, Tim Essington, Marina Alberti, Vera Trainer, and Alison Cullen—provided provocative ideas about the future of Puget Sound in true collaborative fashion with their co-authors, and we are grateful to all of them. Jim Peacock, Su Kim, and their helpers provided the graphic design and illustrations to accompany the text. Stewart Toshach ably steered us through the deadlines and tasks to keep us on track. Ann Seiter turned writing from a hundred voices into the coherent prose of one; her skillful pen is enormously appreciated. We are also indebted to Leo Shaw of the Seattle Aquarium for the generous use of his photos.

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Contents

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Section 1 Problems and Opportunities for Puget Sound

1.1 Puget Sound: Enduring Beauty and Growing Distress

Puget Sound provides a home to approximately four million human residents. Despite the striking visual beauty of the Puget Sound region, it is clear that this growing population has been a powerful force of change to the ecosystem. Over 40 species of marine birds, mammals, fishes, plants and invertebrates are currently listed as threatened, endangered, or as candidates for state and federal endangered species lists. Moreover, some of these listed species, such as Puget Sound Chinook salmon and the resident population of killer whales, are icons of the Pacific Northwest and have been celebrated in art, culture and tradition for many centuries. As of 2006, there are also approximately 290 species of terrestrial plant and 46 species of terrestrial wildlife listed as imperiled (endangered, threatened, or sensitive) by Washington State. Human disturbance, mostly in the form of land conversion, is a contributing factor for decline in many of these species.

Threatened and endangered species listings are not the only indicators of deterioration in the health of the Puget Sound ecosystem. Populations of many species of forage fish and marine birds have also declined since the 1970s. Habitat loss and modification in Puget Sound have been widespread in both marine and terrestrial environments. Over 90 species of alien marine plants and animals have been accidentally or intentionally introduced into Puget Sound. Pollution has left a toxic legacy, and past and present contaminants remain a serious problem for the Puget Sound food web and human health. Freshwater rivers, lakes, and streams have been dramatically modified by dams, water withdrawals and the input of runoff from paved surfaces, lawns and fields. These changes in volume and quality are transferred to the marine waters of Puget Sound. Several important documents, including the State of the Sound Report (PSAT 2005), the Puget Sound Update (PSWQAT 2002; 2006 edition in progress), and the Puget Sound Salmon Recovery Plan (Shared Strategy 2005), contain details of these changes (Table 1-1).

Photo: Leo Shaw, The Seattle Aquarium

Figure 1-1
Projected human population growth in Puget Sound and Georgia Basin

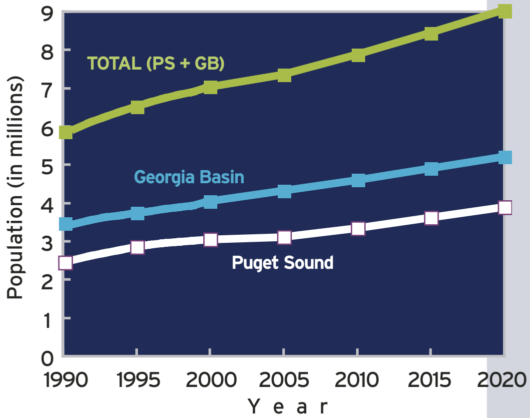


Table 1-1

Contamination from toxins and pathogens, species decline, and habitat loss and modification are widespread in Puget Sound

- Levels of Polychlorinated Biphenyls (PCBs) and Polycyclic Aromatic Hydrocarbons (PAHs) in several species of fish and shellfish have triggered consumption advisories due to the potential risk to human health. Long term monitoring indicates that PAH levels have increased, but metals such as arsenic, mercury and lead have declined.
- Although cleanup activities have resulted in substantial improvement, approximately 5,700 submerged acres of highly contaminated sediments remain in the Sound. Another 24,000 acres are classified as partially contaminated.
- Over the last 50 years, 66% to 84% of old-growth forest, has been lost from the Puget Sound area. Remaining old-growth forests in the Puget Sound watersheds are mostly limited to high-elevation public lands.
- As of 1995, approximately 23% of the land area of Puget Sound watersheds had been converted to human-dominated uses (urban and agriculture), most of which occur in the lower elevations.
- An 1885 survey estimated that there were 267 km^2 (103 mi^2) of tidal marsh and "swamplands" bordering Puget Sound. A comparison approximately 100 years later indicated that 54.6 km^2 (21 mi^2) remained—a decline of 80% Soundwide.
- Approximately one-third of the Puget Sound shoreline has been modified with bulkheads, docks, revetments, or other armoring, all affecting the transport and replenishment of sediment to beaches or other nearshore habitats.
- Approximately 25% of the historic freshwater habitat for Puget Sound Chinook salmon rearing has been lost.
- Impervious land cover in the Puget Sound basin increased by more than 7% in an 8-year period in the 1990s.
- Of the 20,000 acres of historic grassland prairie in the southern Puget lowland landscape, only approximately 8% remains intact.

(Sources: Puget Sound Action Team, Washington Department of Natural Resources, Washington Department of Ecology, Shared Strategy, and The Nature Conservancy)

AN OCEAN BLUEPRINT
FOR THE 21st CENTURY

U.S. COMMISSION ON
OCEAN POLICY

Coastal waters are one of the nation's greatest assets, yet they are being bombarded with pollutants from a variety of sources. While progress has been made in reducing point sources of pollution, non-point source pollution has increased and is the primary cause of nutrient enrichment, hypoxia, harmful algal blooms, toxic contaminants, and other problems that plague coastal waters. Non-point source pollution occurs when rainfall and snowmelt wash pollutants such as fertilizers, pesticides, bacteria, viruses, pet waste, sediments, oil, chemicals, and litter into our rivers and coastal waters . . . Our failure to manage the human activities that affect the nation's oceans is compromising their ecological integrity, diminishing our ability to fully realize their potential, costing us jobs and revenue, threatening human health, and putting our future at risk.

— Executive Summary
An Ocean Blueprint for the 21st Century (2004)

The human population in the Puget Sound and Georgia Basin region is expected to grow by two million new residents within the next 20 years, potentially putting severe stress on the ability of the ecosystem to provide the array of assets we are accustomed to. Many of the ecological problems and human activities of the region are transboundary in nature and should be considered jointly. However, this report focuses on ecosystem processes and changes within Puget Sound that require attention from this region. Without concerted action to protect the structure and function of the Puget Sound ecosystem, the resilience and productivity of the system will decline, and the many benefits, including clean beaches, property values, safe drinking water and local food supplies will be impaired.

1.2 National Calls for Ecosystem-Scale Management

Observable, widespread declines in the status of species, habitats, and functions in marine waters and terrestrial landscapes have led to calls for ecosystem-scale management as a strategy to heal our watersheds and coastal oceans (Pew 2003, USCOP 2004). At the core of a systemwide approach to natural resource management is the importance of considering the factors that drive human behaviors and choices, as well as the potential consequences of our actions on the natural system. Clearly the implementation of an ecosystem approach to natural resource management in our coastal communities will require an understanding of the complexities of terrestrial, estuarine, and marine ecosystems along with insight on how humans fit into the system as consumers, competitors, and producers.

Other regions of the United States have experienced significant natural resource challenges on an ecosystem scale, including the Chesapeake Bay, the Everglades, Louisiana delta, Great Lakes, Prince William Sound, and the Sacramento/San Francisco Bay/delta area. Major modifications to the structure and function of these ecosystems have reduced the services they can provide, and significant funding and several human lifetimes will be required to remediate the problems. Puget Sound still presents a unique opportunity to take proactive measures to recover and maintain a healthy and viable ecosystem before degradation becomes widespread and irreversible.

1.3 Opportunities for Ecosystem-Based Management in Puget Sound

Scientists and resource managers have prepared numerous reports and plans related to the physical condition of Puget Sound and the recovery of particular species in recent years (Table 1-1). Many of the action plans have analyzed how natural processes link to the formation of habitats and species' productivity where such information is known, but there still are significant scientific uncertainties associated with identifying an overall strategy to achieve ecosystem goals in Puget Sound. There is growing support among multiple management interests in the Puget Sound region to move toward a concerted, ecosystem-scale approach to managing local resources, including a new opportunity provided by the governor to bring these forces together in a partnership to restore the health of the Puget Sound ecosystem by 2020. This sentiment coincides with the national call for ecosystem-based management to pull together the fractionated management of our oceans and waterways that is prevalent in many parts of the country. Ecosystem-based management is an opportunity to look at the broader impact of human actions on ecosystem function and how changes in ecosystem function affects the benefits we can reap from the natural system, and to grapple with the potential tradeoffs inherent in balancing the natural and human systems in Puget Sound.

The Sound Science document has been developed to provide a scientific framework for the discussions presently occurring in Puget Sound among federal, state, tribal and local management interests. In developing this document, Puget Sound natural and social scientists have considered a series of broad questions for ecosystem management:

- What are the current processes that form and sustain habitats and species, provide food and fiber, regulate disease and waste, and generate other ecosystem services in Puget Sound?
- How have ecosystem services in Puget Sound changed over the past two centuries?
- What are the drivers of ecosystem change in Puget Sound?
- How might Puget Sound ecosystems respond in the future to changing conditions and actions, and what are some of the uncertainties?
- How can our understanding of the ecosystem enable us to manage the ecosystem sustainably and effectively?

Ultimately, the purpose of Sound Science is to help inform natural resource policies in Puget Sound through the application of broadly-based scientific knowledge at the ecosystem level. The Sound Science document has been prepared with input from the Puget Sound scientific community in order to characterize the elements, processes, and linkages of the Sound ecosystem as a whole; highlight major issues affecting the future; and identify some of the key gaps in current scientific understanding that hinder our ability to manage Puget Sound sustainably.

Table 1-2

A few of the major reports and plans recently produced for Puget Sound . . .

- **State of the Sound 2004** (Puget Sound Action Team (PSAT), 2005). This report on the health of Puget Sound focuses on 15 environmental indicators reflecting the condition of the Sound's water and submerged lands, habitats and species, and the threats to these resources. www.psat.wa.gov

- **Puget Sound Conservation and Management Plan 2005–2006** (PSAT 2005). Action plan covering high-priority activities for Puget Sound, including:
    1. Cleanup contaminated sites and sediments
    2. Prevent toxic contamination
    3. Prevent harm from stormwater runoff
    4. Prevent nutrient and pathogen pollution (Special Focus Area: Hood Canal)
    5. Protect functioning nearshore and freshwater habitats
    6. Restore degraded nearshore and freshwater habitats
    7. Conserve and recover species at risk
    8. Prepare for and adapt Puget Sound efforts to a changing climate.

- **Puget Sound Update: Report of the Puget Sound Assessment and Monitoring Program.** The PSAMP was initiated by the State of Washington in 1988 to integrate environmental quality assessments by local, state and federal agencies in Puget Sound. Coordinated by the Puget Sound Action Team, a technical report is published every few years. The next publication of this "Puget Sound Update" is anticipated in the Fall of 2006. Previous updates are available at www.psat.wa.gov

- **Puget Sound Nearshore Ecosystem and Restoration Program.** PSNERP was formally initiated in September 2001 as a joint study by the U.S. Army Corps of Engineers and the State of Washington Department of Fish and Wildlife to evaluate significant ecosystem degradation in the Puget Sound Basin and formulate solutions with local partners. Additional organizations joined the program and created the Puget Sound Nearshore Partnership. Several technical reports were published by the Partnership in 2004, including "Guiding Restoration Principles," Guidance for Protection and Restoration of the Nearshore Ecosystems of Puget Sound," and "Application of the 'Best Available Science' in Ecosystem Restoration: Lessons Learned from Large-Scale Restoration Project Efforts in the USA." These and other materials are available at http://pugetsoundnearshore.org

- **Georgia Basin-Puget Sound Ecosystem Indicators Report** (Environment Canada, US Environmental Protection Agency, PSAT; Spring 2002 and Fall 2006). Report examining selective aspects of the state of the environment in the bi-national transboundary region and indicators and trends for this shared ecosystem. www.epa.gov/region10/psgb/indicators

- **Draft Puget Sound Salmon Recovery Plan** (Shared Strategy for Puget Sound, 2005). Draft recovery plan for threatened distinct population segments of Puget Sound Chinook salmon and bull trout submitted to the National Marine Fisheries Service and US Fish and Wildlife Service. www.sharedsalmonstrategy.org

- **Preliminary Draft Conservation Plan for Southern Resident Killer Whales *(Orcinus orca)*** (National Marine Fisheries Service, 2005). www.nwr.noaa.gov/mmammals/whales/preliminkwconsplan.pdf

- **Uncertain Future: Climate Change and Its Effects on Puget Sound** (Climate Impacts Group and University of Washington, 2005). http://www.psat.wa.gov/Publications/climate_change2005/climate_home.htm

- Our Changing Nature: Natural Resource Trends in Washington State. (Washington Department of Natural Resources, 1998). Olympia, WA

- Willamette Valley-Puget Trough-Georgia Basin Ecoregional Assessment. The Nature Conservancy, 2004. (Floberg, J., M. Goering, G. Wilhere, C. Macdonald, C. Chappell, C. Rumsey, Z. Ferdana, A. Holt, P. Skidmore, T. Horsman;) Arlington, VA http://www.ecotrust.org/placematters/assessment.html

Reports on the chemical contamination of Puget Sound sediments include . . .

- **Temporal Monitoring of Puget Sound Sediments: Results of the Puget Sound Ambient Monitoring Program, 1989–2000** (Washington State Department of Ecology, 2005). http://www.ecy.wa.gov/biblio/0503016.html

- **Chemical Contamination, Acute Toxicity in Laboratory Tests and Benthic Impacts in Sediments of Puget Sound: A summary of results of the joint 1997–1999 Ecology/NOAA survey.** (Washington State Department of Ecology, 2003). http://www.ecy.wa.gov/biblio/0303049.html

Section 2 Management of Puget Sound on an Ecosystem Scale

The lands and waters of Puget Sound provide a full array of ecosystem products and services that humans enjoy. As a result, goals for Puget Sound are often expressed in terms of clean beaches, healthy seafood, abundant wildlife, stable fisheries, or thriving coastal economies, but many ecosystem benefits are difficult to quantify. Furthermore, the ecosystem may accommodate one set of services, such as waste treatment, at the expense of other services, such as healthy seafood. Recent studies of the relationship of human values to ecosystem services are looking at ways to ensure that potential impacts throughout the entire ecosystem are considered when decisions are made, and that tradeoffs are explicitly recognized.

Photo © Joel Rogers

2.1 A Conceptual Framework

Changes in ecosystems due to natural and human causes result in changes in the goods and services provided by the ecosystem, thus affecting the well-being of humans and other species (Figure 2-1). In order to measure

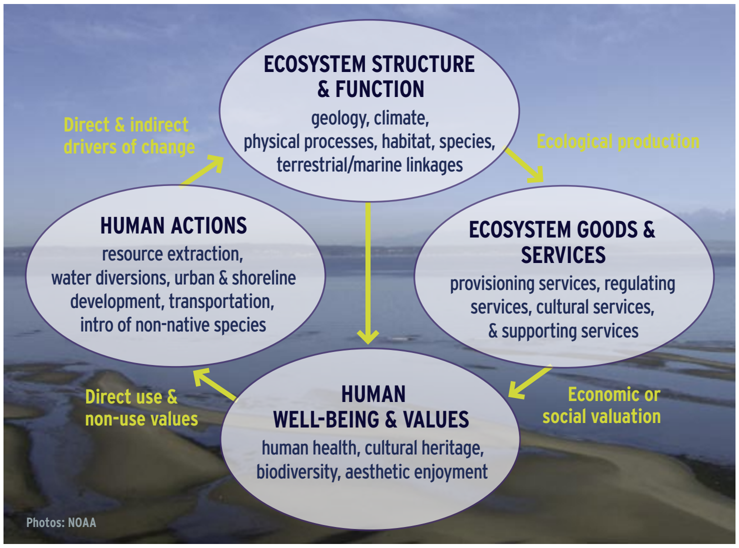


Figure 2-1
Relationship of ecosystem structure & function and human well-being (adapted from National Research Council 2004 and Millennium Ecosystem Assessment 2005)

progress towards achieving ecosystem goals, scientists often convert general goal statements into "ecosystem services" that can be more directly quantified and tracked over time (NRC 2004, MA 2005). The economic and social values ascribed to these ecosystem services, combined with ecological assessments of ecosystem function, can be used to evaluate management strategies and their resulting effect on ecosystem productivity and services.

2.2 Drivers of Ecosystem Change

Direct or indirect changes to the ecosystem may result from naturally-occurring physical and biological processes or, increasingly, from human actions. Direct drivers of ecosystem change in Puget Sound include land use modification; water diversions and dams; species introduction or removals; external inputs such as fertilizers, pharmaceuticals, and pesticides; harvest and resource consumption; climate change; and long-term natural drivers such as volcanoes, earthquakes, or evolutionary changes in species (MA 2005). Indirect drivers of change to the Puget Sound ecosystem are factors such as patterns and rates of human population growth, local and global market behavior, governance and political frameworks, and cultural and religious beliefs and consumption choices (MA 2005).

2.3 Ecosystem Services

Ecosystem services are the "outputs" and experiences of ecosystems that benefit humans, and are generated by the structure and function of natural systems, often in combination with human activities.

Figure 2-1
Examples of ecosystem services from Puget Sound

The Millennium Ecosystem Assessment, a recent global effort to catalog and assess ecosystem status and functions, offers a useful classification scheme (Table 2-1). Their classification includes four categories (MA 2003):

- *Provisioning services* are the products obtained from ecosystems, such as food and fresh water. These services are typically measured in terms of bio-physical production, such as tons of salmon landings.
- *Regulating services* are the benefits obtained from the regulation of ecosystem processes, such as nutrient assimilation. In the case of regulating services, as opposed to provisioning services, the level of "production" is generally not relevant. Instead, the condition of the service depends more on whether the ecosystem's capability to regulate a particular service has been enhanced or diminished.
- *Cultural services* are the nonmaterial benefits people obtain from ecosystems through spiritual enrichment, cognitive development, reflection, recreation, and aesthetic experiences. Recreation, ecotourism, spiritual and religious experiences, and a sense of place are all examples of this type of service. Perceptions of cultural services are more likely to differ among individuals and communities than, say, perceptions of the importance of food production, and so they are harder to measure.

- *Supporting services* are those that are necessary for the production of all other ecosystem services. For example, humans do not consume most marine low trophic-level species like plankton, but these species support higher-level species, some of which are consumed directly. Other examples of supporting services are primary production, production of atmospheric oxygen, soil formation and retention, nutrient cycling, water cycling, and provisioning of habitat.

Puget Sound is home to commercial, recreational, and tribal ceremonial and subsistence fisheries for salmon and other species, as well as clam, oyster, crab, and other shellfish harvests. It provides regulating services as global as the carbon cycle, and as local as waste treatment through the uptake in estuaries of nutrients such as nitrogen and phosphorous. Underlying all of these are Puget Sound's basic supporting services such as primary production and the provision of habitat for salmon, orcas, and other species. A similar set of services are provided by the freshwater ecosystems that are linked to Puget Sound (Postel and Carpenter 1999).

2.4 Human Well-Being and Ecosystem Value

The values of ecosystem services can be categorized as "use values" such as direct consumption or use, or as "non-use values" (such as the value of leaving a legacy of biodiversity). These values in turn motivate actions that may produce effects that feed back to the ecosystem's structure and function. Although most values attached to ecosystem services are economic, they are not just market values but can be any service that contributes to the sustenance and satisfaction of human beings. In building an ecosystem management framework from the conceptual model for Puget Sound (Figure 2-1), it is important to consider the context of an integrated, dynamic system in which humans play the part of both drivers and beneficiaries of ecosystem services (NRC 2004).

Ecosystem services are potentially useful for policy analysis because they can be used as performance measures for different management strategies, and clearly illuminate or trade-offs between goals. It is not necessary to quantify an entire ecosystem to weigh policy choices. Rather, management strategies can consider the connection of physical changes in the ecosystem to a set of changes in ecosystem services (NRC, 2004). Translating these resulting changes into a monetary value, as is commonly done in benefit-cost analysis, is another possible way of evaluating management alternatives, although not a necessary one.

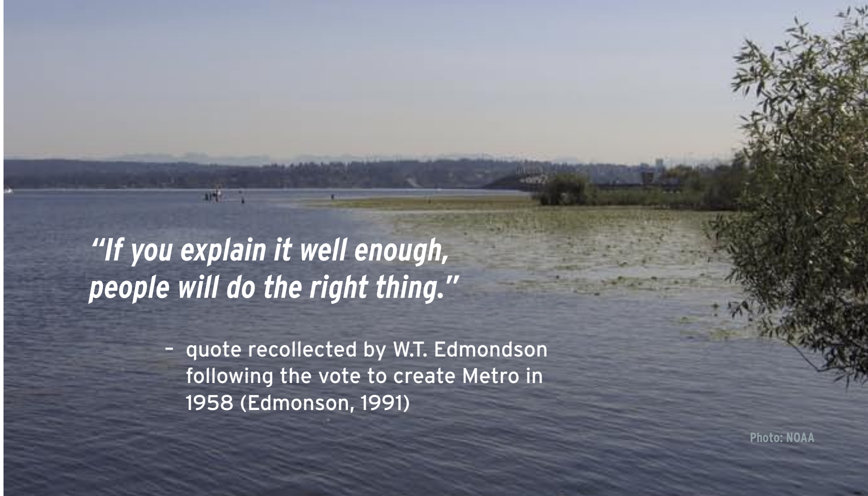
Box 2-1

The rescue of Lake Washington: melding scientific research and public action

In the 1950s, an estimated 20 million gallons per day of sewage effluent entered Lake Washington from Seattle and other communities surrounding the Lake. The discovery of the cyanobacteria *Oscillatoria rubescens* in the lake in 1955, and the implication that phosphorus from sewage effluent was acting as fertilizer for its production, led to predictions by UW Zoology professor W.T. Edmondson and other scientists that nuisance algal conditions and water-quality deterioration would worsen in the future. Although the lake was already visibly impaired, it had not yet deteriorated seriously, and the call for public action led to the creation of Metro in 1958. Between 1963 and 1968, over 100 miles of sewer trunk lines and interceptors were laid to carry sewage to treatment plants, and effluent entering the lake was reduced to zero in February, 1968. The $140 million project, considered the costliest pollution control program in the country at that time, was completely locally financed.

The transparency of Lake Washington waters responded quickly, improving from only 30 inches in 1964 to a depth of 10 feet in 1968. The elimination of the phosphorus load from effluent set off a complex chain reaction of species responses, beginning with the decline of *Oscillatoria*. The water flea (*Daphnia*) is a filter-feeding crustacean that had been suppressed by *Oscillatoria* because it clogs the filter apparatus of *Daphnia*. The decline of *Oscillatoria* led to an improvement in conditions for *Daphnia*. *Daphnia* had also been suppressed by its predator—the possum shrimp (*Neomysis mercedis*). Improvements to spawning habitat in the Cedar River led to increases in long-fin smelt (*Spirinchus thaleichthys*), a predator on *Neomysis*. The combination of these conditions allowed populations of *Daphnia* to increase and the *Daphnia* preyed on algal species, further improving the lake's transparency to depths of 17 to 20 feet after 1976. A maximum depth of nearly 25 feet was recorded in 1993.

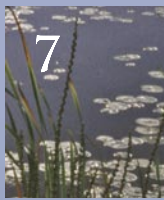
The application of scientific information to public action and the successful rescue of Lake Washington from deterioration has been the focus of followup research by natural and social scientists for decades, and is an internationally known example of how such efforts can work.



"If you explain it well enough, people will do the right thing."

– quote recollected by W.T. Edmondson following the vote to create Metro in 1958 (Edmonson, 1991)

Photo: NOAA



2.5 A Systems Approach to Managing Puget Sound

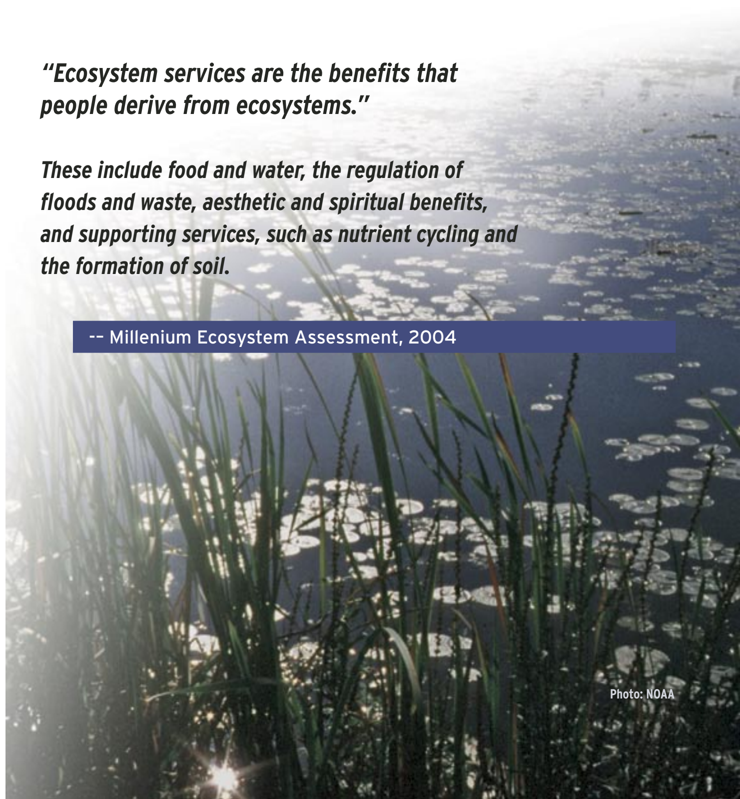
A systemwide approach can assist resource managers within the Puget Sound ecosystem to forecast changes in ecosystem services across different scenarios (MA, 2004; especially Chapter 4). The following examples are intended to illustrate how changes in ecosystem services can have repercussions for other services throughout the Sound:

- It is commonly perceived that shoreline armoring enhances property values (a cultural ecosystem service) but it can also alter beach sediment supply and result in losses of shoreline vegetation (supporting services) and declines in the species that depend on such vegetation, such as herring and other forage fish. This can result in declines in higher-level predators that depend on such forage fish, such as salmon. Salmon declines can lead to reductions in commercial and recreational fishing (a provisioning service) and whale-watching (a cultural service), since salmon are a significant portion of the diets of orcas in Puget Sound. Thus in this example, the benefits of shoreline armoring for private and public-property owners could result in losses to fishing and whale-watching economies, as well as many other biologically based services.
- Dams can produce power generation and water for cities and irrigation (provisioning services) but can also harm salmon populations and interfere with sediment transportation (a supporting service). Disrupted sediment transport from rivers can starve beaches at river mouths, reducing opportunities for beach-combing (a cultural service) or shellfish aquaculture (a provisioning service).
- Fishing and timber harvest have been major provisioning services of Puget Sound for over a century. These activities can affect the nutrients that are available in upland and terrestrial habitats—the return of large numbers of salmon created an annual source of nutrient supply for upland animals and plants, while timber harvest removes of a large quantity of organic material in a short period of time. The change to the structure and quantity of nutrient cycling in the ecosystem (a supporting service) can result in reduced tree growth and declines in large mammal, bird, and fish populations. These changes will affect the provisioning services of fishing and forestry, as well as cultural services such as eco-tourism and recreation.

As illustrated by these examples, enjoying the ecosystem services that Puget Sound is capable of providing involves a delicate balancing act. Ecosystem services are based on what humans find valuable about the natural world. Too much use of the ecosystem, or an emphasis on one type of service at the expense of another, can severely reduce the capacity of the ecosystem to support a broad range of services. For this reason, there will often be tradeoffs. The complex linkages within ecosystem processes often cause these tradeoffs to be invisible unless these connections are made fully transparent. As shown in the first example provided above, it may be difficult to trace the relationship of shoreline armoring to consequences for other services, such as the whale watching industry. The major challenge of ecosystem management is to find ways to assess these tradeoffs, identify any mutual benefits, and to allow a more sustainable integration of the human and natural systems.

An essential element of an ecosystem approach is to understand how habitat-forming processes (such as currents and tides, nutrient cycling, and sediment transport) affect habitat structure and species interactions. In addition, a strong characterization of the interactions among species, and among species and habitats, is a critical component of managing the ecosystem effectively. These linkages are necessary to identify how human behavior and management actions can work together to achieve ecosystem goals and where conflicts and tradeoffs are likely to occur.

The mechanisms by which the Puget Sound ecosystem produces goods and services are not entirely understood, and the method used to assign values to those goods and services are in their infancy. However, as described in Section 3, considerable information exists about the components of the Puget Sound ecosystem that can be used to inform early actions for achieving Puget Sound goals. An ecosystem approach must also be clearly articulated to the larger community by scientists and resource managers to secure support by the public when alternative strategies are proposed. Large-scale ecosystem recovery actions, such as the effort to improve water quality in Lake Washington (Box 2-1), have occurred largely in response to scientific input and an informed and motivated public.



Section 3
The Puget Sound Ecosystem: Changing Ecological and Human Components

ECOSYSTEM STRUCTURE & FUNCTION
geology, climate,
physical processes, habitat, species,
terrestrial/marine linkages

The natural wealth produced by the Puget Sound ecosystem has attracted and sustained human inhabitants for thousands of years. It is the structure and function of the ecosystem that keeps those goods and services coming in the form of fish, timber, clean water, and other benefits. Puget Sound retains a geological legacy from active glaciers and volcanoes that formed mountains, river valleys, marine basins, and islands. The variable upland and underwater topography of the Sound is overlaid by complex physical and chemical processes that have given rise to diverse habitat types and species. Increasingly, however, the actions of humans have also become drivers of ecosystem change.

Although the intricate and interdependent connections within Puget Sound are not entirely understood, Section 3 briefly describes the key components of the Puget Sound ecosystem, including:

- Natural physical, chemical, and biological processes that play a role in the structure and functioning of the ecosystem, including climate, marine water circulation, element cycling, and connections between freshwater or terrestrial systems and the marine system.
- How these processes form and sustain habitat structure and the distribution of habitat types.
- The effect of processes and habitat quality, quantity, and distribution on the community of species and the food webs of the Puget Sound ecosystem.
- The changing role over time of humans in the ecosystem as users of its goods and services, influences on its structure, and how our actions have resulted in large-scale ecosystem change.

Photo: Leo Shaw, The Seattle Aquarium

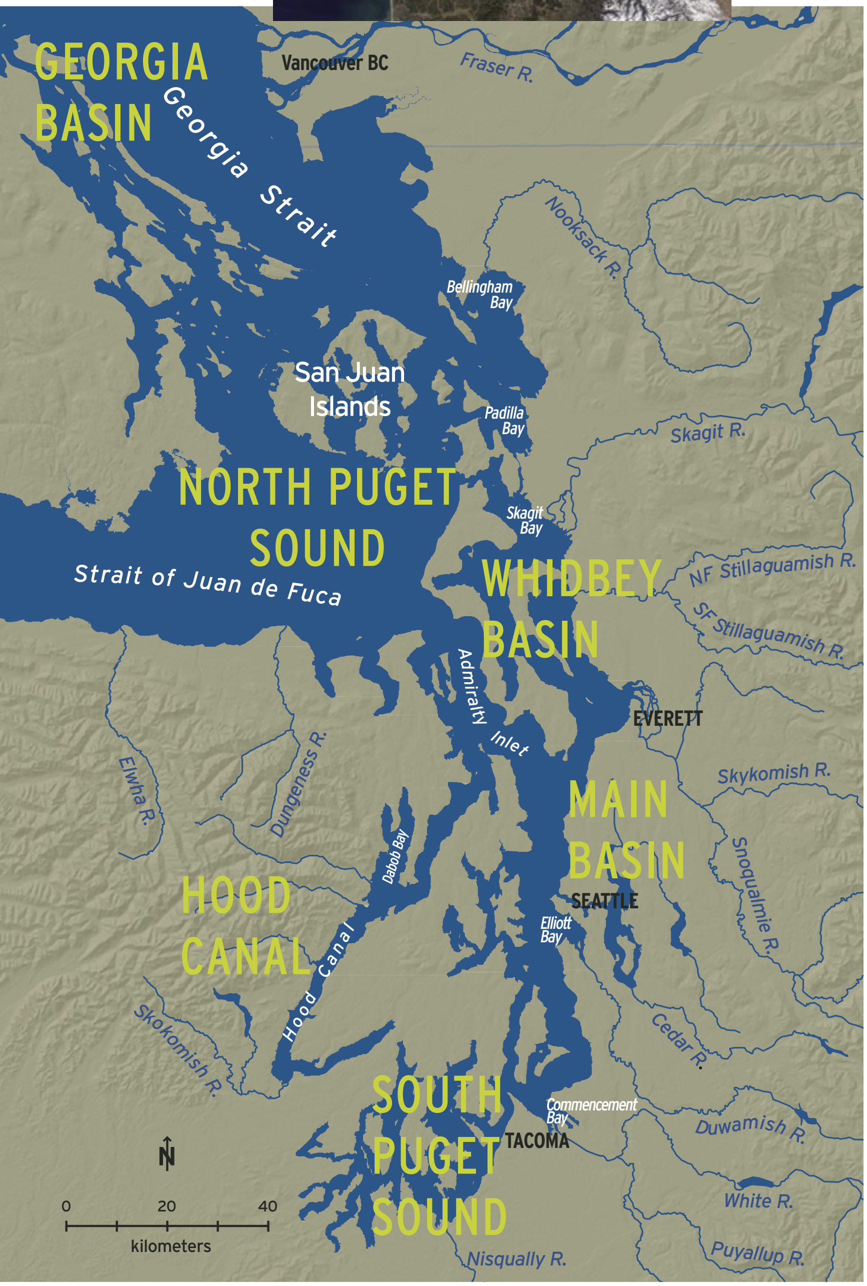


Figure 3-1
Map of the Puget Sound region and major sub-basins

3.1 Geographic Overview of the Greater Puget Sound Region

The greater Puget Sound region[1] includes the lands from the crests of the Cascade and Olympic mountains to the shores of marine waters extending from the entrance to the Strait of Juan de Fuca east, including the San Juan Islands, and south to Olympia (Figure 3-1). The marine waters comprise a large, complex estuary that covers an area of approximately 2,330 km^2, including 4,000 km of shoreline, and is fed by thousands of streams and rivers that drain a total land area of about 35,500 km^2. On average, Puget Sound south of Admiralty Inlet has a depth of 62.5 m, but ranges to nearly 300 m at its deepest. This depth is the result of relatively recent geologic events, as 10,000 years ago, mile-thick glaciers pushed southward into the basin, carving deep fjords and depositing sediments hundreds of meters thick.

The Puget Sound region has a number of unique attributes that make the ecosystem sensitive to change and that should influence regional approaches to ecosystem protection and restoration. The Cascade and Olympic mountain ranges create highly variable local climate patterns and a diversity of habitat types and species, from alpine meadows to the depths of Puget Sound. Projected changes in global climate are rapidly translated into local climate impacts in the Puget Sound region because of its variable topography. Flows in both glacier-fed rivers and streams in lowland areas are very sensitive to changes in climate, such as precipitation and air temperature. The striking variability in regional topography continues underwater in the form of steep bathymetry, resulting in very deep water close to shore. The steeply sloping sides of Puget Sound allow for only a narrow fringe of vegetated habitat near the shoreline where light can penetrate the water. Puget Sound is unique among developed estuaries in the contiguous United States due to its fjord-like shape and form, and the underwater structure of the basin that restricts the circulation of water, sediment, many living organisms, and contaminants.

Based primarily upon geomorphology, extent of fresh-water influence, and oceanographic conditions, Puget Sound can be subdivided into five major basins: North Puget Sound, the Main Basin, Whidbey Basin, South Puget Sound, and Hood Canal.[2] Each of these basins differs in features such as temperature regimes, water residence and circulation, biological conditions, depth profiles and contours, processes, species, and habitats (Table 3-1).

[1] Puget Sound as used throughout this document refers to the lands and water in the greater Puget Sound region including the Strait of Juan de Fuca and the San Juan Islands. This definition has been selected to correspond with the Governor's Puget Sound Initiative and a variety of other management efforts to develop management recommendations throughout a broadly inclusive area.

[2] Several methods have been used to delineate sub-basins within Puget Sound for different programs, e.g., ambient monitoring and salmon recovery. This division into 5 sub-basins is used here to highlight some of the key bathymetric, circulation, and habitat differences in portions of the Puget Sound ecosystem.

Table 3-1

Key physical attributes of major Puget Sound basins

GEOGRAPHIC BASIN	MAJOR ATTRIBUTES
NORTHERN PUGET SOUND Geographic features include the Strait of Juan de Fuca (SJF), Admiralty Inlet, the San Juan Islands, and the southern part of the Georgia Strait. Freshwater input from the Fraser River in Canada has a major effect on processes of this basin.	• The western SJF is strongly influenced by ocean currents while the eastern end is influenced by intense tidal action in numerous small passages. • Surface flow in the SJF is primarily seaward, with the exception of easterly flow along the shoreline between Port Angeles and Dungeness Spit, and landward flow in many embayments. • Freshwater runoff makes up about 7% of the volume in the SJF and is primarily derived from the Fraser River. • This region contains approximately 93% of the rocky-reef habitat in Puget Sound (approx 200 km^2). • About 45% of the shoreline of this region consists of kelp habitat (compared to 11% in other Puget Sound basins). • Approximately 71% of the area draining into Northern Puget Sound is forested, 6% is urbanized, and 15% is used for agriculture; this basin is the most heavily used for agriculture of the basins in Puget Sound. • WDNR estimates that 21% of the shoreline in this basin has been modified by human activities.
WHIDBEY BASIN: Includes the marine waters east of Whidbey Island, and the delta areas for the two largest river systems in Puget Sound—the Skagit and Snohomish.	• 30% of the freshwater flow into Whidbey Basin is derived from the Skagit River. • Salinity in the northern portion of the basin is generally lower than the Main Basin due to the major rivers. • Predominant forms of intertidal vegetation include green algae, eelgrass, and salt marsh. Eelgrass beds are most abundant in Padilla Bay and Skagit Bay and the northern portion of Port Susan. • Approximately 85% of the drainage area of this basin is forested, 3% is urbanized, and 4% is in agricultural production. • Approximately 60% of the nutrient contribution from freshwater sources entering Puget Sound (as inorganic nitrogen) enters through the Whidbey Basin by way of the major river systems. The Pacific Ocean is the largest contributor of nutrients to Puget Sound through bottom layer inflow. • WDNR estimates that 36% of the shoreline in this basin has been modified by human activities.
MAIN BASIN: Geographic features include Sinclair and Dyes inlet and Colvos and Dalco passages on the west side, and Elliott and Commencement bays.	• The Main Basin is generally stratified in the summer due to river discharge and solar heating, and mixed in the winter due to cooling and wind. • Oceanic waters from the SJF flow over the northern sill at Admiralty Inlet. • In the southern section, currents generally flow northward along Colvos Passage on the west side of Vashon Island, and southward on the east side through the East Passage. • The sill at Tacoma Narrows causes an upwelling process that reduces the seawater/freshwater stratification. • Major circulation patterns in this basin are greatly influenced by decadal climate regimes. • The Main Basin has a relatively small amount of intertidal vegetation, predominated by green algae and eelgrass. • Areas bordering the Main Basin include the major urban and industrial areas of Puget Sound, and 80% of the waste discharged from point sources into Puget Sound comes from this region. • Approximately 70% of this drainage is forested, 23% is urbanized, and 4% is used for agriculture. • WDNR estimates that 52% of the shoreline in this area has been modified by human activities.
SOUTHERN PUGET SOUND: Includes all waterways south of the Tacoma Narrows. This basin is characterized by numerous islands and shallow inlets with extensive shoreline areas. The largest river entering this basin is the Nisqually.	• Currents in this basin are strongly influenced by tides due largely to the shallowness of this area. • In general, surface waters flow north and deeper waters flow south. • Major channels in the southern basin are moderately stratified because no major river systems flow into the basin. • Temperatures in the inlets are elevated in the summer. • This basin has the least amount of intertidal vegetation; saltmarsh and green algae are the most common types. • Approximately 85% of this drainage is forested, 4% is urbanized, and 7% is in agriculture. • Important sources of waste include sewage-treatment facilities from urban centers and a paper mill in Steilacoom. Non-point sources from this basin contribute 5% of the nutrients (as inorganic nitrogen) entering Puget Sound. • WDNR estimates that 34% of the shoreline in this basin has been modified by human activities.
HOOD CANAL: Major geographic features are the Entrance, Dabob Bay, the central region, and the Great Bend. Dabob Bay and the central region are the deepest portions, while other areas are relatively shallow.	• Like many of the other basins in Puget Sound, Hood Canal is partially isolated by a sill at its entrance that limits the transport of deep marine waters. • Aside from tidal currents, currents in Hood Canal are slow. The strongest currents tend to occur near the entrance and involve a northerly flow of surface waters. • Portions of the Canal are stratified, with marked differences in temperature and dissolved oxygen between the entrance and the Great Bend. • Saltmarsh and eelgrass are the most abundant intertidal plants; eelgrass is found throughout the Canal, especially in the Great Bend and Dabob Bay. • Hood Canal is one of the least developed areas in Puget Sound with 90% of the drainage forested, 2% urbanized, and 1% in agriculture. However, the shoreline has been widely developed with seasonal and year-round residences. • WDNR estimates that 33% of the shoreline in this region has been modified by human activities.

3.2 Climate and Ocean Processes

The climate of Puget Sound is a product of the interaction between large-scale wind and weather patterns and the complex topography of the region. Seasonal changes in the movement of moisture-laden air that collides with the sudden barrier of the Olympic and Cascade mountains bring Puget Sound the record-breaking precipitation for which it is so famous. These circulation and topographic differences also lead to remarkable climate differences within Puget Sound itself, influencing the species and habitats that are found in the Sound.

3.2.1 Seasonality in Atmospheric Forcing

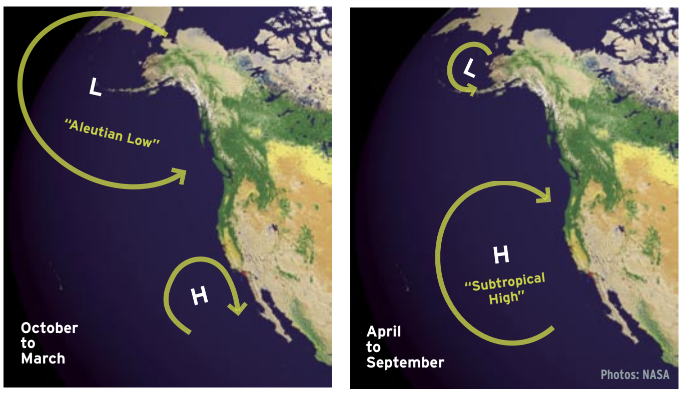


Figure 3-2
Seasonal changes in weather patterns in the Pacific Northwest (PNW) region

Beginning about mid-October, a semi-permanent low-pressure cell, commonly called the Aleutian Low, intensifies and migrates southeastward over the Aleutian Islands and Gulf of Alaska. Surface winds blow in a counterclockwise circulation around the Aleutian Low. Further south, winds blow in a clockwise circulation around a semi-permanent center of high pressure typically centered offshore of southern California. Together, these high- and low-pressure cells typically bring moist, mild, onshore flow into the Pacific Northwest from October through early spring (Figure 3-2). As the moisture-laden air encounters the Olympic or Cascade mountains, it rises and cools, and the cooling causes water vapor to condense into liquid cloud and rain drops. Because of the seasonal shifts in large-scale wind patterns, the PNW's wet season typically begins in October, peaks in midwinter, and ends in the spring; about 75% of the region's annual precipitation falls in the period October–March. During late spring, the Aleutian Low retreats to the northwest and becomes less intense, while the high-pressure cell to the south expands northward and intensifies. The result is a strong reduction, from late spring through summer, of landfalling storms for the Pacific Northwest.

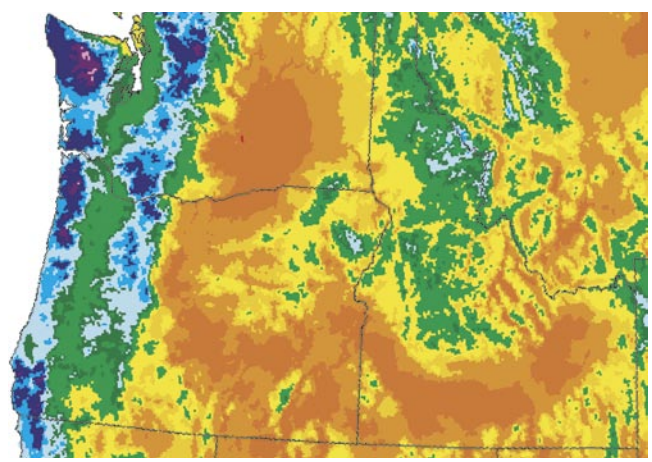
3.2.2 Precipitation Patterns and Localized Variability

The west (windward) slopes of the Cascade and Olympic mountains receive enormous quantities of rain and snow, exceeding 200 inches (5 meters) of water equivalent per year at some locations on the Olympic Peninsula (Figure 3-3). At Paradise Ranger station on Mount Rainier, the average spring sees an end-of-season snow depth of 4.1 meters (~170 inches). The Cascades are often among the snowiest places on Earth: in 1956 the snow at Paradise piled to a depth of nearly 9.1 meters (30 feet) during a year in which that location's annual snowfall was nearly 28.5 meters (94 feet); the Mount Baker Ski Area, located in the North Cascades near the U.S./Canada border, set a new world record for the highest annual snowfall ever recorded (October–September) in 1998–99 with a total of 29 meters (96 feet) (Bell et al. 2000).

Figure 3-3
Pacific Northwest average annual precipitation 1961–1990

Legend (cm)

0-15	75-100	205-255
15-25	100-125	255-360
25-40	125-150	360-510
40-50	150-205	510-1015
50-75		



Although the west side of the Cascades is generally a very wet region, it contains several areas that receive significantly less precipitation than the west-side average. Washington's Puget Lowlands, the northeast extreme of the Olympic Peninsula, and the San Juan Island archipelago are relatively dry areas that lie in "rain shadows." Rain shadows in these areas are caused by the Olympic Mountains located to the west and southwest that shield them from the direct impact of storms that follow the wet season's prevailing storm track.

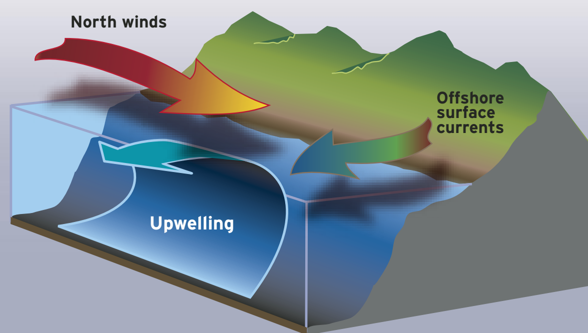
The Cascade Mountains also bear strongly on seasonal variations in the region's climate. West of the Cascades, the low-lying valleys have a maritime climate with typically abundant winter rains, infrequent snow, dry summers, and mild temperatures year-round (usually above freezing in winter, so that snow seldom remains for more than a few days). East of the Cascade crest, the region's climate is much more continental, with rainfall and cloudiness less common and sunshine and dry conditions more common year-round. On a finer scale, gaps and low-elevation passes in specific locations provide connections between the east-west climate differences, affecting habitat-forming processes and the spatial distribution of the biota of the west slopes of the Cascade mountain range.

3.2.3 The El Nino-Southern Oscillation (ENSO) and the Pacific Decadal Oscillation (PDO)

The year-to-year and decade-to-decade changes in the strength and location of the Aleutian Low have been a prominent feature of Pacific climate variation in the last century. Climate records indicate that one of the most prominent features of Pacific climate variation are expressed through annual and decadal changes in the strength and location of the Aleutian Low pressure pattern. This is of special importance for Puget Sound because an intense Aleutian Low brings relatively warm and dry winters to the region, while a weak Aleutian Low favors a cooler and wetter winter. Variability in the Aleutian Low comes from a variety of sources, but two important influences on the Aleutian Low are the large-scale variations in sea-surface temperatures known as the El Niño-Southern Oscillation (ENSO) and the Pacific Decadal Oscillation (PDO).

ENSO is a natural part of Earth's climate that spontaneously arises from interactions between tropical trade winds and ocean-surface temperatures and currents near the equator in the Pacific. Warm extremes of the ENSO cycle, commonly called El Niño, favor an especially intense Aleutian Low that is associated with the displacement of the storm track in the eastern North Pacific. As the displacement moves the track southerly towards California, the conditions favor a warm and mild Puget Sound winter. Cold extremes of the ENSO cycle, commonly called La Niña, favor the opposite. Individual ENSO events (either El Niño or La Niña) typically occur over the course of a single year, and over the past century one year in four (on average) has been an El Niño extreme, and one year in four has been a La Niña extreme.

The Pacific Decadal Oscillation plays out over a longer time-scale, with a typical lifetime of 20 to 30 years for the extremes. Warm eras of the PDO prevailed during 1925–46 and 1977–98, while cold eras prevailed during 1900–24 and 1947–76. Warm eras of the PDO are associated with a prevalence of intense Aleutian Low winters, while cold eras are associated with weak Aleutian Low winters. Because the PDO and ENSO have similar impacts on the character of the Aleutian Low, both La Niña and cool PDO periods are typically accompanied by cooler than average sea-surface temperature, shallow thermocline (temperature layer), and high productivity. Warm periods (typical of warm PDO and Niño periods) are characterized by warmer sea-surface temperatures, deeper thermocline and lower productivity. Biological changes throughout the ecosystem in the northeast Pacific Ocean are associated



Box 3-1
Coastal upwelling

An ecologically important consequence of the seasonal changes in PNW coastal winds is the relationship between wind patterns, currents, and the input of nutrient-rich waters, a phenomenon known as "coastal upwelling." The switch from northward, winter wind patterns to more frequent southward winds in the summer months drives ocean surface currents offshore which are replaced by cool, nutrient-rich waters from greater depths. Upwelling is important for marine ecosystems because it helps supply nutrients to the upper ocean where sunlight is generally abundant during the summer. Phytoplankton require a combination of sunlight and nutrients to produce food through photosynthesis, and high phytoplankton production helps fuel high productivity throughout the marine food web.

Photo: Leo Shaw, The Seattle Aquarium

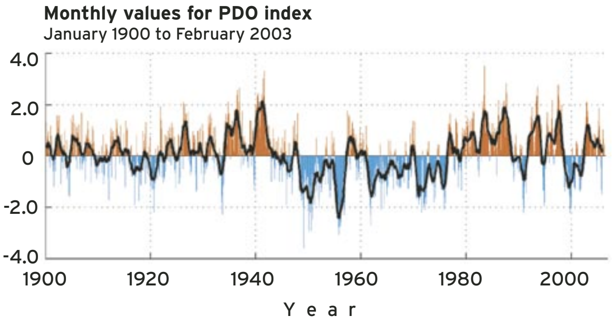


Figure 3-4
Monthly values for the PDO Index, January 1900 to February 2003. Positive (red) index values indicate a warm-phase PDO; negative (blue) index values indicate a cool-phase PDO. While short-term flips in PDO phases do occur, evaluation of 20th-century instrumental records has shown that PDO phases generally persist for 20–30 years, as indicated in this figure.

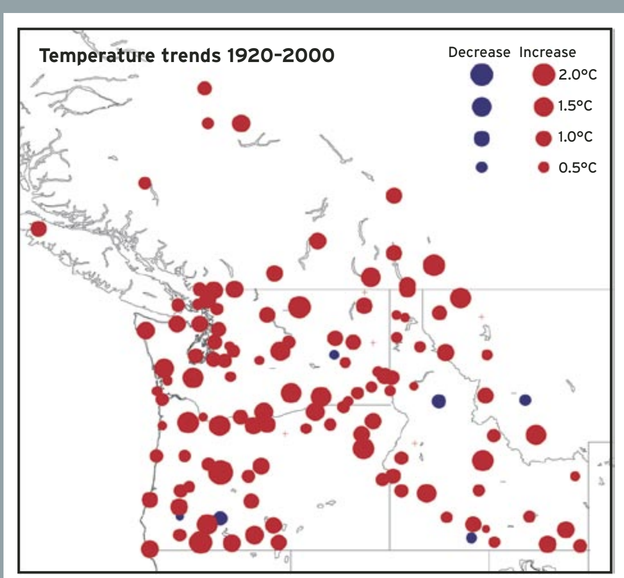
with different climate regimes—including changes in zooplankton, benthic algae, meso-crustaceans, rocky-reef fishes, and apex predators. The effects of regime shifts vary geographically—Pacific salmon from Alaska increased in abundance in response to the 1976 regime shift while populations from the Pacific Northwest declined.

Potential changes in global climate patterns are likely to have important consequences to Puget Sound ecosystem processes. Changes in precipitation, temperature, and the frequency of intense Aleutian Low systems will alter freshwater input, nutrient cycling, and stratification with ramifications throughout the food web. The Climate Impacts Group at the University of Washington has published two important reports (Snover et al. 2005; Mote et al. 2005) that document a number of potential impacts that climate change may have on the Puget Sound ecosystem (Box 3-2). More information on climate change is contained in Section 4.

Box 3-2

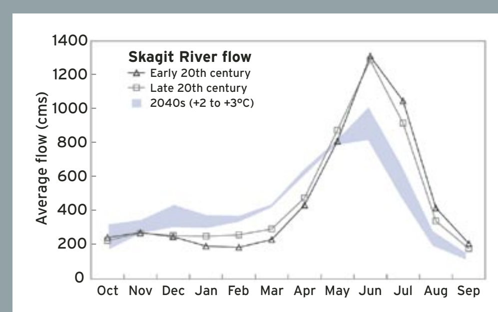
Observed and projected impacts of climate change in the Pacific Northwest

Based on extensive review of climate records, the University of Washington Climate Impacts Group (CIG) concluded that there is compelling evidence for climate change in the Puget Sound region. Evaluation of temperature records, for instance, shows that nearly every climate record in the Pacific Northwest shows evidence of substantial warming. Climate models predict an average rate of continued warming of 0.34°C per decade through 2040.



Trends in precipitation are less clear, but most monitoring stations show increases. However, as rising temperatures cause mountain snowpack to diminish, PNW rivers will see reduced summer flow, increased winter flow, and earlier peak flow. Monitoring by the CIG shows that these trends have already been observed, with more water entering the Sound earlier than historically.

The amount of water currently entering Puget Sound during June–September has declined by 18% as compared to the historical record. Additionally, most of the glaciers in the region have been retreating for 50–150 years, affecting freshwater flow rates in some systems.



Land in some regions of south Puget Sound is sinking more than 2 mm per year, while portions of north Puget Sound appear to be stable. Overall sea-level increases in south Puget Sound could be up to 1 meter in the next 100 years. Additionally, some climate models predict shifts in winds that could increase sea-level rise by an additional 20 cm in some regions of the Sound.

(Sources: http://www.cses.washington.edu/cig/pnwc/pnwc.shtml; Mote et al. 1999; Miles et al. 2000; Mote 2003; Snover et al. 2003; Steward et al. 2004; Wiley 2004 as cited in CIG, 2004)

3.3 Physical Processes within Puget Sound[3]

3.3.1 Circulation in Puget Sound

Puget Sound circulation is driven by tidal currents, the surface outflow of freshwater from Puget Sound rivers, and deep inflow of saltwater from the ocean; and is influenced by wind strength and direction. Tidal currents dominate the circulation, and typically a two-layered pattern of estuarine circulation is superimposed on the tides. Deep, dense saltwater enters Puget Sound from the Strait of Juan de Fuca through Admiralty Inlet, part of it flowing south into the Main Basin and part flowing north up into Whidbey Basin. The resulting landward-flowing water replaces the bottom water of Puget Sound and keeps it from becoming stagnant, and the out-flowing surface water flushes Puget Sound (Figure 3-5). The rate at which water flows out of Puget Sound (a net flow after tidal exchange back and forth) is dictated in part by upwelled deeper saltwater and the amount of freshwater flows entering the Sound through the major river systems. Because of shallow sills at Admiralty Inlet, the Tacoma Narrows, and the mouth of Hood Canal, some fraction of the water and its dissolved and suspended constituents do not leave the area immediately, but make additional trips. Within the main basin of Puget Sound, an exception to the typical two-layered flow pattern occurs along Vashon Island, where the outflow from the Narrows (up Colvos Passage) is a driving force.

The movement of water due to tides is about 5–10 times larger than the actual estuarine circulation observed throughout the Sound. As the tidal currents flow past points of land, the water forms eddies in the lee of the points. These tidal eddies provide a transport mechanism for offshore water to reach the shoreline, bringing nutrients and plankton to nearshore communities. Tidal currents in the main basin of Puget Sound, a region with depths of 200 m or more, typically are less than 0.25 meter per second. In contrast, tidal currents in Admiralty Inlet and in The Narrows, regions with depths of 40–80 m, can be as large as 2.2 and 3.3 m/s, respectively (NOAA, 1984).

The large tidal exchanges and distinctive bathymetry and shallow sills within Puget Sound mean that the flushing rate of waters and the sediments and dissolved constituents they carry are restricted and slowed, and the sills prevent sediment, many organisms, and contaminants from readily leaving Puget Sound. Water movement also plays an important role in shaping the location and quality of shoreline, nearshore, and deepwater habitats of Puget Sound. An understanding of general circulation conditions is essential to the assessment of element cycling throughout the ecosystem, as well as site-specific conditions for locating facilities such as sewage treatment plants. Puget Sound is also a collection of smaller estuaries with various flow patterns influenced by freshwater input and tidal mixing.

[3] Physical processes within Puget Sound such as hydrology, nutrient cycling, and sediment transport occur in terrestrial, freshwater, and marine environments. For terrestrial and freshwater environments, these are described in some detail in the Northwest Forest Plan (FEMAT, 1993) and other publications on upland habitats listed in Section 3.5. Because of the availability of these publications, the Sound Science document emphasizes the marine environment, noting the close connections between upland processes and marine conditions.

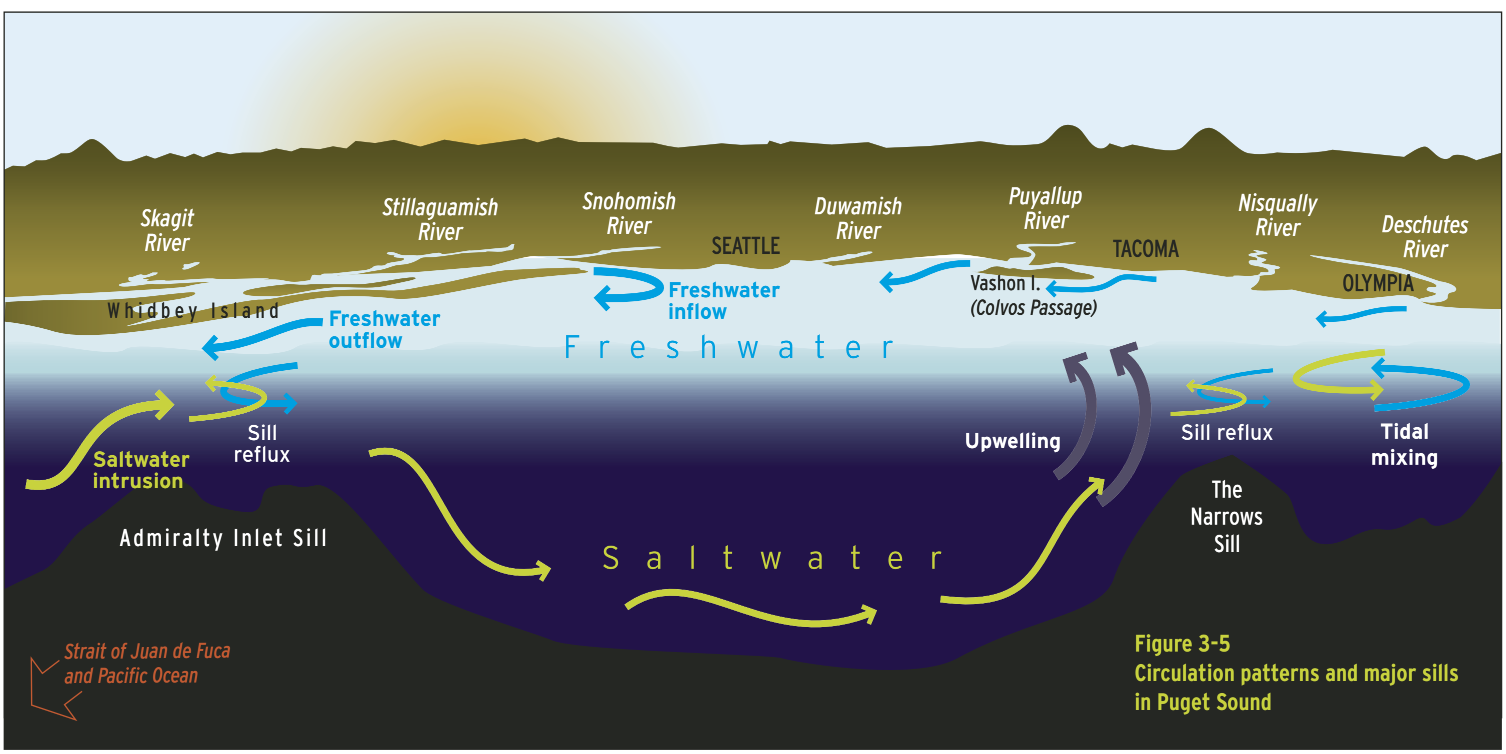


Figure 3-5
Circulation patterns and major sills in Puget Sound

3.3.2 Element Cycling and Stratification

Nutrient concentrations in the upper layers of the ocean tend to be lower than in the deeper waters due to their uptake of nutrients by phytoplankton in the euphotic (i.e., sunlight-rich) zone. Replenishment of nutrients in the upper layers can be accomplished through coastal upwelling, vertical diffusion from deeper waters, and contributions from land through rivers, streams, treatment plants, stormwater, and runoff. Certain nutrients, including nitrogen and phosphorus, are necessary for phytoplankton growth.

The process of vertical mixing between surface and underlying waters is a major driver of nutrient and phytoplankton dynamics, which in turn affect dissolved oxygen (DO) levels. Stratification refers to the horizontal layering of water masses due to density differences (Figure 3-6).

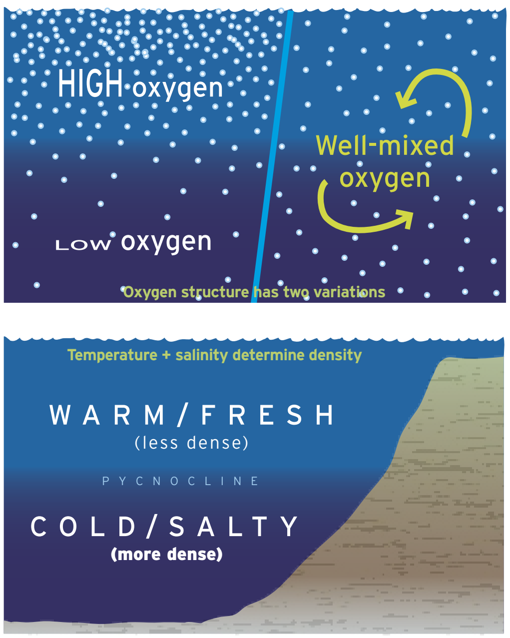


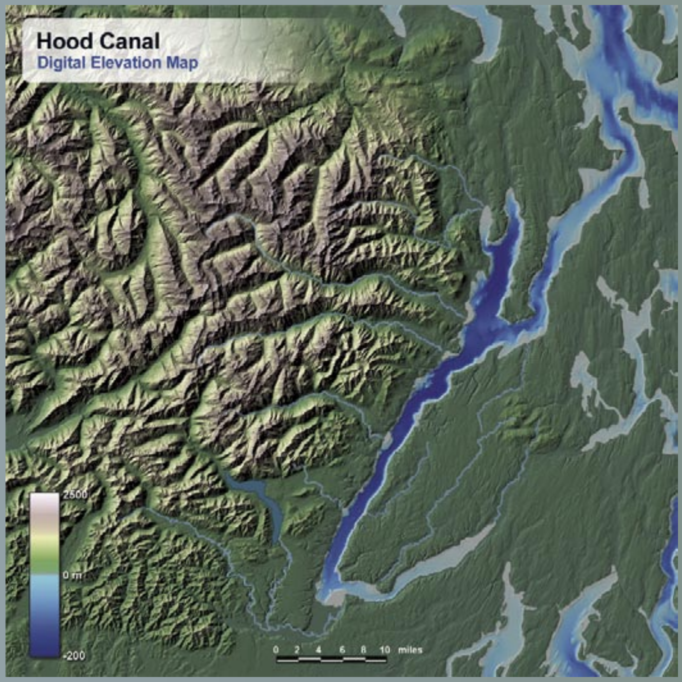
Figure 3-6
Stratification and oxygen structure in estuarine waters.

The development of stratification within the water column is significant because of the physical barrier it presents with respect to vertical water movement. For example, turbulent eddies, driven by winds and tides, cause vertical mixing of phytoplankton, dissolved oxygen, and nutrients. If, however, the water is stratified, then the ability of turbulent eddies to accomplish vertical mixing will be greatly decreased. This is particularly true at the pycnocline, which is often occurs in the top several meters of the water column. Thus stratification effectively isolates the surface water from the deep water.

When stratification is intense, two environmental conditions can result—surface waters can become depleted of nutrients (dissolved nitrogen and phosphorus), and bottom waters can become depleted of oxygen. When external supplies of nutrients are increased in a system that exhibits low circulation and stratification, the condition can result in dense algal blooms (Box 3-11 on Harmful Algal Blooms in Section 3.6) and, after the algae sink and decay, a correspondingly large deficit of dissolved oxygen in bottom waters (Box 3-3 on Hood Canal).

Low precipitation can lead to reduced river flows that can markedly affect water properties. For instance, reduction of freshwater inflow in the 2000–2001 drought reduced the density difference between surface and bottom waters in Puget Sound. Although weakened stratification allows localized vertical mixing, it can reduce the flushing pattern of Puget Sound as a whole. If the pattern of estuarine circulation (Figure 3-5) is weak, the movement of organisms and nutrients in the top layer towards the ocean will be reduced. Altering exchange rates between the Sound and the coastal ocean has implications for the dispersal of numerous small species of open-water invertebrates and fish larvae as well as water quality within the Sound. Additionally, low freshwater river flows shift the location of the saltwater-freshwater mixing zone, affecting the location of critical rearing habitat for juvenile salmon and allowing saltwater to penetrate further upstream.

Box 3-3
Dissolved oxygen and water quality in Hood Canal and south Puget Sound



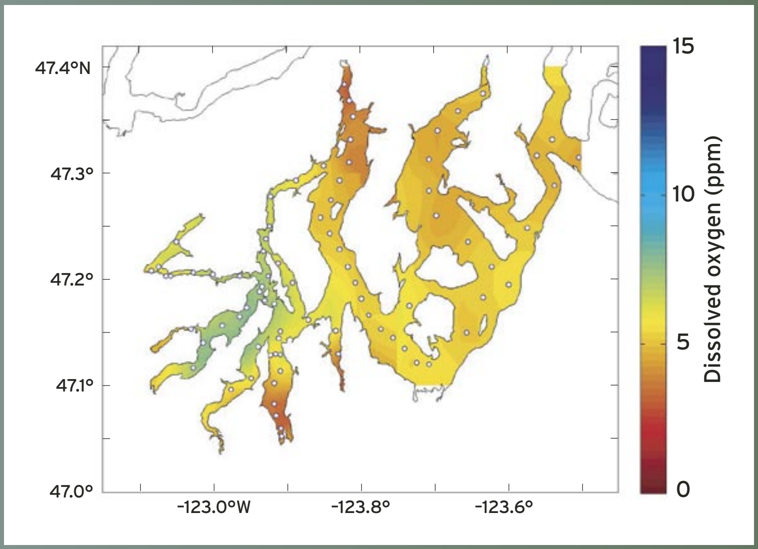
Hood Canal
Low dissolved oxygen (DO) concentration in Hood Canal is not a new phenomenon, but considerable evidence suggests that this problem has increased in severity, persistence, and spatial extent (Newton et al., 2002). The most severe low DO conditions occur in the southern end of the canal, the point furthest from water exchange with the rest of Puget Sound. Comparing oxygen data from 1930–1960s with data from 1990–2000s shows that in recent years the area of low dissolved oxygen is getting larger, spreading northwards, and that the periods of hypoxia last longer through the year.

Although records of fish kills in Hood Canal date as far back as the 1920s, repetitive fish kills during 2002, 2003, 2004, and 2006 indicate that the increasing hypoxia may be having biological consequences. In 2003 the Washington Department of Fish and Wildlife closed Hood Canal to commercial and recreational fishing for all finfish, except salmon and trout, and for octopus and squid. This was the first time in Washington State's history that a fishery was closed due to a water-quality issue such as low dissolved oxygen.

A number of physical, chemical, and biological factors are thought to contribute to the low dissolved oxygen conditions in Hood Canal. These include the circulation and flushing of the canal, which is affected by ocean and river waters; the degree of seawater stratification, which controls vertical mixing and is affected by river, ocean, and weather conditions; the productivity of algae, which is affected by sunlight; and nutrient (nitrogen) and carbon availability, which can come from both natural and human sources. Like classic fjords, Hood Canal is prone to hypoxia because deepwater exchange with Puget Sound is limited by a shallow sill at the outlet of the canal and thus circulation in Hood Canal is slow relative to other Puget Sound basins (Warner et al., 2001). Anthropogenic sources of nitrogen, such as septic-system and hatchery discharges, fertilizer use, and salmon-carcass disposal, may thus stimulate phytoplankton growth, increase microbial decomposition, and subsequently decrease dissolved oxygen levels. Although overall human population density in the Hood Canal basin is generally low, shoreline development is intensive in a number of regions of the canal and may influence oxygen conditions.

The Hood Canal Dissolved Oxygen Program and its Integrated Assessment and Modeling study (HCDOP-IAM) arose out of the need to quantify what is driving the increasing hypoxia, to address whether human activities (and which ones) are major causes, and to evaluate the efficacy of potential corrective or mitigative actions. These programs are described at www.hoodcanal.washington.edu.

South Puget Sound
Residential development in south Puget Sound has risen dramatically over the past two decades, raising concern that its waters could be adversely affected by the increased nutrient and pollutant loading that typically accompanies a growing population. The South Sound is particularly susceptible to water-quality problems because its many blind inlets and distance from incoming oceanic waters contribute to high water-residence times and slow the rate at which pollutants and nutrients are flushed into greater Puget Sound and ultimately the Pacific Ocean. At present, several South Sound embayments have already been identified as impaired under federal Clean Water Act criteria for dissolved oxygen, fecal coliform bacteria, and other variables. The Washington State Department of Ecology completed phase I of the South Puget Sound Water Quality Study in 2002 to measure existing water quality and assess the potential for future water-quality problems.



The study found that phytoplankton productivity in parts of the South Sound increased significantly when nutrients were added and that low dissolved oxygen occurred in several inlets, with Case, Carr, and Budd inlets appearing to be the most susceptible. The Phase 1 report is available at http://www.ecy.wa.gov/pubs/0203021.pdf.

3.4 Connections between Terrestrial, Freshwater, and Marine Habitats

The terrestrial and freshwater habitats in the Puget Sound region span high-elevation glaciers and alpine meadows. Mid-elevation forests of Douglas fir, western hemlock, red alder, and big-leaf maple drop to lower-elevation areas that historically supported stands of spruce, cedar, and Pacific madrone (Kruckeberg 1991). The elevation of the Cascade and Olympic peaks–exceeding 4,000 m–drops dramatically to sea level on the shores of Puget Sound in a short linear distance. Powerful rivers spill from glaciers over this steep terrain and pass through the diverse forest communities. In the process, the rivers create dynamic riparian zones, and may change channel locations several times throughout a decade as they migrate throughout their floodplain.

Streams and rivers in the watersheds of Puget Sound provide ecological corridors and transport water, wood, sediment, organic matter, and nutrients downstream where they influence freshwater and estuarine ecosystems. The delivery of these building blocks of habitat create a variety of habitat types within the river system and near the river mouth, including low-elevation forests, freshwater and saltwater marshes, and numerous shoreline and beach habitats—all utilized by Puget Sound's fish and wildlife. Circulation of water, nutrients, and sediment continues along the shoreline interface and throughout the estuary via tides and currents, gravitational forces, and freshwater inflows. Substantial quantities of nutrients are returned to the upland environment through the movement of thousands of animals, notably the returning runs of adult salmon.

3.4.1 Freshwater discharge in Puget Sound

Freshwater flows are important determinants of aquatic food web function, estuarine and nearshore habitat structure, and circulation in the marine waters of Puget Sound. Coastal areas within Puget Sound generally are characterized by high levels of rainfall and river discharge in the winter, while inland mountains are characterized by heavy snowfall in the winter and high snowmelt in late spring and early summer. This local weather pattern creates two major periods of freshwater runoff into Puget Sound, with maxima in December and June (Figure 3-7).

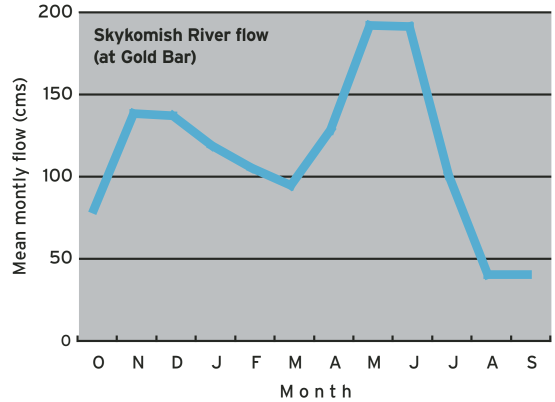


Figure 3-7
Mean monthly flow in the Skykomish River (US Geological Survey)

The major sources of fresh water from Puget Sound river systems are from the Skagit and Snohomish watersheds in the Whidbey Basin (Figure 3-8); however, the annual amount of freshwater entering Puget Sound is only 10–20% of the amount entering the Strait of Georgia, primarily through the Fraser River (NOAA Technical Memorandum NMFS-NWFSC-44).

Figure 3-8
Annual freshwater inflows from Puget Sound rivers are one of the major drivers of marine circulation patterns. Width of arrows indicates the average volume of annual fresh water flows from Puget Sound streams.

3.4.2 Shoreline Formation and Sediment-Transport Processes

Puget Sound has over 4,000 km (2,500 miles) of shorelines, ranging from rocky sea cliffs to coastal bluffs and river deltas. The exchange of water, sediment, and nutrients between the land and sea is fundamental to the formation and maintenance of an array of critical habitat types. Terrestrial-aquatic exchanges generally occur at two distinct interfaces between freshwater and saltwater environments: 1) marine shorelines, and 2) river-mouth estuaries.

3.4.2.1 Marine Shorelines

Marine shorelines in Puget Sound perform unique and critical ecosystem functions, providing the substrate for eelgrass and kelp and supporting shellfish production, foraging by marine birds, rearing and migration for juvenile salmon, and other services. These shorelines consist mainly of coastal bluffs and sea cliffs. Sea cliffs are rocky cliffs with low erosion rates, often dropping steeply into deep water, and are more prevalent in northern Puget Sound, particularly the San Juan Islands.

Most of Puget Sound's shorelines are coastal bluffs, which are composed of erodable gravel, sand, and clay deposited by glaciers over 15,000 years ago (Downing, 1983; Shipman, 2004). Along the marine shorelines of Puget Sound, the erosion of bluffs is essential to the formation of beaches, sand spits, berms, and other features. River sediment is also an important contributor to Puget Sound beaches (Figure 3-9).

Beach habitats along coastal bluffs are commonly delineated into "drift cells," consisting of zones of beach-sediment transport separated by headlands, embayments, or other landscape features. The volume of material added to beaches from bluff erosion is also closely related to wave energy, as the sediment within a drift cell is moved along the beach by waves breaking along the shoreline. Hundreds of drift cells and net drift directions have been mapped for most of the Puget Sound shoreline (Department of Ecology, 1978; http://www.ecy.wa.gov/programs/sea/SMA/atlas_home.html; Schwartz et al., 1989; Schwartz et al., 1991).

Figure 3-10
Typical drift cell on Protection Island near Discovery Bay

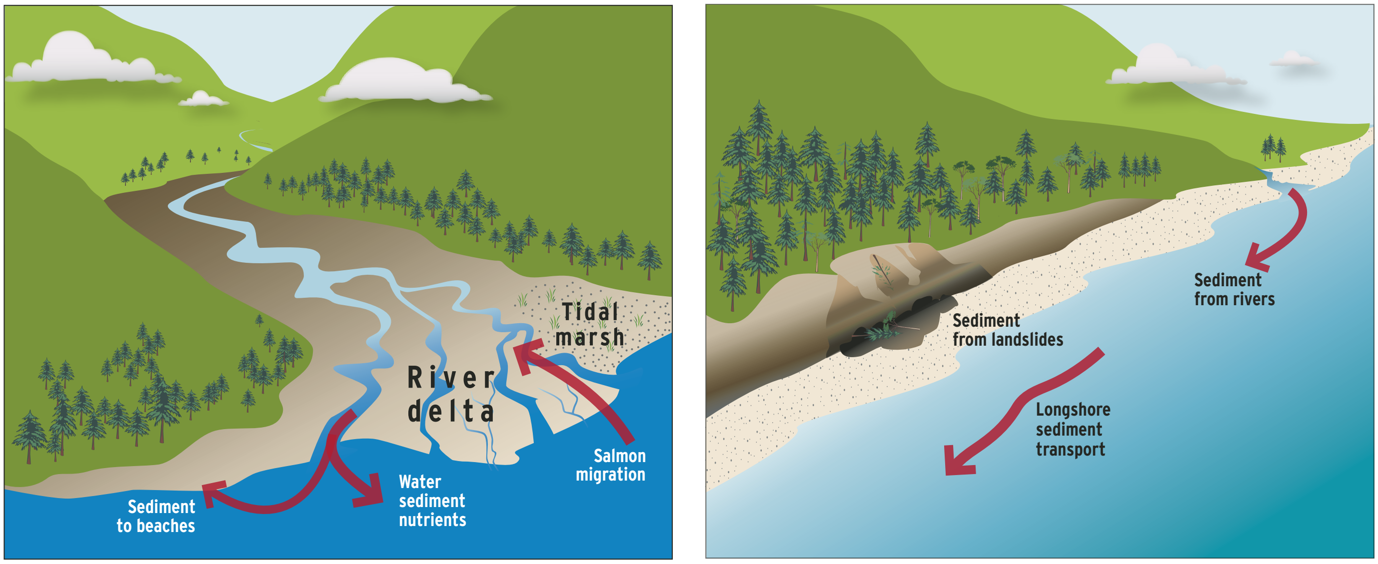


Figure 3-9
Sediment delivery and transport processes along Puget Sound beaches

Figure 3-11
Bluff failures contribute sediment to beaches
Photo: NOAA

Figure 3-12
Railroad grade along shoreline from Seattle to Everett
Photo: NOAA

Extensive development of coastal bluffs along the Sound has led to the widespread use of engineered structures designed to protect upland properties, railroads, and roads. However, shoreline armoring can also interrupt sediment-transport processes, leading to burial or starvation of beaches in specific locations, increased wave energy or scour, and changes to habitat types such as eelgrass meadows, mud flats, and saltmarsh. These modifications have increased dramatically since the 1970s with substantial deleterious effect on the ecosystem health of the Sound (Thom et al. 1994).

Species of forage fish that spawn in the upper tidal zone depend on the natural nourishment of beaches through coastal bluff erosion. Hundreds of miles of spawning habitat for surf smelt (*Hypomesus pretiosus*), for example, are known to exist along Puget Sound and many beaches have yet to be surveyed for evidence of spawning activity and timing of use. Disruption of sediment-transport processes, or even beach renourishment projects, can damage forage-fish spawning activities (Moulton, 2006).

In addition to shoreline armoring, the removal of the marine riparian forest corridor along Puget Sound has reduced the habitat available to many species of wildlife that travel regularly between the terrestrial and saltwater environment or along shoreline corridors. Raptors and many shorebirds rely on forested lands for roosting in close proximity to foraging areas in the estuary (USDA Forest Service, 1985).

3.4.2.2 River and stream Deltas

Sediments ranging from gravel to fine silts and sands are eroded from river edges and transported downstream and into estuarine and nearshore habitats. These river sediments provide important gravels for salmon spawning and rearing in the freshwater system along the way. Further downstream, sediment is deposited at the river mouth forming extensive deltas with freshwater and saltwater marsh habitats for a multitude of fish, bird, and supporting species. More far-reaching impacts of river-borne sediments also affect the Puget Sound marine environment. For example, suspended sediments carried in the Fraser River plume attenuate the light in the upper water column, thereby causing declines in primary productivity.

Sediment is not the only factor affecting habitat formation along the terrestrial-aquatic interface. While the importance of large woody debris is well known for habitat formation within rivers and streams, the delivery of wood to deltas and shorelines is also necessary to ameliorate shore erosion and enhance nearshore habitats. This is especially the case in river deltas, where the wood can break up saltmarsh and form patches of habitat for terrestrial species.

Historically, delta forests often consisted of sparse spruce, pine, and alder groves and served as important habitats for many Puget Sound species such as raptors and beavers. The beaver modified and constructed expansive freshwater wetlands, used in turn by other species including juvenile salmon. Saltwater and freshwater marshes, and sand and mud flats on deltas, were historically dominant parts of the Puget Sound landscape, providing critical habitat and transitional zones for young salmon and many other species of birds, fish, and mammals (Figure 3-13).

Physical destruction of habitat resulting from human-development activities along river deltas has been severe in several major river systems in Puget Sound. Extensive marsh and nearshore habitats were eliminated by levees that separated rivers from their floodplain and delta, eliminating thousands of acres of habitat. Changes in upstream hydrology have also changed circulatory patterns and sediment deposition in nearshore environments. For example, the concentration of flow into a few

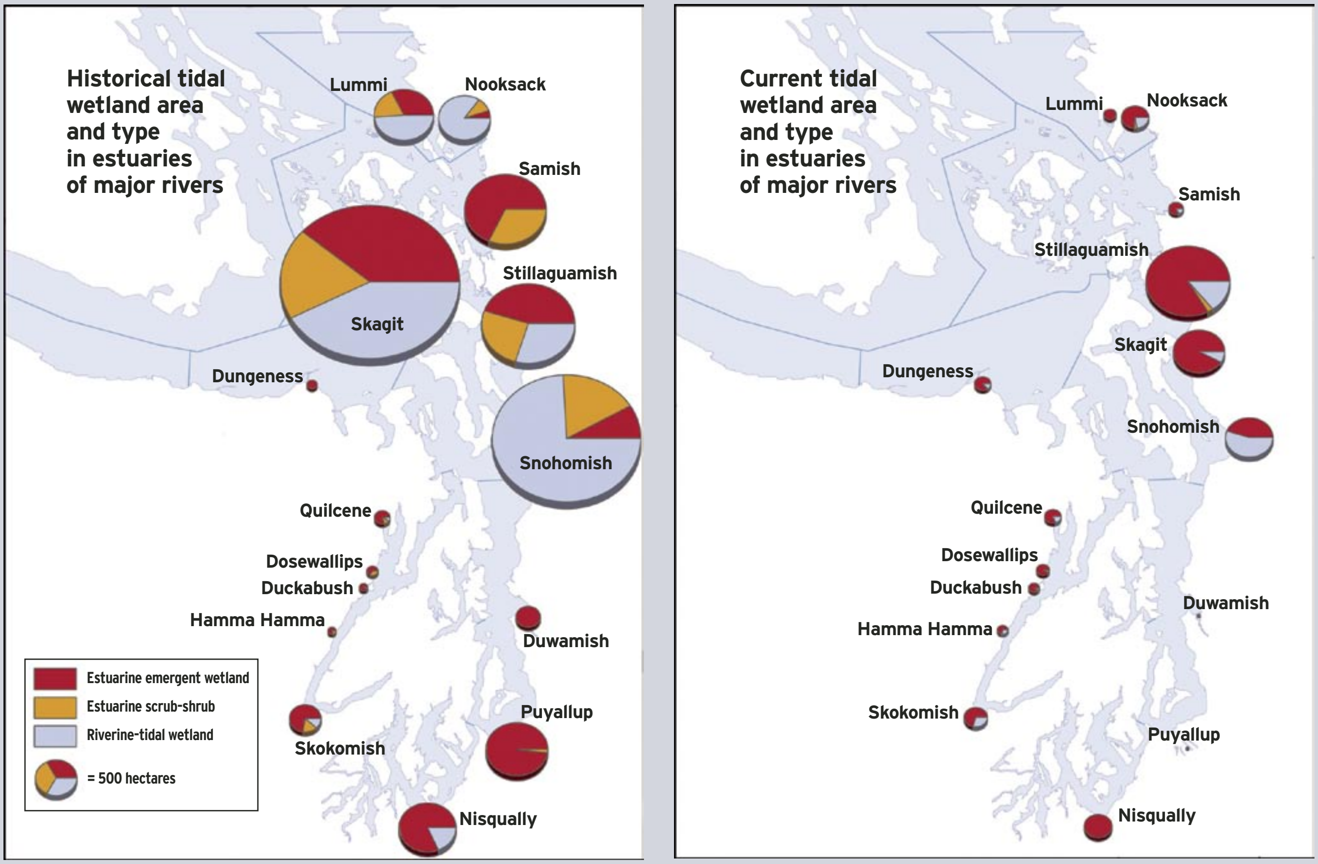


Figure 3-13
Loss of historical habitat types in Puget Sound (Collins, 2006)

channels at the mouth of the Skagit River, and increased sediment delivery immediately offshore of these channels, is fragmenting eelgrass meadows and altering sea-surface salinity and turbidity that can affect the migratory pathway for outmigrating juvenile salmon (USGS, Grossman; pers. comm. 2006). Delta habitats have also been affected by activities such as upstream culvert placement, which can create hydrological changes that accelerate upland erosion and contribute to downstream sedimentation problems. Increasing urbanization and industrialization of many river deltas, including those of the Duwamish and Puyallup, have been so altered that there virtually remains no indication of their historical extensive saltmarsh habitat (Figure 3-14). These cumulative physical changes have led to dramatic habitat loss for salmon and other species that reside in, or transit, delta habitats.

Damming of rivers has locally reduced the flow of sediments to key nearshore environments, most notably at the mouth of the Elwha River (Box 3-4). Such reductions have resulted in significant beach erosion, costly shoreline protection measures, and loss of nearshore habitats. Dams have further restricted the river habitat accessible to salmon, reducing habitat capacity for salmon and eliminating the return of marine nutrients to portions of river food webs.

Figure 3-14
Duwamish River Delta
(Photo: Port of Seattle)

3.4.3 The Two-Way Traffic of Nutrient-Transfer Processes

Nutrients originating from decomposing vegetative and animal matter are an important and necessary part of ecosystem function in Puget Sound. However, human activities have accelerated and concentrated many of these processes. Elevated levels of nutrients entering Puget Sound come from point sources such as sewage-treatment plants and paper mills, or non-point sources including

Box 3-4

Restoring ecosystem processes in the Elwha River

The Elwha River is one of ten major rivers on Washington State's Olympic Peninsula, and has 83% of its watershed located within Olympic National Park. Over 90 years ago, two dams were constructed 4.9 and 13 miles from the river mouth. Due to a lack of fish-passage technology, the dams effectively blocked 10 runs of anadromous fish from returning to over 70 miles of spawning habitat in the upper Elwha River. Prior to dam construction, these fish numbered in the hundreds of thousands, making the Elwha River one of the most productive salmon rivers in the Pacific Northwest (Wunderlich et al. 1994).

The physical and ecological effects of the Elwha River dams were large and cumulative, with complex impacts to food web composition, habitat structure, and sediment transport that are only partially understood. Major changes to habitat-forming processes in the lower river, estuary, and nearshore resulted from the blockage of large woody debris and sediment from the upper river. In addition to the obvious losses to fish populations, the upper river was depleted of marine-derived nutrients once provided by salmon carcasses. At least 22 species of birds and mammals were deprived of this important nutrient source, creating cascading effects in food webs of the riparian and upland areas.

The reservoirs created by the dams (Lakes Mills and Aldwell) have acted as sediment traps, storing 13.8 and 4.0 million cubic yards of fine-grained sediments. These reservoir traps have starved the lower river, the delta at the river mouth, and the nearshore and beach areas of these sediments, resulting in the transition of nearshore habitat from a predominantly sand into a cobble-dominated system. The interruption of normal shoreline sediment transfer processes also resulted in severe erosion to Ediz Hook, a natural sand spit to the east of the river mouth, and major revetments were installed to protect the Port Angeles harbor.

Congress enacted the Elwha River Ecosystem and Fisheries Restoration Act of 1992 (PL102-495) to address these problems. The stated goal of this legislation is, "…the full restoration of the Elwha River ecosystem and native anadromous fisheries." The Elwha River Restoration Project (ERRP) will begin with the removal of the two dams on the Elwha River, slated to begin in 2008–09. Ecological and physical responses to the restoration—such as the effects of restoring sediment delivery processes—are expected to occur at multiple spatial and temporal scales. Dam removal is hypothesized to provide significant amounts of sediment to the lower river and nearshore marine environments. Sediment delivery will likely take years and is expected to preferentially add finer sediment (sand) to the existing coarse-grained river and nearshore marine habitats. The finer substrates are likely to have major impacts on habitat quality and species responses, and these unknown responses are the focal point of ongoing research.

The Elwha River drains part of the high Olympic Mountains and delivers sediment to the Strait of Juan de Fuca. Two large dams that have been in place for over 90 years are slated for removal in 2009. Lake Mills delta is shown below.

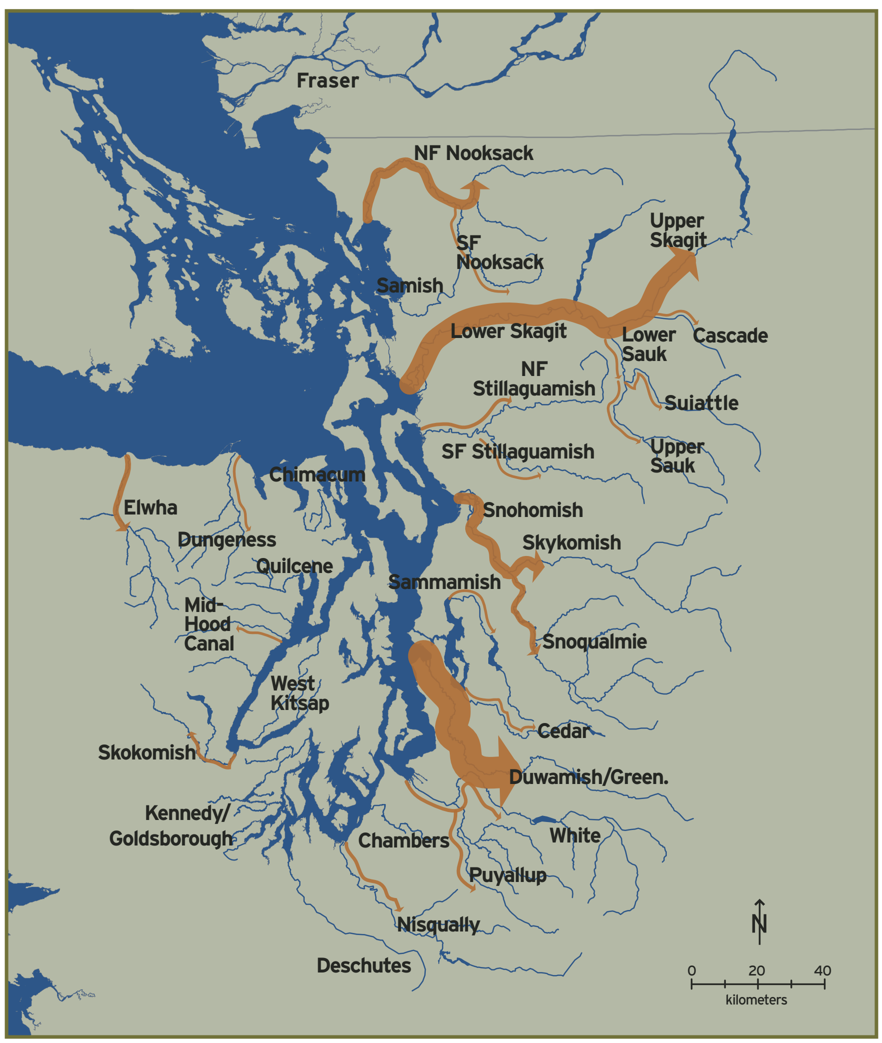
Photos: Robert Lundahl, National Park Service fertilizers, septic systems, and animal waste. When nutrient traffic loads are excessive, and combine with low circulation rates and topographic barriers, site-specific problems may arise, such as the hypoxia conditions in Hood Canal and south Puget Sound (Box 3-3).

Although freshwater runoff is a primary pathway for nutrient transport from terrestrial to marine environments, the thousands of mobile animals in Puget Sound, such as insects, birds, and fish, are also effective transfer agents of energy. Moreover, these transfers can occur in both directions and return nutrients from the ocean to freshwater and terrestrial environments. Birds feeding at sea and nesting and roosting on land can transport large quantities of nutrients (Cederholm et al. 1999). Anadromous fish such as salmon also carry nutrients back from the marine environment up into freshwater and terrestrial habitats, enriching food webs far from the sea. The life histories of these Puget Sound species reflect their biological requirements to move back and forth between terrestrial, freshwater, and marine habitats depositing substantial quantities of nutrients in the process.

Pacific salmon (*Oncorhynchus* spp.) accumulate most of their body mass in the sea, which is transported to freshwater lakes and streams around the Pacific Rim when these fishes return to spawn (Figure 3-15). As most species of this genus generally die after spawning, the nutrients and organic matter contained in their body tissues and reproductive products are deposited near the spawning grounds. Research has shown that the annual deposition of salmon-derived nutrients contributes to the productivity of freshwater and riparian communities throughout the Pacific coastal region (Figure 3-16). These nutrients can be incorporated into the stream food web through direct consumption of carcass tissue by fish or invertebrates or uptake of the dissolved chemicals released during decomposition of carcasses (Bilby et al. 2001). Salmon-derived nitrogen comprised from 10% to 20% of the nitrogen in some species of fish and invertebrates in a western Washington salmon stream (Bilby et al. 1996), and reaches much higher proportions in Alaskan systems supporting greater abundances of spawning fish (Kline et al. 1990).

Figure 3-16
Nutrients from salmon also enter terrestrial ecosystems. The importance of salmon carcasses for plants, insects, bears, and birds has been well documented (Cederholm et al. 1989; Ben-David 1998).

Figure 3-15
Salmon migrations upstream provide critical nutrients to river ecosystems. Here, width of arrows indicates relative number of Pacific chinook salmon currently migrating into main rivers. The magnitude of anadromous salmon returning to rivers is an indication of the potential for transport of marine-derived nutrients into watersheds.



3.5 Habitats of Puget Sound

"Habitat" describes the physical and biological conditions that support a species or species assemblage and refers to conditions that exist at many scales. An oyster shell provides habitat for some algae and invertebrates, whereas cubic miles of sunlit water in Puget Sound comprise the habitat for many planktonic species. Similarly, alpine meadows support lichen and drought-tolerant plants, and riparian corridors along streams are home to shrubby willows and towering conifers.

Habitats are created and sustained by long-term physical processes such as sedimentation, stream flows, and tidal currents, and can be structured by habitat-forming species such as cedar forests, eelgrass, mussels, and bull kelp that are also integral to the distribution and abundance of other species. Section 3.4 described the connections between terrestrial, freshwater, and marine habitats. Within each of these portions of the Puget Sound ecosystem, a complex set of physical processes determine the habitat that is present and the groups of species that are thus able to thrive.

A number of thorough habitat classifications and typologies have been developed for marine and terrestrial environments in the Puget Sound region and are described in Table 3-3. Freshwater and terrestrial habitats have also been described in considerable detail in major species' recovery plans, including the Puget Sound Salmon Recovery Plan (Shared Strategy, 2005) and the Federal Forest Plan (FEMAT, 1993) and are not presented here in depth. At the regional ecosystem level, a guide for prioritizing habitat conservation efforts has been organized by The Nature Conservancy (Floberg et al. 2004) to assess biological diversity and the availability of related habitat in the Puget Sound/Willamette Valley/ Georgia Basin region.

3.5.1 Freshwater and Terrestrial Habitats

Freshwater and terrestrial habitats of Puget Sound (Box 3-5) are built around the soils formed by glacial deposits and coniferous lowland forests. Changes in soil, gradient, and related variations in precipitation have given rise to diverse plant and animal communities on land. Before European settlement, lowland forests were dominated by western red cedar, western hemlock, and Douglas fir, with mixed stands of Douglas fir, Garry oak, and Pacific dogwood in drier areas. Today forest plant and animal groups coexist in a mosaic with agricultural and urban lands. Considerable attention has been placed on the need to create or preserve habitat of adequate quality, quantity, and connectivity for species migration and colonization throughout the Pacific Northwest region (Georgia Basin-Puget Sound Ecosystem Indicators, 2002).

3.5.2 Marine and Estuarine Habitats

The shallow nearshore areas of Puget Sound contain the vegetated habitats where light can penetrate the water, allowing numerous species to thrive. These habitats support eelgrass, seaweeds, and most marine fish and invertebrate populations at some time during their life cycle. As in other estuaries, the interface between terrestrial or freshwater environments and the marine environment is an important transition; actions in the headwaters affect habitats throughout the marine regions of Puget Sound. Additionally, numerous species continually move back and forth between terrestrial and marine environments. Bald eagles, marbled murrelets, and many other bird species utilize marine areas for forage while roosting and nesting on land. Adult bull trout repeatedly transit between freshwater and marine areas; their seaward migration is limited, thus placing great reliance for this species on the Puget Sound nearshore. Several species of salmon migrate and rear in these environments at different life stages. When the narrow fringe of habitat along the Puget Sound shoreline is degraded or destroyed, the support system for numerous plants and animals is disproportionately removed.

In marine systems, the **pelagic zone** is the part of the open sea or ocean comprising the water column, as opposed to the **benthos** or bottom. The couplings of pelagic and benthic systems are dynamic processes essential to ecosystem function. Just as gradient, soil, and precipitation contribute to terrestrial and freshwater ecosystems, physical characteristics such as depth, substrate, exposure, salinity, and gradient largely define the plants and animals that can utilize any given area in the marine and estuarine environment.

- ❑ **Depth** and its correlates **(temperature and light)** influence the areas that can support primary productivity. In Puget Sound pelagic areas, the euphotic, or lighted, zone extends to about 20m in the relatively clear regions of the northern Puget Sound, and to 10m in the more turbid waters of the South Sound. In shallow nearshore regions, both the water and the substrate can support primary producers. Epibenthic diatoms are found on muddy bottoms; both micro- and macroalgae, such as *Fucus* sp. or *Nereocystis*, grow on cobble or rocky substrates.

- ❑ **Substrate** is another primary contributor to habitat type and is strongly affected by wave and current **exposure**. Exposed areas do not generally accumulate fine sediments, and thus tend to have clean and mobile sand, or are rocky, either with bedrock or large cobble and boulders. More protected areas accumulate finer sediments, and the most protected areas collect very fine sediment and organic matter, making them muddy or silty.

Box 3-5

Freshwater and terrestrial habitats

Habitat conditions are the prime determinants of the abundance of wildlife—for both the quantity of species and the number of individuals. Like estuarine, nearshore, and open-water habitats, the diverse mosaic of terrestrial and freshwater habitats in Puget Sound directly determines the ability of species to thrive, whether feeding, resting, or breeding.

Late successional stands of forest are characterized by decay in living trees, downed woody material, snags, and multiple canopy layers. These mixed conditions support a greater diversity of wildlife habitats than plant communities that have been recently disturbed by fire, flood, or cutting. (USDA, 1985) Several terrestrial species utilize unique habitats such as tree cavities, snags, and downed logs during some portions of their life cycle.

Large areas of Puget Sound lowlands once contained prairie, oak woodland, and pine forest types, but those remaining are largely relics due to the conversion of land to urban and agricultural uses, invasive species, fire suppression, and other disturbances.

The remaining forests in the region provide important habitat for reptiles, amphibians, and snails; roost sites for bats; perching and nesting sites for birds; and forage, shelter, and travel corridors for deer and other mammals.

Complexity is also essential for freshwater and riparian habitats used by aquatic, amphibian, riparian, terrestrial, and avian species. Many species are totally dependent on freshwater streams, riparian areas, or wetlands and ponds, including salmon, beavers, salamanders, and frogs. The diverse vegetation layers, groundcover, and downed logs in the riparian zone produce forage material and insects for hundreds of wildlife species, areas for wildlife to breed and rear their young, cover for resting and migration, and thermal shelter from the extremes of summer and winter temperatures. Within freshwater streams, the "roughness" provided by large trees and boulders in the stream channel creates pockets of gravel, plunge pools, riffles, overhanging vegetation, and other features necessary for salmon and char to migrate, rest, spawn, and rear. Numerous studies have documented the impact that upland habitat modification can have on downstream, nearshore, and estuarine habitats and the slow rate of recovery once these terrestrial habitats have been modified.


Photo: George Pess, NOAA


Photo: NOAA

Table 3-2

Example habitats in Puget Sound and some of their more commonly associated species

Tide flat
Photo: NOAA

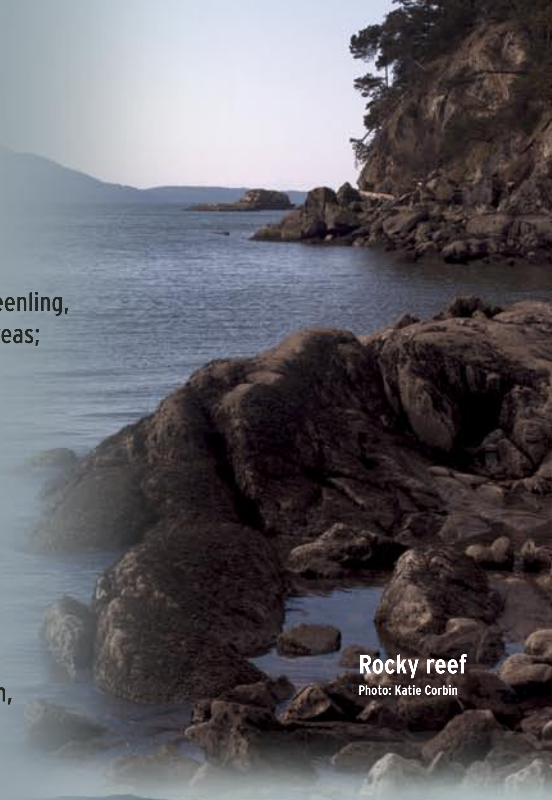
Subtidal
Photo: Leo Shaw, The Seattle Aquarium

Eelgrass
Photo: Peter Dowty, WA DNR

Pelagic
Photo: NOAA

Habitat	Description
Rocky reefs	Rocky reefs are characterized by strong currents and tidal action and the presence of kelps and other large seaweeds. Many organisms in these habitats cling tightly to the rocks or hide in crevices. These areas support benthic suspension feeders and multiple species of fish, including several species of rockfish (*Sebastes* spp.). Adult rockfish tend to associate with rocky substrates (bedrock, boulders) to which they appear to have high site fidelity. Within Puget Sound, 95% of the rocky reef habitat is located in the north Puget Sound basin.
Kelp beds	Kelp beds moderate currents in relatively open-water areas such as the Strait of Juan de Fuca and provide refuge for mobile organisms and small fishes, which in turn support migrating salmon and marine mammals as well as forage for marine bird species. Urchins and abalone are among the species found in association with kelp communities, especially in northern Puget Sound regions; both species have declined sharply due to removals by humans for food.
Mixed sediment intertidal beaches	Mixed-sediment intertidal beaches are widespread in Puget Sound and are the most visited type of beach habitat by human users for both consumptive and non-consumptive uses. These beaches are affected to a large extent by sediment-transfer processes along Puget Sound. The array of hardshell and softshell clam species of Puget Sound can be found in these beaches along with the spawning habitat of surf smelt and sand lance. Mixed-sediment beaches also serve as habitat for barnacle and mussel beds, the inner edges of marine algal turfs, and are nursery corridors for out-migrating juvenile salmon.
Saltmarsh	Rooted saltmarsh grasses such as *Salicornia* or pickleweed, are often associated with the sediment deposits at river deltas. Marsh plants are essential to the development of nearshore food webs, including those important to migratory birds. These vegetated estuarine habitats are also used extensively by crabs, shrimp, and juvenile fishes. However, it should be noted that areas infested by *Spartina* are not usable by most native species.
Tide flats	Tide flats, such as river deltas and protected coves, are characterized by weak circulation, gradual slopes, and sandy or muddy substrate. They provide habitat for organisms in the detritus-based food webs that support most of the biomass in Puget Sound. Numerous species of burrowing invertebrates and fish utilize these areas during some portion of their life cycle. Higher zones may have large populations of burrowing mud shrimp, clams, introduced oysters, and a variety of snails and crabs. Microalgae (diatoms and other species) often cover the surface of such mudflats and can be highly productive. Tide flats are also important forage areas for marine birds at low tide and, along with intertidal rocky reefs, provide important haul-out and pupping areas for harbor seals.
Subtidal soft sediments	Subtidal soft sediments, ranging from coarse sands to fine silts and clay, are the predominant subtidal substratum in Puget Sound. While a diverse array of large invertebrates—including snails, seastars, and sea cucumbers—live on the sediment surface, a rich variety of burrowing and tube-dwelling microscopic organisms dwell within the sediments—including marine worms, bivalves and snails, crustaceans, seastars, sea urchins, sea cucumbers, and an assortment of other taxa. Communities of these sediment-dwelling organisms vary according to sediment type, water depth, and geographic location throughout Puget Sound. They provide a rich food source for an abundance of bottom-feeding organisms, and serve as indicators of environmental quality.
Eelgrass beds	Eelgrass beds serve as a refuge for mobile organisms such as crab and small fishes, and forage areas for marine birds, salmon ,and marine mammals. Eelgrass beds are essential spawning habitat for herring, which support numerous other species in the Puget Sound food web. Eelgrass beds occur along 37% of Puget Sound, primarily in the north, and are uncommon in the south Sound.
Open water/ pelagic	Open waters of Puget Sound are characterized by variable light, current, and temperature conditions. Open water/pelagic habitats support plankton communities including the dispersing larvae of many species whose adults occupy other habitats. These in turn support open-water fishes.

Energy inputs	Invertebrates	Vertebrates
Macroalgae, sessile microalgae, detritus	Anemones, urchins, sea stars, chitons, sponges, gammarid amphipods, mussels	Shorebirds and gunnels; sculpins and pricklebacks in shallows; lingcod, greenling, and rockfishes in deeper and reef areas; sea lions and harbor seals
Bull kelp, detritus	Chiton, limpets, abalone, harpacticoid copepods, gammarid amphipods, some crabs, sponges and bryozoans	Yellowtail rockfish, lingcod, Pacific sand lance, herring, Puget Sound rockfish, sea lions
Micro- and macroalgae, detritus	Bivalves, copepods, amphipods, shrimp	Rock sole, juvenile salmonids, sculpin, echinoderms, cabezon, shorebirds, merganser, other ducks
Emergent and woody wetland vegetation, detritus	Copepods, amphipods, isopods, cumaceans, crabs, bivalves, snails, terrestrial insects	Sculpins, gunnels, juvenile salmonids, juvenile flatfishes, great blue heron dowitchers, yellowlegs, other shorebirds, pintail, mallard, other ducks
Micro- and macroalgae diatoms, detritus, eelgrass	Burrowing bivales, burrowing polychaete worms, sand dollars, burrowing crustaceans	Shorebirds, flatfishes, other shallow-water demersal fishes
Detritus, benthic diatoms	Bivalves, polychaetes and other worms, crabs, shrimp, copepods, amphipods, isopods, sea cucumber, sea pens, hydrocorals in deeper areas	Sculpin, flatfish, juvenile sand lance and herring in shallow tide flats, sand lance, shorebirds, gulls
Eelgrass, detritus, epiphytic algae	Gammarid amphipods, flatworms, snails, isopods, amphipods, copepods, bivalves	Pacific herring, juvenile salmon, juvenile flatfish, crabs, Brandt geese, American coot, other ducks
Phytoplankton	Calanoid copepods, gammarid amphipods, other crustacean larvae, adult crustaceans, larvaceans, jellyfish	Pacific herring, sand lance, salmonid juveniles and adults, fish larvae, orca, Dall porpoise, auklets, grebes, murres



Rocky reef
Photo: Katie Corbin

Kelp bed
Photo: Leo Shaw, The Seattle Aquarium

Intertidal beach
Photo: Leo Shaw, The Seattle Aquarium

Saltmarsh
Photo: Randy Johnson, WDFW

Most of the bottom of Puget Sound is comprised of soft sediments, ranging from coarse sands to fine silts and clay. Communities of sediment-dwelling organisms vary according to sediment type, water depth, and geographic location throughout Puget Sound. For example, shallow areas are often dominated by eelgrass, while deeper areas are dominated by sea pens (*Ptilosarcus gurneyi*) and the rich community of predators they support. Deeper sand or mud may contain geoduck clams and other burrowing organisms. Very deep basins contain unusual heart urchins, sea cucumbers, bivalves, and a variety of bottom-dwelling fishes.

Rocky shores are composed of bedrock or a mixture of boulder and cobble substrates and tend to occur in areas where sediments do not accumulate. Cobble and mixed-substrate sites have communities of diverse bivalves, gastropods, sea stars, brittle stars, and many other invertebrates. Rocky substrates are more stable than sediment-dominated habitats, and the biological communities that develop on rocky shores reflect this. Often, so-called 'ecosystem engineers' such as kelps and mussels are species that themselves influence the physical conditions of local habitats so that they are more hospitable to other species. For example, *Fucus* (or rockweed) communities on rocky substrates support a rich array of small grazers and their predators. In lower intertidal and shallow subtidal areas, *Fucus* is replaced by several species of kelp and red algae that support a different and even richer community of grazers and predators.

❑ **Salinity** and the **gradient** from freshwater to brackish and marine waters affect habitat types and the species that can be supported. Deltas and small estuaries within Puget Sound tend to be characterized by soft sediments as well as gradual salinity change. Rooted vegetation, including marsh grasses such as invasive *Spartina* and native species such as *Salicornia* or pickleweed, tend to be more common in deltas than in other areas of Puget Sound.

Table 3-3

Habitat classification information in Puget Sound

Marine and Estuarine Habitats

- Dethier, M.N. 1990. A marine and estuarine habitat classification system for Washington State. Natural Heritage Program, WA DNR, Olympia, WA. 60 pp.
- Ritter et al. 1996. Puget Sound intertidal habitat inventory 1996: Vegetation and shoreline characteristics classification methods http://www2.wadnr.gov/nearshore/textfiles/pdf/skagit96.pdf
- Collins and Sheikh 2005. Historical reconstruction, classification and change analysis of Puget Sound tidal marshes. http://riverhistory.ess.washington.edu/project_reports/finalrpt_rev_aug12_2005.pdf
- 1996 PSAT report/workshop Puget Sound Intertidal Habitat Inventory 1996: Vegetation and Shoreline Characteristics Classification Methods (same as Ritter et al. 1996?)

Rivers and Streams

- Beechie, T.J., M. Liermann, E.M. Beamer, and R. Henderson. 2005. A classification of habitat types in a large river and their use by juvenile salmonids. Trans. Am. Fish. Soc. 134:717–729.
- Montgomery, D.R., and J.M. Buffington. 1997. Channel-reach morphology in mountain drainage basins. Geol. Soc. Am. Bull. 109(5):596–611.
- Bisson, P.A., J.L. Nielsen, R.A. Palmason, and L.E. Grove. 1982. A system of naming habitat types in small streams, with examples of habitat utilization by salmonids during low streamflow, p. 62–73. In Armantrout, Neil B. (ed.), Acquisition and utilization of aquatic habitat inventory information, Proceedings, Oct. 28–30, 1981. Western Div. Am. Fish. Soc., Portland, OR.
- Bisson, P.A., K. Sullivan, and J.L. Nielsen. 1988. Channel hydraulics, habitat use, and body form of juvenile coho salmon, steelhead, and cutthroat trout in streams. Trans. Am. Fish. Soc. 117: 262–273
- Naiman, R.J., D.G. Lonzarich, T.J. Beechie, and S.C. Ralph. 1992. General principles of classification and the assessment of conservation potential in rivers. In Boon, P.J., P. Calow, and G.E. Petts (eds.), River conservation and management, p. 93–124. John Wiley & Sons, New York.
- Rosgen, D.L. 1994. A classification of natural rivers. Catena 22:169–199

Forests/Terrestrial

- Forest Ecosystem Management and Assessment Team. 1993. Forest ecosystem management: An ecological, economic and social assessment. USDA Forest Service.
- Franklin, J.F., and C.T. Dyrness. 1973. Natural vegetation of Oregon and Washington. USDA Forest Service, Pacific Northwest Region, Gen. Tech. Rep. PNW-8.
- Kruckeberg, A.R. 1991. The natural history of Puget Sound country. Univ. Wash. Press, Seattle, WA.
- Chappell, C.B. 2006. Upland plant associations of the Puget Trough ecoregion. Natural Heritage Rep. 2006-01. Natural Heritage Program, WA DNR, Olympia, WA
- USDA Forest Service, Pacific Northwest Region. 1985. Management of wildlife and fish habitats in forests of western Oregon and Washington. Publ. R6-F&WL-192-1985. Portland, OR

Regional Ecosystem

- Floberg, J., M. Goering, G. Wilhere, C. Macdonald, C. Chappell, C. Rumsey, Z. Ferdana, A. Holt, P. Skidmore, T. Horsman. 2004 Willamette Valley-Puget Trough-Georgia Basin Ecoregional Assessment. The Nature Conservancy. Arlington, VA

In the greater Puget Sound these physical characteristics generally occur in a transition from north to south, as the influence of the ocean is moderated. Areas to the north and in the Strait of Juan de Fuca are more exposed and consequently tend to be rockier, less turbid, and more saline. The South Sound tends to be more protected, somewhat shallower, with more sandy and muddy bottoms. Circulation is weaker here, and thus the area is slightly less saline than the more exposed region.

3.6 Puget Sound Species and Their Interactions

One of the most striking features of the Puget Sound ecosystem is the diverse and abundant flora and fauna it supports. Although a complete census of many taxonomic groups (or 'taxa') has not been accomplished, Puget Sound hosts more than 100 species of seabirds, 200 species of fish, 15 marine mammal species, hundreds of plant species, and thousands of invertebrate species (Armstrong et al. 1976; Thom et al. 1976; Canning and Shipman 1995). The array of species found in Puget Sound reflects its high productivity, the wide diversity of habitats present, and its unique geographic location at the interface of "northern" and "southern" ranges for many species. These species do not exist in isolation, but rather interact with each other in a variety of ways: they eat and are eaten by each other; they serve as vectors of disease or toxins; they are parasitic; and they compete with each other for food, habitat, and other resources.

3.6.1 Who Eats Who in Puget Sound Food Webs?

There is no single food web in the Puget Sound ecosystem. Instead there are many marine food webs that reside in the soft-bottomed nearshore, in rocky-bottomed areas, in habitats dominated by eelgrass or kelp, and in pelagic areas as well. Similarly, there are terrestrial and freshwater aquatic food webs that occur in alpine habitats, mid-elevation and lowland forests, and rivers, lakes, and streams. The food webs in each of these areas are not discrete and independent, but rather are highly interconnected by organic matter sources, physical proximity, exchange of water, and organisms that change habitats during the course of their life cycles.

Food webs also change both in time and space due to variation in stratification, prey availability, organic-matter source availability and quality, and other local and regional conditions. In addition, some species occupy multiple places or play multiple roles in the food web depending on their life stage, size, habitats they occupy, and time of year. Juvenile crab zoea, for example, live in the water column and are planktivorous, while adult crabs are bottom scavengers and predators.


Juvenile Dungeness crab zoea

Photo: David Misitano, NOAA

Information on terrestrial and freshwater food webs may be found via the resources listed in Table 3-2, and the discussion of food web interactions presented here is thus confined to providing an overview of the Puget Sound marine food web. Although considerable information is lacking on species interactions among Puget Sound organisms, the best understood elements are the interactions that occur in the food webs, particularly those of the nearshore environments (Simenstad et al. 1979). A variety of approaches has been used to investigate food webs, such as measurements and calculations to analyze the energy flow among species, observations of species eating one another or competing for food or space, or manipulation experiments aimed at identifying network relationships and interactions.

A diagram of a food web is essentially a map of the feeding interactions among species, and the complexity of food webs in Puget Sound makes them very difficult to depict. Additionally food-web diagrams vary depending on their purpose—just as a map of a bus route will look quite different than one that describes topography. One type of food-web map depicts the flow of energy among species. Another type of food-web map tries to depict the strength of interactions among species. Some maps may be very detailed for specific taxonomic groups (e.g., salmon, orcas) but very loosely described for others (e.g., deep-water bivalves, etc.).

3.6.1.1 Energy Inputs

During the past 50 years, energy-transfer processes in Puget Sound have gone through major transformations. Tideflats, a key venue for the exchange of energy in the food web through transfer of nutrients and sunlight, have been modified dramatically. Additionally the tremendous increase in human population around the Sound has increased the input of nutrients in the form of sewage and other wastes, with corresponding changes to the organisms that utilize them throughout the food web. These changes point to the need to look at Puget Sound with a wider ecosystem perspective, beginning with attention to the species that form the basis of the food web. Energy inputs to the Puget Sound food web originate from marine primary producers, detritus, and from terrestrial or freshwater systems.

- *Primary producers:* Primary producers are plants that employ sunlight to convert organic and inorganic nutrients into living tissue. The major classes of producer organisms in Puget Sound are phytoplankton, sediment-associated microalgae, and rooted or attached algae and vascular plants in the Sound, freshwater, and on land. Each type of producer plays a different role in Puget Sound, and its level of importance in food webs

Photo: Leo Shaw, The Seattle Aquarium

TOP-LEVEL PREDATORS

Birds, fishes, and mammals with a diet consisting almost entirely of fish or other vertebrates, e.g.,

- Rhinoceros auklet, pigeon guillemot, common and red-throated loon, horned grebe, bald eagle, and marbled murrelet
- Adult Chinook salmon, spiny dogfish, cabezon, six gill shark, and some rockfish species
- Humans, harbor porpoise, orca, and California sea lion

Photo: NOAA

Photo: Joni Packard, NOAA

Photo: Leo Shaw, The Seattle Aquarium

MID-LEVEL CONSUMERS

These eat the suspension-feeders, filter-feeders, grazers, and detrivores that serve as a link between the primary producers and detrial pathways and the remainder of the food web, e.g.,

- Planktivores such as juvenile fish, herring, anchovy
- Some benthic invertebrates e.g., starfish, snails, crabs
- Some bird species such as plover, killdeer, sandpiper

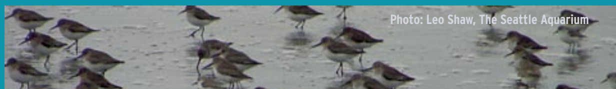


Photo: Leo Shaw, The Seattle Aquarium

Photo: Desmond Maynard, NOAA)

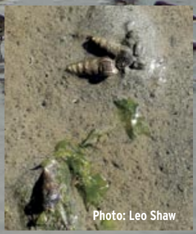


Photo: Leo Shaw

Photo: NERR, NOAA

HERBIVORES AND DETRITIVORES

Zooplankton and benthic invertebrates, e.g.,

- Geoduck, butterclams, oysters
- Dungeness crab
- Grazers such as sea urchins
- Detritivores such as sea cucumbers, some crabs, copepods, amphipods, other benthic invertebrates

Photo: Peninsula Clarion (AK)

Photo: Leo Shaw, The Seattle Aquarium

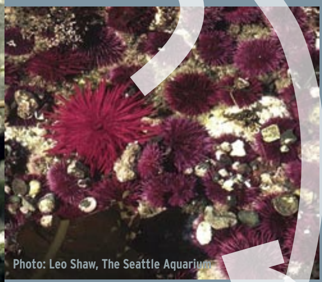


Photo: Leo Shaw, The Seattle Aquarium

FRESHWATER & TERRESTRIAL INPUTS

Non-marine plants and animals that are utilized in the marine system:

- Aquatic insects and other freshwater invertebrates
- **Detritus from freshwater or terrestrial sources**

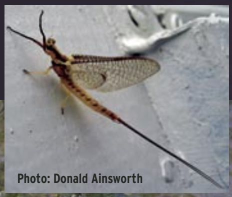


Photo: Donald Ainsworth

Photo: NOAA

DETRITUS

Plant and animal matter and associated invading bacteria

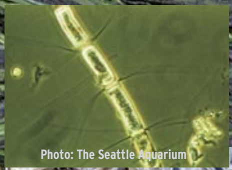


Photo: The Seattle Aquarium

PRIMARY PRODUCERS

Plants that employ sunlight to convert organic and inorganic nutrients into living tissue:

- Phytoplankton, e.g., diatoms, dinoflagellates
- Rooted or attached algae, e.g., bull kelp, rockweed
- Vascular plants, e.g., eelgrass, saltmarsh grass

Photo: Leo Shaw, The Seattle Aquarium

Box 3-6
A simplified view of the various pathways by which energy flows from primary producers up through the ecosystem to humans and other top-level consumers in the Sound. It is important to note that the pathways of the food web also act as routes for the transfer or accumulation of toxins.

Photo: Leo Shaw, The Seattle Aquarium

varies among the nearshore and offshore marine habitats and in different terrestrial environments.

Phytoplankton production in Puget Sound occurs in both nearshore and offshore marine waters. Pelagic phytoplankton in Puget Sound consist are mainly large-sized phytoplankton of two major groups: diatoms and dinoflagellates, with diatoms accounting for most of the biomass. These single-celled plants are eaten directly by zooplankton and some benthic filter-feeders (e.g., oysters). Phytoplankton abundance and distribution are highly heterogeneous or "patchy," both spatially and temporally, and are linked to the degree of stratification, light availability, turbidity, and nutrient availability in particular areas. This variability in phytoplankton density and distribution in turn affects the distribution and abundance of the various phytoplankton consumers (e.g., benthic filter-feeders, zooplankton) as well as their predators. Some single-celled algae or diatoms adhere to benthic substrates or are motile within sediments and are eaten directly by grazing invertebrates and fish.

Factors such as substrate, light penetration, and salinity largely determine the species composition of attached or rooted plants in a particular area. In addition to microscopic plants are larger taxa, including macro-algae such as bull kelp that are found in the less- turbid marine waters of Admiralty Inlet, the Strait of Juan de Fuca, and the San Juan Islands; and rockweeds (*Fucus* spp.) that are abundant on rocky shores throughout the region where they support a rich array of small grazers and their predators. Familiar vascular plants are eelgrass (Box 3.6.2: *Zostera marina*) and the salt-tolerant marsh grasses found in estuarine environments. With the exception of Brant geese that eat eelgrass, the majority of these macrophytes are not eaten directly by grazers but contribute to the food web through detrital pathways. Several introduced and invasive species, most notably the saltmarsh cordgrasses *Spartina alterniflora*, *S. anglica,* and the eelgrass *Zostera japonica*, remain in Puget Sound. However, efforts to eradicate or control the spread of some of these species have been successful at some site-specific locations (PSAT, 2005).

- *Detritus:* When estuarine and marine macrophytes die or senesce (or terrestrial plant material is washed in), they are colonized by microbes—including bacteria, protists, and fungi—that break down and transform the organic matter into a form that can be used again by producers. This non-living organic material with its associated microbial community is termed detritus. Detritus in the marine environment also encompasses molts from crustaceans and other animals, fecal pellets, and other animal-related sources. Detrital material is eaten by an extremely wide variety of consumers, including gammarid amphipods, ostracods, crabs, sea cucumbers, insect larvae, copepods, and cumaceans. This consumer pathway is a very important trophic pathway in the nearshore areas and deep benthic habitats of Puget Sound.

- *Terrestrial and freshwater inputs:* The marine food web in Puget Sound is not isolated, but relies on nutrients and energy from terrestrial and freshwater sources as well as marine sources (see Sections 3.3–3.4). Organic material from terrestrial and freshwater environments washes into Puget Sound and is consumed directly by marine organisms. Anadromous species may directly consume freshwater or terrestrial organisms in

Box 3-7

Detritus: The end and the beginning

At the base of the food web in terrestrial, freshwater, and marine environments is the mass of dead organic matter known as detritus. Billions of pounds of decaying plant and animal tissue continually drift to the floor of the Puget Sound basin. In the forests, these decomposing leaves, cones, trees, and tissue are broken down by fungi that release the nutrients into the soil for primary producers (plants) and consumers. Similarly in marine waters, bacteria, water molds, and zooplankton pick up the decaying matter from kelp, eelgrass, other vegetation, and animal species where they can be recycled into the food web for other trophic levels.

The importance of detritus in retaining the productivity of forest ecosystems has been studied in recent decades and has led to adjustments in timber management to retain more nutrients on-site for the next generation of trees. In the marine environment, the contribution of decaying riparian and nearshore vegetation is not well understood, and the ripple effect to the food web of continued loss of eelgrass beds and other vegetation along marine shorelines is unknown.

Photo: NOAA

Photo: Leo Shaw, The Seattle Aquarium

Box 3-8
Eelgrass natural history and distribution in Puget Sound

Photo: Jeff Gaekle, WA DNR

Photo: Peter Dowty, WA DNR

Eelgrass *(Zostera marina)* is not a seaweed, but a flowering plant that lives underwater in marine environments. Eelgrass lives in shallow, subtidal zones with muddy or sandy substrate and spreads via rhizomes or seeds. The seeds are released when mature and settle within meters of the parent plant, or are dispersed when mature plants are uprooted, float to other embayments or shallow subtidal areas, and the seeds fall to the bottom. Seeds typically germinate the following spring. Eelgrass meadows build up in the spring and summer and growth slows in the fall and winter. The decomposing biomass provides detritus for many species of invertebrates, which in turn provide food for fish and marine bird species. It is estimated that Puget Sound's 20,000 hectares (50,000 acres) of eelgrass (Gaeckle et al. 2006) may produce as much as 3 to 6 billion pounds of detritus annually (Solomon 2003).

Eelgrass distribution in Puget Sound from the Washington State ShoreZone Inventory (2001), Nearshore Habitat Program, WA DNR. The ShoreZone inventory is a conservative representation of the actual extent of the resources. The data were collected from a helicopter, thus many seasonally ephemeral features were missed. The following rule of thumb was used to determine what features are included: 'Was the feature visible from the window of a helicopter traveling at 60 mph at a 300-foot altitude?'

freshwater and estuarine habitats. In addition, animals such as some marine birds, salmon, and other species that are not restricted to marine habitats serve as transfer agents of marine nutrients and energy to terrestrial or freshwater habitats.

3.6.1.2 Herbivores and detritivores

Many consumer organisms in Puget Sound are both herbivores and detritivores. Zooplankton and benthic invertebrates that are scavengers, herbivores, or detritivores are considered jointly in this section. Some of these organisms can be predatory as well. Hundreds of invertebrates and fish species have a planktonic larval stage that eats plants and occupies the nearshore and offshore pelagic waters of Puget Sound. While many species of invertebrates (e.g., copepods) complete their entire life cycles in the water column, many cnidarians, arthropods, mollusks, echinoderms, annelids, tunicates, and fish species are present in the plankton for only a portion of their life cycle. Most filter-feeding pelagic zooplankton, as well as many suspension-feeders, are dependent on phytoplankton for food. They are thus an important step in the pelagic part of the food web, transforming the organic matter derived from primary production into food for invertebrates, fish, birds, and mammals. The distribution and abundance of zooplankton are probably correlated with changes in distribution of phytoplankton (Strickland 1983), but quantitative studies of the zooplankton assemblage in the Puget Sound region are rare and quite limited in scope.

The benthic habitats of Puget Sound are home to thousands of species of herbivorous/detritivorous invertebrates. These species include those that live in the bottom (infauna) and on the surface of the bottom (epifauna) and that may be motile or sessile (Kozloff 1983). The adult stages of a number of benthic species are economically important and include native species such as pandalid shrimp (*Pandalus* spp.), Dungeness crab (*Cancer magister*), geoduck clam (*Panopea abrupta*), and butter clam (*Saxidomus giganteus*), as well as non-native species such as Japanese littleneck clam (*Tapes philippinarum*) and Pacific oyster (*Crassostrea gigas*). These benthic invertebrates also use a variety of feeding methods, including filter or suspension feeding (mussels, clams, scallops, oysters, worms, and barnacles) and grazing (sea urchins, snails, limpets, and chitons). Detritivorous invertebrates include sea cucumbers, crabs, amphipods, and isopods. These taxa are preyed on by other invertebrate, fish, mammal, and bird species as adults or as eggs and larvae when vast amounts are released during reproduction.

3.6.1.3 Mid-level consumers

A variety of animals, including invertebrates, fish, mammals, and birds, consume the suspension-feeders, filter-feeders, grazers, and detritivores that serve as a link between the primary producers and detrital pathways and the upper levels of the food web.

The juvenile and adult stages of many fishes and bird species are also important mid-level consumers. The diet of these species in Puget Sound can vary dramatically in breadth and complexity and can contain prey from many different habitat types. For example, some juvenile Chinook salmon have eaten (at any one time) terrestrial insects, aquatic insects, amphipods, copepods, polychaetes, fish larvae, and crab zoea (Brennan et al. 2004).

Planktivorous fish feed in water-column habitats associated with nearshore and open marine waters of Puget Sound. Based upon their abundance/biomass, Pacific herring, juvenile salmon, juvenile Pacific sand lance, and northern anchovy are probably the most important planktivores. Other noteworthy species in this group include several important rockfish species (black, canary, widow, and yellowtail rockfish), and some species of marine birds that forage on amphipods and euphausiids (e.g., Bonaparte's gull). A wide variety of species of copepods, crab larvae, and euphausiids or krill are usually elements of planktivore diets (Strickland 1983). Diets of planktivores can vary over relatively small spatial and temporal scales, which is consistent with the boom-and-bust dynamics of their prey (e.g., barnacle larvae, copepods, and crab larvae).

In contrast to the planktivorous fish, there are many species of birds and fish that eat mostly invertebrate food items found on or in the benthos. There are far more species in this trophic group than in any other groups. What any one species eats depends upon many factors, including varying environmental conditions, habitat (e.g., deep vs. shallow), and predator and prey morphology (e.g., bill size and shape). Shorebirds such as plovers, yellowlegs, killdeer, and many migrating sandpiper species forage in the sediments left exposed by the ebbing tide—a common scene in sand and mudflats around Puget Sound. Flatfish often eat the tips of bivalve siphons, and there are species that eat their prey off the substrate surfaces such as oystercatchers, gulls, and scoters. Some of the abundant surfperches such as shiner perch primarily also forage on organisms that occupy substrate surfaces.

3.6.1.4 Top-level predators

Fishes, birds, and mammals (including humans) serve as top-level carnivores in the Puget Sound ecosystem. With the exception of humans, these organisms have a diet that consists almost entirely of fish or other vertebrates. Food habits of some top-level predators, such as orcas, throughout the Sound have been studied. Pacific herring is widely considered to be a key species in the Puget Sound food web due to its abundance and prevalence in diets of many species and its role transferring primary-producer biomass into higher trophic levels (Box 3-9).

Fish predators at this trophic level include larger size-classes of Chinook salmon, spiny dogfish, some rockfish species, and large pelagic and rocky-reef species. Populations of most species of rockfish in Puget Sound have declined sharply, and most now are conservation targets (PSAT 2004). The depleted condition of many salmon populations is well-known in Puget Sound. Due to their extended range, the factors affecting salmon abundance extend well beyond the lands and waters of Puget Sound. Lingcod (*Ophiodon elongatus*) is another voracious predator that forages near rock outcroppings and underwater structures. It utilizes a set of 18 sharp teeth to feed on large fish, crustaceans, and mollusks. Puget Sound is also home to the third-largest predatory shark in the world, the bluntnose sixgill shark (*Hexanchus griseus*), that grows up to 15 feet in length, and can be found in the region year-round.

Common bird species in the top trophic level are piscivorous (fish-eating) birds such as rhinoceros auklet, pigeon guillemot, common and red-throated loons, horned grebes, and marbled murrelets, glaucous-winged gulls, and Caspian terns (Nysewander et al. 2001; Bower 2004; Lance and Thompson 2005; Litzow et al. 2004). In Puget Sound, these birds prey primarily on small pelagic fish (Pacific herring, Pacific sand lance, salmonids, threespine stickleback). One striking feature about the birds that prey on pelagic fish is that many of them have experienced dramatic declines in abundance. Bald eagles will scavenge from spawned-out adult salmonids but are also predators of many of the piscivorous bird species.

Marine mammals that primarily eat eat fish include harbor porpoises, Dall's porpoises, California sea lions, Steller sea lions, and harbor seals. Harbor seals, the most common pinniped in Puget Sound, eat mostly schooling fish such as herring as well as salmon, squid, pollock, hake, smelt, midshipman, and sculpin. Top-level mammalian predators include humans, orcas, seals and other marine mammals. Killer whales include both the piscivorous ecotype that eats largely adult and sub-adult salmon and the marine-mammal-eating ecotype that eats such species as harbor seals. People, of course, forage at all levels of the food web on prey ranging from algae, eggs and larvae, invertebrates of all sizes, to large food fish such as salmon and rockfish.

3.6.1.5 Food Web Linkages

Photo: Leo Shaw, The Seattle Aquarium

Photo: Leo Shaw, The Seattle Aquarium

The relationships between species and "levels" in the food web are not strictly linear (Figure 3-17), as some species eat at many levels. Additionally, changes to the abundance and distribution of a single species (top-level predator or primary producer) may indirectly affect numerous other species. For example, the presence and abundance of sea otters (a top-level predator) has been shown to have a cascading effect on the structure of the food web in kelp forests. Sea otters consume herbivorous sea urchins which consume bull kelp and other fleshy algae.

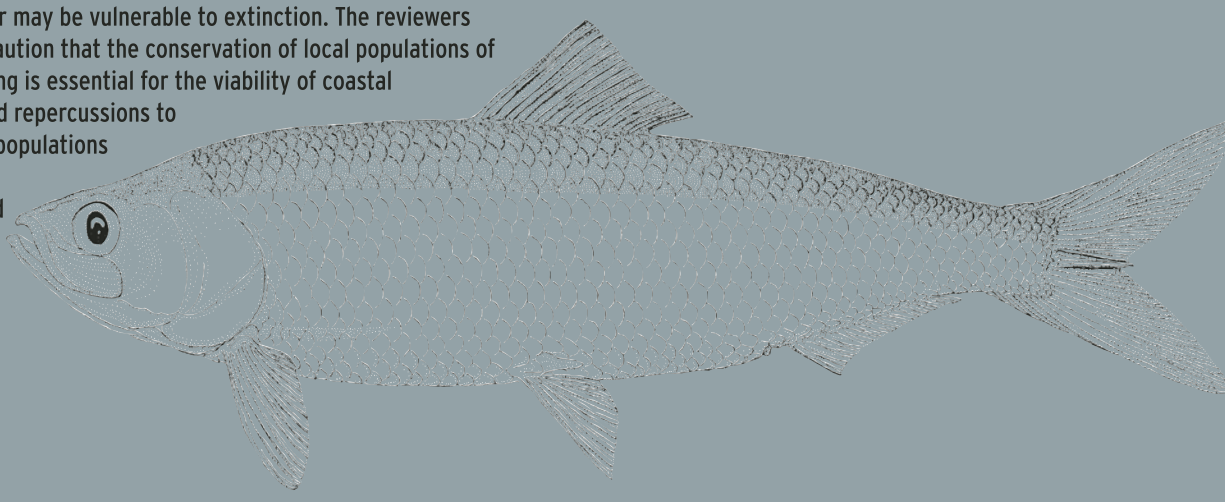
Box 3-9

Pacific herring *(Clupea pallasi)*: A vulnerable member of the food web 'hall of fame'

Pacific herring are a favorite prey of many Puget Sound species. Their eggs and larvae are eaten by walleye pollock, juvenile salmon, invertebrates, and at least 14 species of ducks and gulls. Adult herring are eaten by salmon, seals, sea lions, killer whales, dogfish, hake, halibut, sablefish, cod, and many species of marine birds including loons, grebes, cormorants, herons, mergansers, terns, and puffins. Studies of the diets of fish off the west coast of Vancouver Island indicated that herring comprise 71% of lingcod, 62% of Chinook salmon, 58% of coho salmon, 53% of Pacific halibut, 42% of Pacific cod, 32% of Pacific hake, 18% of sablefish, and 12% of dogfish diets (Environment Canada 1998).

Pacific herring usually spawn at night in the shallow subtidal zone, depositing their eggs primarily on eelgrass, but also utilizing kelp, brown and red algae, or occasionally gravel. Their use of shallow subtidal areas for spawning makes them susceptible to changes in currents and wave action resulting from shoreline development. Eighteen recognized stocks of Pacific herring spawn in Puget Sound's protected bays and inlets.

A biological status review of Pacific herring was conducted in 2001 by NOAA Fisheries (Stout et al. 2001). The reviewers determined that Puget Sound herring populations were not distinct enough from the more abundant herring populations of the Georgia Basin to merit a listing under the Endangered Species Act; however, they recognized that herring populations in north Puget Sound and Puget Sound proper may be vulnerable to extinction. The reviewers expressed caution that the conservation of local populations of Pacific herring is essential for the viability of coastal fisheries, and repercussions to marine bird populations from their demise could be severe.



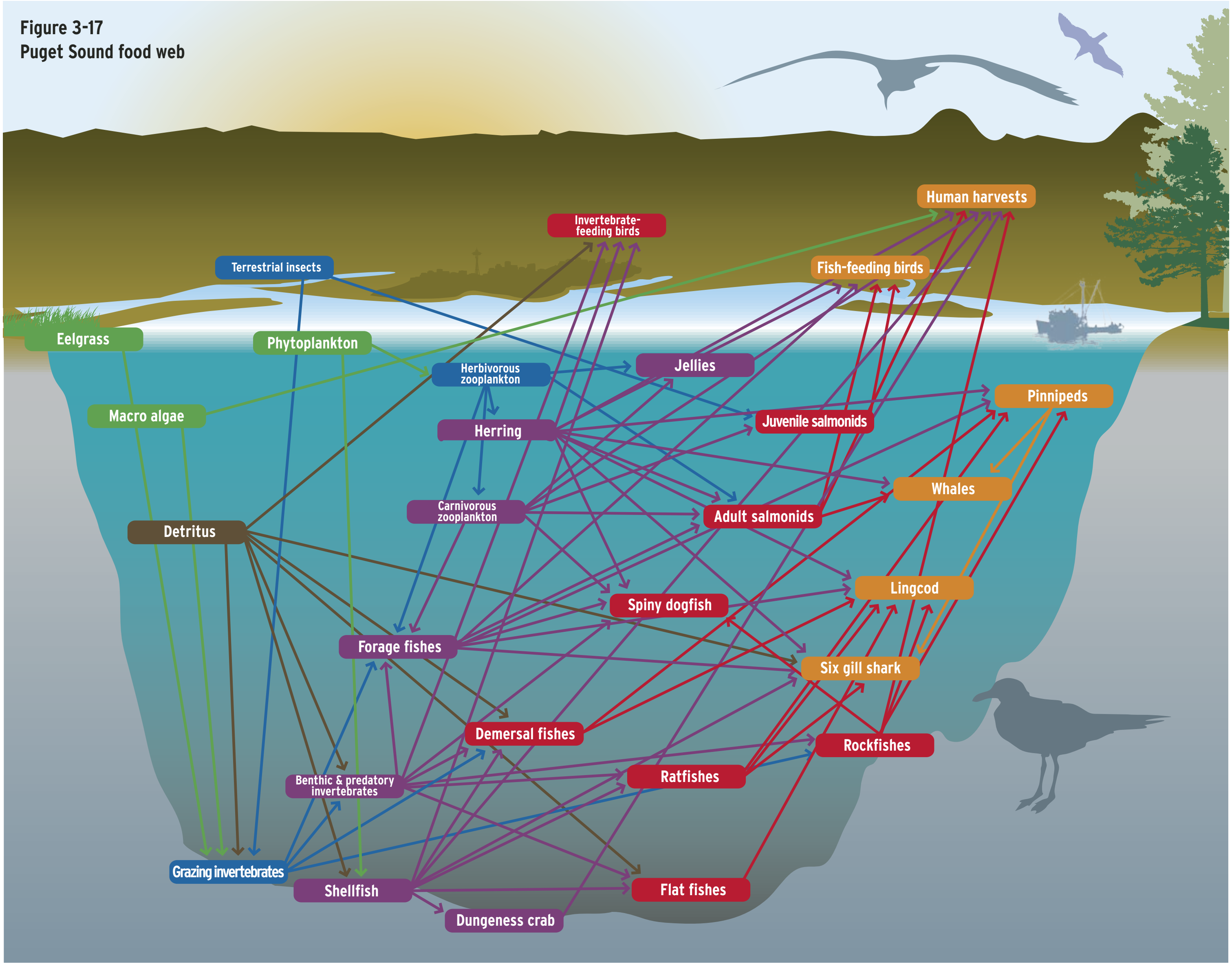


Figure 3-17
Puget Sound food web

Photo © Joel Rogers

By keeping the urchins in check, the sea otters allow kelp forests to thrive which provides three-dimensional habitat and nutritional fuel for fish species such as rock greenling that use the kelp forests for feeding, shelter and egg laying (Reisewitz et al. 2006).

At the other end of the food web, the loss of primary producers such as eelgrass may have similarly complex ramifications for other species. Eelgrass plays an important role to several commercially-important species in Puget Sound. Eelgrass is the preferred medium for Pacific herring for laying eggs and foraging. Meadows of eelgrass provide cover from predators and refuge from currents for migrating juvenile salmon in the nearshore, who will in turn depend on the availability of herring and other prey species as they mature and return. Dungeness crab mate and take refuge in eelgrass meadows. Eelgrass and the epiphytes that live on its blades are a major food source for small species of invertebrates. Eelgrass also contributes substantially to detrital food pathways. As eelgrass declines or the vegetated areas become fractured and dispersed, the entire chain of dependent organisms is affected.

3.6.1.6 Food web connections beyond the marine areas of Puget Sound

In the same way that Puget Sound physical processes are linked to ocean, freshwater, and terrestrial environments (Sections 3.3–3.4), the Puget Sound food webs described above do not exist in isolation and are connected by organisms that reside or migrate outside of Puget Sound marine waters. Changes to the abundance and relationships of species within Puget Sound may be affected by changes in the open ocean or terrestrial landscape.

For example, many waterbird species, including loons, grebes, scoters, murres, and murrelets, move to the protected waters of Puget Sound for the winter and feed on Puget Sound species, thus are transient members of the food web. Recent studies in Puget Sound and surrounding waters have shown 50–95% declines in populations of many marine bird species during the past 20 years (Nysewander et al. 2001, Bower 2004). The species that have shown the most alarming declines (80–95%) are diving birds such as common and red-throated loons; western, red-necked and horned grebes; and marbled murrelets, all of which specialize on schooling pelagic fish (Nysewander et al. 2001, Bower 2004). Marked declines have also been observed in summer breeding populations of fish-eating seabirds. Moderate but still serious declines (50–60%) have also been observed in a variety of birds that are less dependent on pelagic forage fish because they can also subsist on benthic or demersal fishes (e.g., cormorants and guillemots) and subtidal or intertidal invertebrates (e.g., gulls and scoters). Declines in these waterbirds may reflect declines in species that are harder to count, such as small benthic or pelagic fishes. Forage fish species may be affected by changes in habitat and physical processes both within and outside of Puget Sound, with ramifications to food webs across broad areas.

The movements of transient and migratory species also connect Puget Sound with the rest of the North Pacific. Some marine mammals such as sea lions and orcas spend just a portion of the year in the waters of Puget Sound, migrating to other areas at other times of the year. Salmon are an outstanding example of complex food-web linkages as they rear in freshwater and estuarine environments, migrate to marine waters and the open ocean, and return to transfer nutrients to terrestrial species such as eagles and bears. Additionally, salmon can simultaneously occupy multiple places in the food web depending on their life stage, size, habitats, and time of year.

3.6.2 Competition

In addition to the transfer of energy up a food chain, other species interactions can be important to the functioning of the freshwater, estuarine, and marine communities that comprise the Puget Sound ecosystem. Competition within and among species can influence food-web dynamics and species distribution and abundance.

Photo: Leo Shaw, The Seattle Aquarium

Photo: Leo Shaw, The Seattle Aquarium

For example, on the rocky habitats of Puget Sound, the survival of species can depend on their ability to adapt to the vagaries of wind and waves, to compete for space, and to outgrow their predators. Starfish (*Pisaster ochraceus*) prey on mussels (*Mytilus* spp.) in this rocky, intertidal zone, yet these species can be found living in close proximity for decades. Where starfish are dense and have been present for a long time, there are no large mussels and local species diversity is low. However, if the mussels can survive for a few years at the high edge of the intertidal zone, or by accident or ineptness on the part of their predators, they become too large for the starfish to eat, reproduce disproportionately, and develop complex, multi-dimensional colonies that serve as habitat for other, smaller species. The ability of the mussels to use the limited space available on rocky shorelines also enables them to outcompete other species, such as barnacles, that vie for the same habitat areas. Eventually, because of physical disturbances and occasional predation by starfish, patches of different-aged mussel beds develop across a rocky shore, giving rise to a mosaic of habitat and species diversity. This phenomenon is not unlike the process of forest succession, whereby seedlings that survive to a certain threshold become too large for grazing predators, eventually producing canopies that serve as habitat for other species.

The intentional and accidental introduction of alien species to Puget Sound through ship ballast, aquaculture, and plant propagation has had serious effects on species competition in terrestrial and marine environments (Box 3-10). In many instances, these invaders can out-compete native species but do not fulfill the same functions within the Puget Sound food web as the native plants and animals they displace.

3.6.3 Other Species Interactions—Disease, Parasites, Bio-contaminants and the Transfer of Pollutants

Food-web linkages and structure can serve to transfer more than energy. Parasites and pathogens, both endemic and introduced, can affect the health of marine populations and human populations. A variety of parasites, pathogens, and biotoxins pose a threat for the upper trophic levels of Puget Sound. However, little is known about the transfer mechanisms in natural settings or from artificial propagation.

Most notably for human health and management, toxins can be accumulated and concentrated at higher trophic levels. Both naturally-occurring toxins, such as those resulting from harmful algal blooms (Box 3-11), and toxic manufactured pollutants, such as pesticides and polychlorinated biphenyls (PCBs), are transferred and concentrated by organisms in the Puget Sound food web. Food-web dynamics can also contribute to the geographic movement of toxics. As organisms or their predators move from contaminated areas, toxic substances may be distributed to less polluted areas.

3.6.3.1 Effects of pathogens and toxics on marine species

Orcas and seals in Puget Sound are among the most contaminated marine mammals in the world; relatively high levels of PCBs and flame-retardant chemicals (PBDEs) have been found in orcas and harbor seals throughout the Puget Sound and Georgia Basin. Even though U.S. manufacturers stopped producing DDT and PCBs in the 1970s, both chemicals are still found in the environment because they break down slowly and they accumulate in the fat of organisms. Their position at the top of Puget Sound food webs has made harbor seals the unfortunate indicators of persistent contaminants in the Puget Sound food chain because toxics, such as PCBs and DDT, accumulate in their abundant fat layers. A recent scientific study found levels of PBDEs in Puget Sound orca whales that were 2–10 times higher than levels found in other whales around the world. Toxics that accumulate in the sediment make their way up through the detrital food webs of Puget Sound into top consumers. The Puget Sound Update and State of the Sound Report (PSAT 2002, 2005) describe these issues in detail.

Pathogens that have received the most extensive study in marine species are those that occur in artificial propagation settings, such as the bacteria and viruses affecting hatchery salmonids. For example, *Renibacterium salmoninarum*, the causal agent of bacterial kidney disease (BKD), is endemic in many salmonid populations and is a significant cause of mortality in hatcheries and captive-broodstock programs for ESA-listed salmon stocks. There currently are no completely efficacious

Close-up of *Styela clava* in Hood Canal
Photo: Charles Waters, WDFW

Box 3-10

Alien invaders in Puget Sound

It is estimated that at least nine non-native species of marine plants and 83 species of marine animals have been introduced into Puget Sound (WDFW pers. comm., 2006). Some of these were intentionally introduced, such as the Pacific oyster and Manila clam, to substitute for the loss of native shellfish species. Other animals have arrived through ship ballast water and other accidental introductions, including several species of tunicates or "sea squirts" (i.e., *Didemnum lahillei, Styela clava, Ciona savignyi and Ciona intestinalis*).

Invasive species are those species alien to a particular ecosystem whose introduction does or is likely to cause economic or environmental harm or harm to human health (Executive Order 13112, 2/3/99). Tunicates are a clear example of just such a serious threat. Without known predators and with rapid reproductive characteristics, these siphon-feeding animals can out-compete or suffocate other sea life, including clams, mussels, and oysters. *Styela clava*, for example, can spawn every 24 hours and has ten sets of gonads, each carrying both egg and sperm.

Tunicates can quickly blanket pilings, the underside of docks, traps, lines, equipment, and other hard surfaces, along with the hulls of boats—increasing the risk that the species will spread. In addition to the potential economic damage to the shellfish industry in Puget Sound, these alien invaders can create disruption throughout the Puget Sound food web.

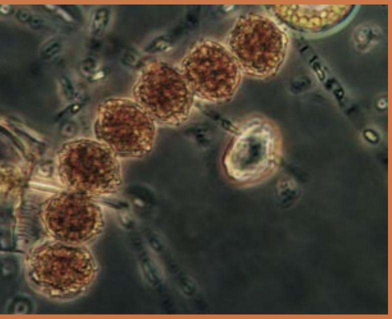
The tunicate *Didemnum lahillei* was first discovered near Edmonds in 2004 and has since been observed at a dozen sites including Hood Canal, Totten Inlet, Des Moines, and Neah Bay. Aggressive eradication programs have been launched to prevent the spread of tunicate species throughout Puget Sound. Although all of the tunicate species pose a serious problem, nuisance-species management experts are particularly worried about the *Ciona* species of tunicates that have developed dense population colonies over two miles long in Hood Canal (WDFW).

Patch of *Ciona*
Photo: Wayne Paulson, WDFW

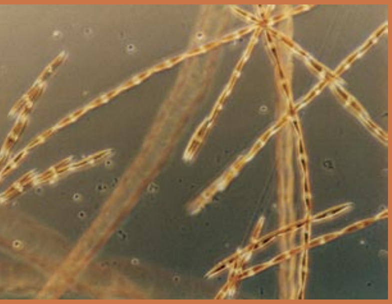
Box 3-11

Harmful algal blooms (HABs) in Puget Sound

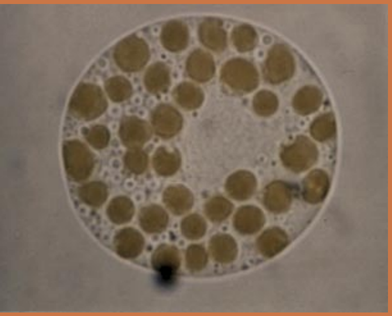
A visible but not harmful algal bloom of *Noctiluca*
Photo: Leo Shaw, The Seattle Aquarium



***Alexandrium catnella*, an organism responsible for PSP (magnified 200x)**



***Pseudo-nitzschia australis*, one of the species responsible for domoic acid poisoning (magnified 100x)**



***Heterosigma akashiwo* (magnified 500x)**

Out of the thousands of species of microscopic marine algae in the world, a handful of species occur in Puget Sound that can produce toxins that are harmful to humans and wildlife. These toxin effects are the most pronounced during periodic "blooms" when these naturally-occurring species proliferate due to a combination of warm temperatures, sunlight, and nutrient-rich waters (described in Section 3.3). The algae are ingested by shellfish, such as clams, oysters, mussels, and geoduck, which concentrate the toxins. Three types of HABs in Puget Sound are closely monitored by state agencies and tribes for issuing public health warnings, and long-term trends are being evaluated in a number of studies.

Paralytic shellfish poisoning (PSP) is caused by toxins produced by the marine alga *Alexandrium*. Although the toxin does not harm shellfish, it can induce serious neurological disorders or even death when ingested by humans or marine mammals. The earliest documented case on the West Coast was in 1793, when five members of Vancouver's expedition became ill and one died after eating mussels from the coast of British Columbia. In Washington State, illnesses and deaths in the 1940s launched long-term monitoring programs that have recently been assessed for geographic and temporal changes in PSP incidences. A geospatial map of the first shellfish closures or PSP event in each Puget Sound basin suggests that over time, toxigenic *Alexandrium* cells have been transported from northern to southern Puget Sound, with the initial "seed" population of cells in Washington State likely originating from the inland or coastal waters of Canada (Trainer et al. 2003). Most recently, closures due to PSP concerns were wide spread in Puget Sound in 2006.

Domoic acid intrusion into Puget Sound: Some species of the marine alga *Pseudo-nitzschia* produce a toxin called domoic acid that was first documented in razor clams (at levels above U.S Food and Drug Administration action levels) on the outer coast of Washington in 1991. The toxin causes amnesic shellfish poisoning and interferes with nerve signal transmission; in severe cases it can cause short-term memory loss, repiratory distress, and even death. Following emergency closures, a domoic acid monitoring program was established, and from 1991 to 2003 domoic acid remained an outer-coast problem. However, in September 2003, a bloom occurred near Marrowstone Island in Jefferson County. Domoic acid was detected at low levels over a wide area: as far west as Port Angeles, as far east as east Whidbey Island, and as far south as Port Ludlow (Bill et al. 2006). In September and October 2005, levels of domoic acid exceeding regulatory action limits were measured in commercial mussels from Penn Cove and in clams from Holmes Harbor. Numerous other shellfish species were also affected in other areas including Saratoga Passage and Sequim Bay. If domoic acid closures follow the same southward-migrating trend as PSP closures have in the past several decades, much of Puget Sound will be impacted by this toxin in the near future.

Fish kills: ***Heterosigma akashiwo*** is usually rare in plankton, but is capable of forming dense blooms that are often associated with low-salinity surface waters. It is not known to be toxic to humans but can cause extensive fish kills, especially of cultivated salmonids,and wild fish may also be affected. It has been present in Pacific Northwest waters at least since the 1960s and has been associated with fish kills since 1976 (Taylor and Horner 1994). Kills of finfish reared in net pens have also been caused by several species of diatoms, including *Chaetoceros convolutus* and *C. concavicornis*, since the early 1960s.

Nontoxic algal species: Several other species of algae that are found in Puget Sound waterways can cause damage to fisheries or result in nuisance water discolorations. A summary of these species and their effects is found in Horner et al. (1997).

vaccines or therapeutics to control BKD, and breaking the cycle of infection is exacerbated by the fact that the pathogen can be transmitted from the adult female into her eggs. Another pathogen affecting salmonids is infectious hematopoetic necrosis virus (IHNV). This virus readily infects fry and small fingerlings during the freshwater life stage, where mortality can reach 100%. Fish that survive can become carriers, capable of transmitting the virus to other fish through feces, urine, and external mucus. In both of these examples, studies continue on the potential for transmission of the pathogens from hatchery to wild stocks, as well as on methods to control their respective diseases.

3.6.3.2 Pathogen transfer and human health

An example of the interconnectedness of human actions and other species is the relationship between oceans and human health (Box 3-12). Human activities may release pathogens (bacteria, viruses, and parasites) into the marine environment through inadequate sanitation practices, with the potential to directly infect humans during recreational use of contaminated beaches, directly infect marine mammals, and contaminate fish and shellfish. The release of antibiotics and antimicrobial-resistant bacteria into the environment can also form a reservoir for transmission of antimicrobial resistance to pathogenic bacteria, making them more difficult to treat in clinical settings. Moreover, naturally occurring marine bacteria, such as members of the *Vibrio* genus, can accumulate in shellfish, crustaceans, and fish and can cause significant disease through ingestion of raw or undercooked seafood or through contamination of wounds.

Changes to ecosystem processes such as nutrient availability and temperature regimes further influence the potential for amplification of pathogens and subsequent transmission of pathogenic diseases to humans and other species. The full valuation of a particular ecosystem service, such as water purification and waste treatment, must consider all of the linkages to species, habitats and physical/chemical processes throughout the system.

Box 3-12

Oceans and human health

Currently, ocean factors affect human health via the transmission of disease, as well as exposure to marine biotoxins and chemical contaminants. For example, a variety of naturally occurring pathogens exist in the marine environment in fish and shellfish that are capable of causing human disease. In the United States, most seafood-related bacterial infections in humans are due to two members of the *Vibrio* species, *Vibrio vulnificus* and *Vibrio parahaemolyticus*. Bacteria shed in animal feces are a major cause of gastrointestinal disease acquired by the ingestion of contaminated food or drinking water by animals and humans. There are approximately 1 million cases of *campylobacteriosis* in the U.S. (with about 100 fatalities) and about 40,000 cases of *salmonellosis*, annually. In addition, there are about 25,000 cases of foodborne disease that require hospitalization every year. Many pathogens present in estuaries and oceans are the direct and indirect result of human activities, including poor sanitation, inadequate water treatment practices, and agricultural runoff. Such infectious bacteria and viruses also have the capability to infect marine species that become carriers of these pathogens. Infectious bacteria often possess genes conferring resistance to antimicrobial compounds, and form a reservoir for transfer of these genes to human pathogens.

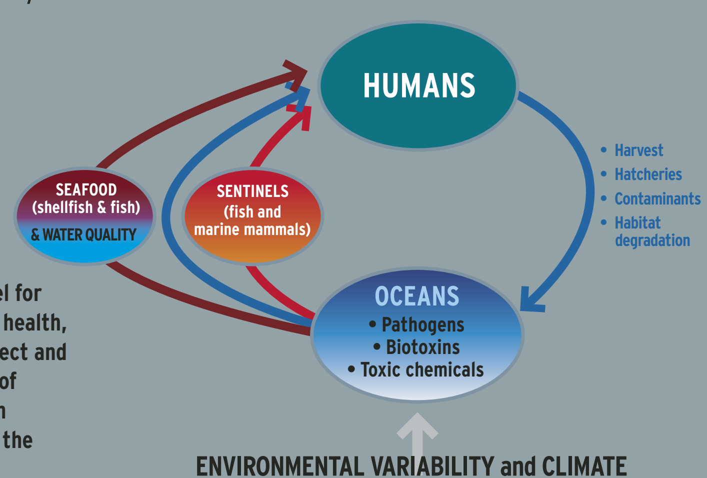
Importantly, the oceans may also provide clues about current and potential impacts to public health through examination of how toxics and pathogens affect marine fish and shellfish. Sentinel species can serve as important indicators of the status and trends in ocean health, and the observation and study of appropriate marine organisms can lead to a better understanding of potential public health risks.

Direct human health effects:

- Human disease risk as a function of exposure to shellfish contaminated with pathogens and marine biotoxins.
- Finfish and shellfish as vectors for pathogens and substances toxic to humans.
- Impact of microbial disease on marine mammals and potential risk of direct disease transmission from marine mammals to humans.

Indirect human health effects:

- Role of climate in amplifying pathogens and marine biotoxins and altering inputs of toxic substances and pathogens to marine ecosystems.
- Marine mammals may be sentinels of existing or "emerging" human pathogens in marine ecosystems, or of the effects of anthropogenic and natural stressors on human health.
- Using fish as a model to determine effects of anthropogenic stress on disease-transmission dynamics.



A conceptual model for oceans and human health, illustrating the direct and indirect pathways of pathogen and toxin transmission from the oceans to humans.

Box 3-13

Pollution transfers in the Puget Sound food web

Throughout the United States, pollution is widely recognized as one of the most significant and emerging threats to coastal ecosystems. This is particularly true of Puget Sound, where decades of nearshore industrial activity have left a legacy of persistent and bioaccumulative chemicals in sediments and the estuarine food web. Pollution is not merely a problem of the past, however. Today, simply driving a car can pollute the Sound. Roads, farms, highways, parking lots, residential homes, lawns, and golf courses all leave a chemical signature on the landscape. These chemicals are mobilized by rainfall and transported via stormwater runoff to receiving waters and sediments in the marine environment. Deposition of contaminants from air pollution is increasingly being noted as a pollutant source as well.

Toxic chemicals have been the focus of research and monitoring efforts in Puget Sound for several decades. In the 1970s and 1980s, the attention of early investigators was mostly drawn to a few toxic "hot spots" around the region. These were generally areas that had been heavily polluted by specific industrial activities, including several sites that were targeted for cleanup under the Comprehensive Environmental Response, Liability, and Compensation Act, also known as Superfund. Much of this work focused on assessing the environmental health of species living in or near contaminated sediments. Among their many discoveries, researchers found that sediment-associated flatfish from polluted sites had high prevalences of liver disease and cancer. Numerous additional adverse health effects have since been documented in fish exposed to pollution. These include, for example, developmental defects, reduced growth, increased disease susceptibility, and reproductive abnormalities.

Chemicals such as PCBs and DDT, that were banned in the 1970s, are often referred to as "legacy contaminants" because of their long-term persistence in the environment. The list of persistent pollutants also includes mercury, dioxins, and brominated flame retardants (PBDEs) that originate from modern industrial and manufacturing activities. Once released into the environment, these chemicals are picked up from sediments by benthic (bottom-dwelling) organisms and transferred through the food web to species that frequent open waters and freshwater and terrestrial areas. As they move through the food web, concentrations increase, a process known as "biomagnification," and pose an important health risk for top-level feeders such as salmon, raptors, marine mammals, and humans.

Growing evidence suggests that toxic contaminants are not confined to a few specific hot spots associated with industrial uses. Treated municipal sewage contains a complex mixture of personal care products, caffeine, endocrine-modulating chemicals (e.g., birth control pills), antidepressants, and other pharmaceuticals. Airborne particulates from the fuel emissions of cars, trucks, and stationary sources wash into rivers, streams, and marine waters and upload back into the food web. In 2001, an estimated 7.7 million pounds of toxic chemicals were released into the air in the Puget Sound basin from stationary sources alone (not including mobile sources such as cars or trucks). Hundreds of oil spills (major and minor) occur annually.

In response to ecological and human health concerns, the Puget Sound Assessment and Monitoring Program (PSAMP) has been documenting the levels of persistent pollutants in different components of the marine ecosystem for more than 15 years. This long-term monitoring effort has shown that bio-accumulative contaminants are present at all levels of the food web, and at much higher concentrations in Puget Sound (and particularly in southern Puget Sound) than in the Georgia Basin or the coastal northeast Pacific Ocean. Trends in the levels of toxic contaminants for several indicator species are discussed in the PSAMP reports as well as the "State of the Sound" report (PSAT, 2005), and the 2002 series by the Seattle Post-Intelligencer, "Our Troubled Sound" (http://seattlepi.nwsource.com/specials/sound). A few indicators include:

- Concentrations of persistent organic pollutants are higher in the blubber of southern resident orcas than in other

North Pacific orcas. The accumulation of these compounds may cause immune suppression, reproductive dysfunction, and thyroid disruption in these top Puget Sound predators.

- Harbor seals (a top level predator) inhabiting Puget Sound were found to be seven times more contaminated with PCBs than those inhabiting the adjacent Strait of Georgia.
- Dissolved metals such as copper from roads and other impervious surfaces have been shown to interfere with the ability of juvenile salmon to detect and respond to predators.
- Levels of PCBs in herring, a key mid-level species in the Puget Sound food web, are several-fold higher in central and southern Puget Sound than those from sites in the Georgia Basin. Recent sampling indicates that brominated flame retardants (PBDEs) are also higher in Puget Sound herring and are rapidly increasing in the marine food web in general.
- Male English sole exhibit signs of feminization in nearshore habitats that receive untreated sewage effluent from combined sewer overflows, reflecting the ability of stormwater to transfer pollutants.
- In October, 2006 the Washington Department of Health issued a health advisory for the consumption of Puget Sound Chinook due to levels of PCBs and mercury, particularly for pregnant women.

The effects of toxic contaminants remain the focus of considerable research. What is already clear is that these substances are causes for concern and that activities occurring now will have repercussions for the Puget Sound food web and the health of many species—including humans—for decades.

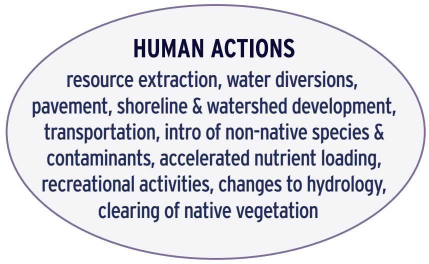
Photo: Leo Shaw, The Seattle Aquarium

Photo: NOAA

Adult coho salmon returning to spawn in a Seattle-area urban creek in the fall of 2005 (above). This female died prior to spawning as is evident by the complete retention of eggs. This phenomenon has been termed "pre-spawn mortality" and has been consistently observed around the region for several years. At present, the weight of evidence indicates that these recurrent fish kills are caused by polluted stormwater.
Photo: Sarah McCarthy, NOAA

Photo: Joni Packard, NOAA

3.7 Humans and Ecosystem Change



Early residents of Puget Sound inhabited a much different ecosystem. A projectile found in a mastodon rib near Sequim signifies the everchanging nature of climate, species, and habitat. Humans have clearly been an integral part of the Puget Sound ecosystem for millennia, but in the last two centuries the pace and magnitude of resource utilization has changed dramatically. Although we think of impacts to Puget Sound as recent, many resource-extraction and construction activities that were initiated in the 1800s have altered ecosystem processes in ways that continue to affect Puget Sound today (Table 3-4 Timeline).

As humans have expanded their footprint on this landscape, we have increasingly become drivers of ecosystem change. While much of the terrestrial area draining into Puget Sound is still forested, the structure and composition of the forest is much different than it was when 18th-century European explorers arrived. Timber harvest, extensive roads and pavement, dams, and dikes have altered freshwater and sediment-transport processes between terrestrial and marine landscapes. Fully one-third of the shoreline in Puget Sound is estimated to have been modified by humans, further interrupting the processes that move sediment and nourish beaches and vegetation along the nearshore (PSWQAT, Puget Sound Update 2002). The alteration of these ecosystem processes has changed the quantity, quality, and connectivity of habitat for numerous species of freshwater and marine organisms and reduced the ability of the ecosystem to meter peak flows, deliver nutrients, absorb waste, and provide other services.

Puget Sound urban centers are poised for expansion and are located along shorelines and bays where their impacts to the marine environment are the most immediate. Since the 1800s, it is estimated that Puget Sound has lost 73% of its saltmarsh habitat, primarily due to urbanization (PSAT 2005, State of the Sound). Many patches of marine and freshwater habitat have become too fragmented for migratory species to use. Intentional and accidental introductions of non-indigenous species have affected the composition and abundance of native species that once thrived in Puget Sound. Large-scale harvest of salmon, depletion of top-level predators such as orcas, and active farming of oysters and other shellfish have further affected native species abundance with likely impacts to prey organisms and the food web.

Humans have benefited directly from the high productivity of Puget Sound as users of timber, fish, shellfish, water, fertile soil, transportation corridors, eco-tourism, and other ecosystem services. For example, Puget Sound hosts myriad forms of recreation, such as kayaking, scuba diving, walking shorelines, and an active whale-watching industry (Box 3-14). However, as some ecosystem services have expanded (transportation, waste treatment, water supply) others have declined (shellfish- growing areas, populations of forage fish and marine birds). Assessing Puget Sound in terms of its provision of ecosystem services requires specific measures that can be used as a common currency for evaluating tradeoffs and adapting strategies over time. The development of such measures is complicated but is being attempted in many cases with existing science. A clear and transparent decision framework can organize what is known about both the natural and socioeconomic systems and highlight the choices for the benefit of citizens, scientists, and policy- and decision-makers. More information on the integration of natural and social sciences in developing decision frameworks is contained in Section 4.

People living in the region are attentive to the expansion of the human role in the Puget Sound ecosystem and have supported steps to protect ecosystem health for several decades. Large-scale actions such as the effort to eliminate the disposal of sewage into Lake Washington (Box 2-1) have occurred largely in response to scientific input and a motivated public. The Puget Sound Action Team reports on a series of actions being implemented to remediate and prevent further habitat damage. Key accomplishments have included the cleanup of hundreds of acres of contaminated sediments and shellfish growing areas, removal of invasive *Spartina*, and assistance to communities in protecting forage-fish habitat and preventing oil spills (PSAT 2005). Although these actions are often local in nature, protection and restoration of the smaller systems that comprise Puget Sound are necessary for the cumulative protection of the ecosystem as a whole.

Significant efforts to protect and restore terrestrial and freshwater habitats in the Puget Sound region also are underway. The Puget Sound Salmon Recovery Plan summarizes many of these actions and their anticipated benefits to watersheds and the fish (Shared Strategy 2005). Major focal areas of attention include restoration of estuarine and river floodplain habitats through dike and levee setbacks; regulation of forest practices such as road-building and harvest schedules; protection of ecologically intact habitats through acquisition, incentives, and regulation; and barrier removals designed to improve natural stream flows and movement of fish, sediments, and nutrients throughout watersheds.

Fisheries harvest levels have always been difficult to assess as a measure of ecosystem function because fish populations respond to multiple, interacting, and unpredictable ecosystem dynamics. However, harvest management forums for Pacific salmon and groundfish are attempting to incorporate a broader look at ecosystem services in the development of long-term management plans. Sophisticated modeling tools are being developed that look at multiple species, predator-prey abundance, and the spatial distribution of the fishers themselves. The Puget Sound Salmon Recovery Plan (Shared Strategy 2005) highlights the relationship of the three H factors for salmon—habitat, harvest, and hatcheries—and the importance of integrating these factors during recovery and ongoing management (Box 3-15).

In addition to these efforts, many scientists and resource managers in the Puget Sound community are looking at fundamental ecosystem processes that will affect human well-being in the future. Potential and anticipated changes to climate, pathogen distribution, habitats, and food-web dynamics require analysis and action on a Soundwide basis. Some groups, such as King and Snohomish Counties and their cities, already have begun to explore the impacts of future climate conditions on water supply. Further, businesses, policymakers, and local communities will need tools to address ecosystem services across the entire range of values and tradeoffs.

In Section 4, groups of social and natural scientists report on historic changes and possible futures for Puget Sound—how the Puget Sound ecosystem may respond to changing conditions, actions, and likely shifts in ecosystem services as a result of natural and human-induced changes. Additionally, Section 4 includes approaches for decision-makers to use in implementing a systemwide view considering linkages and tradeoffs toward sustainable ecosystem management.

HUMAN WELL-BEING & VALUES
human health, cultural heritage, biodiversity, aesthetic enjoyment

Box 3-14

Ecosystem services and human values—*whale watching in Puget Sound*

Photo: Dawn Noren, NOAA

Killer whales *(Orcinus orca)* are considered one of the foremost icons of the Pacific Northwest, and whale watching is an increasingly important tourism industry in the Puget Sound region. An estimated 52,000 people participated in commercial boat-based tours during 1998. The current whale-watching industry in Puget Sound is estimated to contribute approximately $18.4 million annually and 205 jobs to the 19 counties adjacent to Puget Sound through direct and indirect expenditures related to the industry (IE 2006). In addition to these economic benefits, orcas are valuable contributors to biodiversity, cultural integrity, and the quality of life for Pacific Northwest residents.

The whale-watching industry represents the intersection of complex linkages in both ecological and human-made systems. The existence of the orca and other whales relies on the production of prey (e.g., salmon and herring) which in turn depend on supporting plant species such as eelgrass and an array of freshwater, nearshore, and marine habitats. Fractures in these supporting ecosystem structures, or the input of toxic chemicals and contaminants detrimental to the health of the whales, will harm the single species that has been the foundation of an important Puget Sound industry.

This ecosystem service, however, is also the output of human-made capital (boats and gear), fuel, labor, and advertising. Without either the whales themselves or the human components that make viewing them possible, this industry could not exist; thus it is difficult to assign the entire economic value of the industry to any single factor or to assess how the value may change over time. If the orca population increases through habitat restoration and management efforts, whale-watching opportunities may also rise, increasing the economic value of the service along with biodiversity and cultural benefits. Management restrictions on the whale-watching industry itself, if deemed necessary to protect the orca population, would effectively decrease the economic value of the service in the short term even though the other benefits are maintained or enhanced. The management of Puget Sound with an ecosystem perspective would highlight the changing values to be derived from alternative management actions and the complex linkages among species and human actions throughout the Sound.

Photo: NOAA

Box 3-15

The Shared Strategy Recovery Plan for Puget Sound Salmon: connecting human communities and salmon recovery

Following the listing of Puget Sound Chinook and other salmon as threatened species in 1998-99, a coalition of federal, state, tribal, and local governmental leaders and salmon recovery organizations formed the Shared Strategy for Puget Sound to prepare a recovery plan that would come largely from the communities that would be responsible for its implementation. Within the plan, the factors affecting salmon and the actions needed for recovery were largely organized around the four "H's" of salmon management: Harvest, Hatcheries, Hydropower, and Habitat. For the Puget Sound region, the Shared Strategy plan for salmon, included Hydropower effects within Habitat.

Habitat: The communities of Puget Sound were asked to evaluate habitat conditions within each watershed, assess the capability of their river system and nearshore areas to form and sustain habitat, and identify a suite of actions that would cumulatively lead to recovery. The need for suitable habitat for spawning, foraging, resting, hiding from predators and feeding throughout the salmon's complex life cycle was considered in scientific and community discussions in the 14 watershed planning areas described in the plan. Specific strategies designed to protect and restore sufficient habitat to recover salmon are outlined in each watershed plan.

Hatcheries: The decline of salmon during the 20th century led to the increased use of artificial propagation to compensate for dwindling returns. Although hatcheries can be used as a tool in the recovery process and provide opportunities for harvest, their operations can create risks with respect to the loss of genetic diversity, domestication, disease transfer and competition with wild populations. The salmon recovery plan describes ongoing actions by state, tribal and federal managers of hatchery facilities to minimize risks, and integrate hatchery operations with harvest plans and habitat restoration.

Harvest: Fishing for salmon in Puget Sound is structured around the cultural, legal and economic history of the Puget Sound region, international agreements, and the biological patterns of the species' life histories. The co-managers of salmon in Puget Sound, consisting of the treaty Indian tribes and the State of Washington, have developed a comprehensive harvest management plan that describes how they will constrain harvest as recovery proceeds.

The Puget Sound Salmon recovery plan is available online at www.sharedsalmonstrategy.org.

Chum salmon eggs
Photo: David Misitano, NOAA

"People are integral parts of ecosystems."

— Millennium Ecosystem Assessment

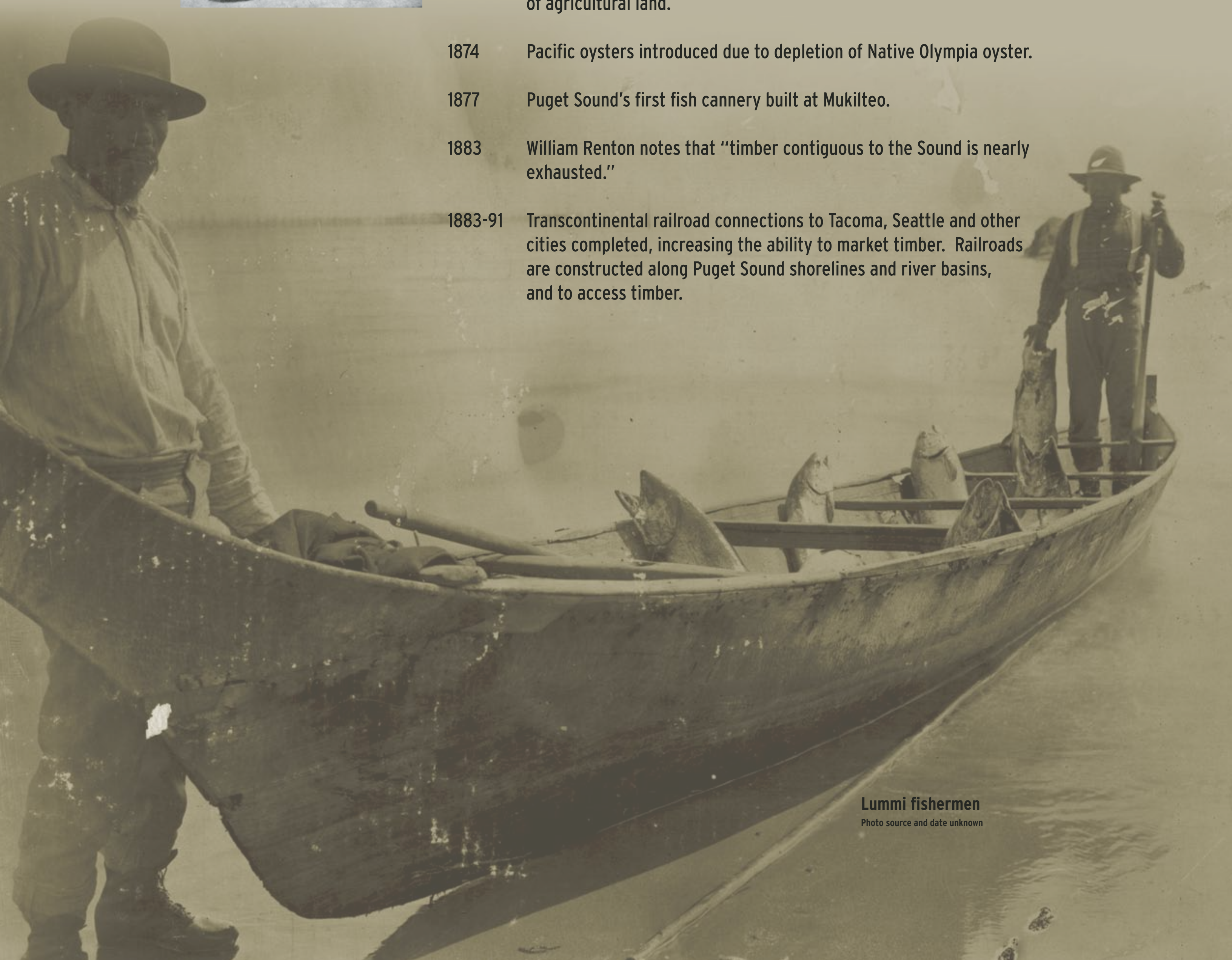
Photo: Roger Peters, USFW

Table 3-4

The Puget Sound Ecosystem: Milestones of Two+ Centuries of Change

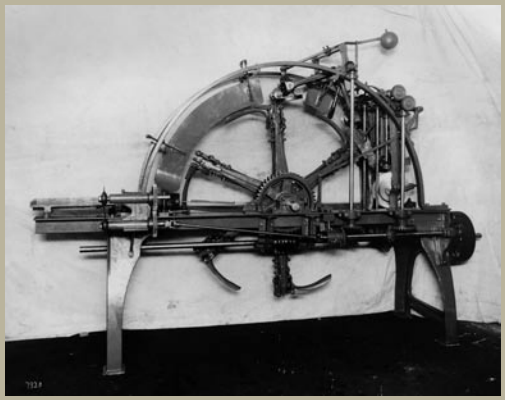
1864 photo of Sealth, known to settlers as Chief Seattle.
Photo © E.M. Sammis/MOHAI

Pre-1790	Tribes develop religious, economic and cultural societies oriented around salmon, cedar and other indigenous natural resources.
1792	Vancouver sails into Puget Sound. Human population estimated at 50,000.
1810-40	Fur trapping depletes beaver populations, a keystone species of habitat formation. Small pox and other diseases wipe out three-quarters of the native human population.
1847-64	California gold rush increases demand for Olympia oysters and other seafood. Small, local mills are constructed to supply building materials for settlers, and expand to meet the demand for the gold rush and ship building. Easy timber along marine and lower river shorelines is harvested first.
1854-5	Tribal treaties signed.
1863	First dike constructed in Skagit County on LaConner flats for development of agricultural land.
1874	Pacific oysters introduced due to depletion of Native Olympia oyster.
1877	Puget Sound's first fish cannery built at Mukilteo.
1883	William Renton notes that "timber contiguous to the Sound is nearly exhausted."
1883-91	Transcontinental railroad connections to Tacoma, Seattle and other cities completed, increasing the ability to market timber. Railroads are constructed along Puget Sound shorelines and river basins, and to access timber.



Lummi fishermen
Photo source and date unknown

Seattle's first railway station stood near the present King Street Station, ca. 1890
Photo © MOHAI

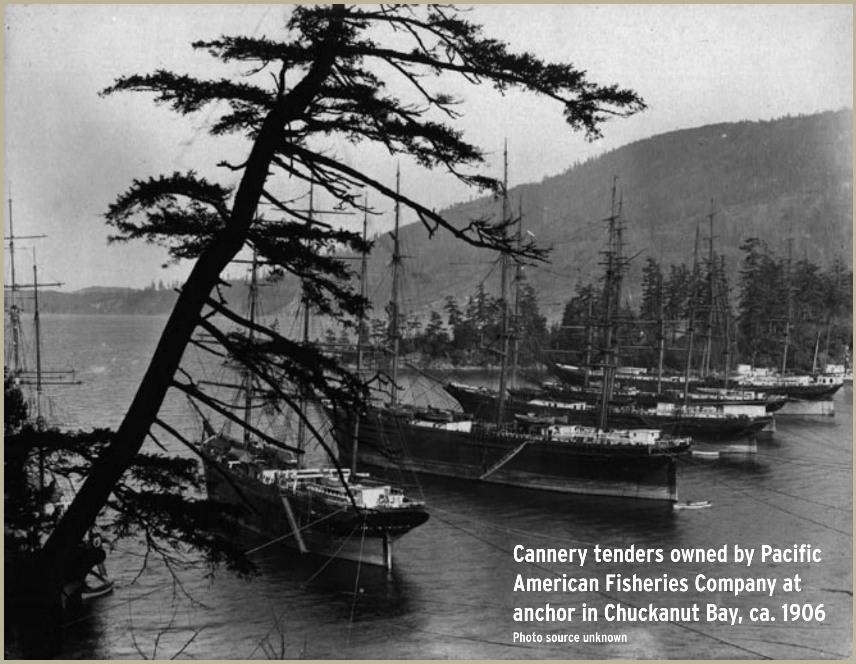


First "Smith Butcher Machine" made and developed in Seattle in 1897
Photo © MOHAI

Denny regrade, Seattle, 1907
Photo © Asahel Curtis/MOHAI

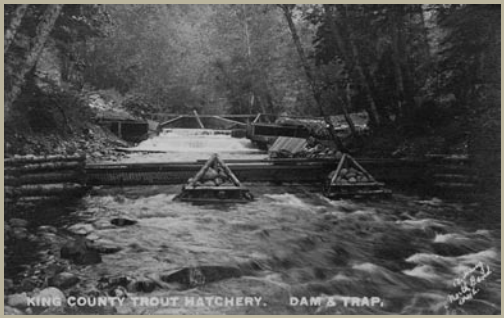
Log pond at North Bend Lumber Company, ca. 1910
Photo © Siegrist/MOHAI

1889	Washington becomes a state.
1896	First Puget Sound salmon hatchery constructed on the Baker River.
1896	First agricultural irrigation system in the Dungeness valley.
1900	Port Blakely in Kitsap County is the location of the largest lumber mills in the world. Technological advances such as the band saw and steam donkey boost lumber production.
1900-10	Seattle population expands from 81,000 to 237,000 due to Alaska Gold Rush.
1900-20	Several major dams constructed on the Cedar, Nisqually, White, Elwha and other rivers for urban water supplies and to power mills.
	White, Cedar and Black rivers are re-routed.
1903-11	Peak period of the Denny Regrade: 16 million cubic yards were removed from Seattle hills, mostly by water blasting. About half of the spoils were deposited in the tideflats, forming Harbor Island.
1906	Puyallup levees constructed.
1913	Peak cannery pack in Puget Sound with 2,583,463 cases of Pacific salmon.
1913-27	Puget Sound salmon hatcheries import eggs from the Columbia River.
1916	Ballard Locks completed, dropping level of Lake Washington by approximately 9 feet and eliminating substantial marsh habitat.
1916-18	Puget Sound Naval Shipyard undertakes major production of military ships during WWI.
1917	Boeing Airplane Company is incorporated.



Cannery tenders owned by Pacific American Fisheries Company at anchor in Chuckanut Bay, ca. 1906
Photo source unknown

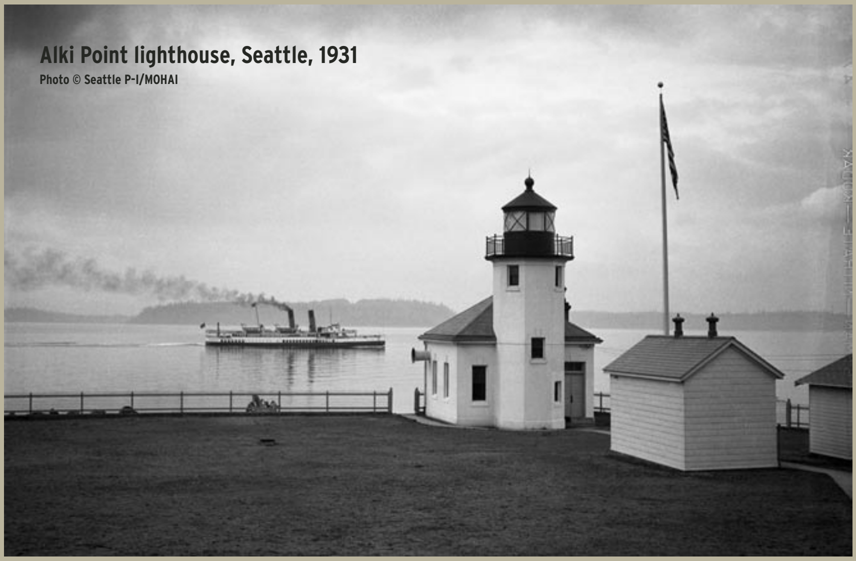
1920s	Highway 101 constructed along the west side of Hood Canal, crossing all major river deltas.
	Dams built on Skokomish and Skagit systems.
1924	Manila clams introduced with shipments of Pacific oyster seed.
1926	All time peak of Washington lumber production at 7.5 billion board feet.
1927-57	One hatchery in the Green River is the source for 67.7% of Chinook releases throughout Puget Sound.
1941	Spartina alterniflora intentionally planted in Padilla Bay by a hunting club.
1942-45	Puget Sound is major center for manufacturing and military staging during WWII.
1945-60	Major expansion of transportation infrastructure in Puget Sound including Interstate 5.
1950s	Recreational fisheries expand following World War II. Recreational catch of Chinook in Puget Sound in 1957 estimated at 238,000.
	Cold war era boosts Boeing production.
	First oil refinery built on Puget Sound.
	According to a federal report, Puget Sound is the sixth most polluted area in the country.
1960s	Flooding leads to expansion of levee systems along Cedar, Sammamish and other rivers.
1962	Howard Hanson Dam constructed on the Green River.
1968	Sewage effluent entering Lake Washington, once estimated at 20 million gallons per day, is diverted to Puget Sound.



King County trout hatchery on Tokul Creek (in the Snoqualmie watershed), ca. 1915
Photo © MOHAI

Ballard locks under construction, 1916
Photo © Webster & Stevens/MOHAI

Lake Washington ship canal entrance (looking west), 1917
Photo © Webster & Stevens/MOHAI



Alki Point lighthouse, Seattle, 1931
Photo © Seattle P-I/MOHAI

Skagit Dam construction site, 1921
Photo © Webster & Stevens/MOHAI

Aerial view of Boeing plant (looking southeast in 1943)
Photo © Seattle P-I/MOHAI

Aerial view of Evergreen Point bridge under construction in 1963
Photo © Seattle P-I/MOHAI

Aerial view of Sea-Tac expansion in 1970
Photo © Stuart Hertz, Seattle P-I/MOHAI

1970s	Peak contaminant levels in Puget Sound sediments. The manufacture of PCBs and several other toxic contaminants are banned nationally.
	Construction of numerous bulkheads, docks, piers and revetments along central Puget Sound basin.
1971	Shoreline Management Act is approved.
1974	Boldt Decision determines that treaty tribes in WA reserved the right to harvest up to 50% of the salmon catch.
1977	Seattle is the second busiest container port in the U.S. and sixth busiest in the world.
1981	Industry giant IBM selects tiny Microsoft's MS-DOS as the operating system for their new personal computer.
1985	Pacific Salmon Treaty signed with Canada.
1999	Endangered Species Act listing of Puget Sound Chinook is the first major listing affecting an urban area. Draft recovery plan completed in 2005.
2000	Human population of Puget Sound estimated at 3.8 million.
2005	Southern resident orca population listed as endangered.
2020	An additional 1.4 million residents expected, bringing the combined total of Puget Sound and the Georgia Basin to over 7 million.

Men looking out over Port Of Seattle docks in January 1987
Photo © Cary Tolman, MOHAI

Section 4 The Future of Puget Sound

The Puget Sound/Georgia Basin region currently supports a large and increasingly urban population from Vancouver, British Columbia to Olympia, Washington that will be faced with a number of pressures in the near future. Population projections suggest that human numbers in the region will continue to grow substantially through the next several decades. In addition, the region already is experiencing detectably different climate conditions, and those changes are predicted to become even more dramatic over the next 50 years. As both the beneficiaries of the goods and services that the Puget Sound ecosystem provides and critical drivers of ecosystem function, inhabitants of the region now and in the future face major challenges in protecting and restoring the system. Such natural resource management choices are often reactive, responding to immediate biological, physical and social conditions and concerns. However, with forethought, we can structure our actions in a way that maximizes our ability to understand the interactions between components of the ecosystem and thoughtfully balance the trade-offs between our multiple goals of flourishing human and natural systems in the region.

In this section, experts in both natural and social sciences were asked to discuss what the future might look like for several aspects of the Puget Sound ecosystem, and to identify approaches and information that would enhance our ability to realize a system that supports both human and ecosystem well-being. Although the rest of this document reflects the consensus of a broad array of scientists throughout Puget Sound, these papers are the work of the authors and reflect their expertise and

Photo: Leo Shaw, The Seattle Aquarium

opinions in each of these areas. The potential list of natural and human impacts on the Puget Sound ecosystem is long, and these papers do not pretend to treat such future impacts exhaustively. Indeed, several authors chose harvest and climate impacts to use as examples. Harvest impacts on species are relatively certain and direct, and thus fit easily into examples about how future management decisions might affect or incorporate complex ecosystem interactions. Climate in our region is a strong natural driver of ecosystem dynamics, and likely future climate conditions for the region recently have been well summarized, heightening both interest in and awareness of this topic. The reader should consider these impacts in the following papers as they were intended—as illustrative of the kinds of factors that more forward-thinking management decisions could address.

In the first three papers, the authors treat components of the natural system. Nathan Mantua from the University of Washington Climate Impacts Group and his colleagues identify likely direct and indirect impacts of climate change throughout the Puget Sound ecosystem in the 21st century. In the second paper, Timothy Beechie (National Marine Fisheries Service) and his co-authors discuss the factors that have led to changes in the distribution and quality of habitats in the region, and point to the benefits of a conservation strategy that focuses on enhancing the natural processes of the system, rather than on engineering solutions whose lasting impacts are less certain. The unintended consequences of human actions on food webs are the focus of the third paper, by Tim Essington (University of Washington, School of Aquatic and Fishery Sciences) and other scientists from the US Geological Survey, NMFS, and Washington State Department of Fish and Wildlife. This paper highlights examples of species interactions that, as a result of human actions on one or a few species, can lead to unanticipated changes in the ecosystem and identifies several areas to be explored.

In the remaining three papers, the authors treat more explicitly the interactions between humans and the ecosystem. Marina Alberti (Department of Urban Design and Planning at the University of Washington) and her co-authors discuss how human decisions about land uses drive changes in ecosystem conditions directly and indirectly and how planning tools, such as scenario development, can contribute to future management. Vera Trainer from the National Marine Fisheries Service and other experts in marine pathogens link human health and ecosystem conditions, and discuss the ways in which the management choices we make can affect the safety of our seafood and the transmission of disease. Finally, Alison Cullen (The Evans School of Public Affairs at the University of Washington) and her colleagues show how decision-support tools can help illuminate difficult tradeoffs in management decisions that include both biological and social or economic components.

4.1
Climate change and Puget Sound

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Documented 20th Century climate change in Puget Sound

Important climate changes have occurred in the Puget Sound region in the past century, and the next several decades will very likely see even greater changes, according to a report prepared by the University of Washington's Climate Impacts Group (Mote et al. 2005). Based on extensive review of climate records and the most current scientific literature, the report finds compelling evidence of past, present, and future change in the region.

Glaciers in the Cascade and Olympic Mountains have been retreating since the 1850s. Since the late 1800s, Pacific Northwest temperatures rose faster than the global average. Puget Sound waters warmed substantially, especially in the period since the early 1970s (Figure 4.1.1), when the sea surface temperature at Race Rocks began a prolonged warming trend that continued through (at least) 2005. Puget Sound air temperatures warmed a comparable amount over the same time period (not shown). As a consequence of regional warming in the 20th century, spring time snow pack has decreased markedly at many sites in Puget Sound (Figure 4.1.2), and the timing of river and stream flow shifted with significant reductions in snowmelt runoff in May-July, reduced summer stream flows, and increased runoff in late winter and early spring (Figure 4.1.3).

Puget Sound's marine life can show dramatic effects of climate impacts that can alter the species composition, behavior, physiology, and year-to-year productivity. While the many relationships between climate and biota may be subtle and are poorly understood, the responses of biota to El Niño events suggest how warmer climates may impact marine life in the future. The greatest impacts have been observed on the coast with the occurrence of unusual fish species from southern waters including striped marlin, tunas, yellowtail jack, and dolphinfish. In Puget Sound, El Niño events have brought increased or unusual occurrences of ocean sunfish, Pacific mackerel, California lizardfish, and California tounguefish (Schoener and Fluharty 1985). Other climate impacts on fish have been related to the Pacific Decadal Oscillation (PDO). The year-to-year survival of marine fish stocks is affected by the warm and cold phases of the PDO (Hollowed and Wooster 1995), favoring some species during warm phases and others during cold phases. Warming temperatures in Puget Sound and the West Coast may be affecting the survival and reproduction of Pacific cod (Tyler 1995). In Puget Sound, this cold-water species is on the southern end of its range and cod abundances have been declining since the 1980s during a period of increasing water temperatures in Puget Sound.

Climate impacts on salmonids are complex and may vary by drainage and have been more affected by phases of the PDO than by El Niño events (Mantua et al. 1997, Hare and Mantua 2000). With warmer climates, lesser snow packs, altered runoff timing, low summer flows, and higher stream temperatures are likely to negatively impact salmon production (Mote et al. 2003). Warmer ocean temperatures affect the migration behavior of Fraser River sockeye by diverting them to the northern entrance to the Strait of Georgia rather than by the Juan de Fuca entrance (Groot and Quinn 1987), dramatically altering commercial fisheries in northern Puget Sound. Some Fraser River sockeye stocks experience poorer growth and lesser adult weights during warm ocean years (Hinch et al. 1995).

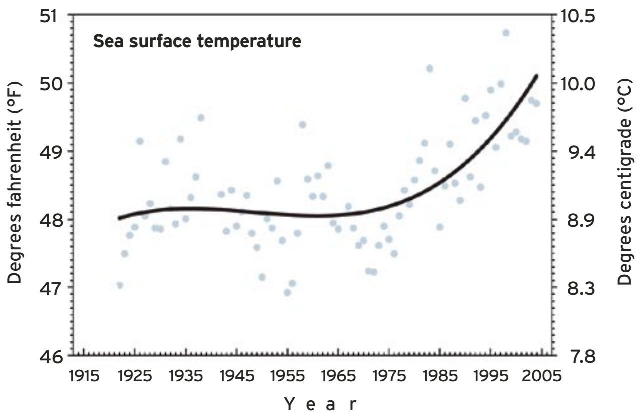

Figure 4.1.1: Averaged annual sea surface temperature at Race Rocks, near Victoria B.C. in the Strait of Juan de Fuca. Each year's temperature is shown as a circle and the smooth curve indicates a long-term warming trend of 1.7°F (0.9°C) between 1921 and 2005, nearly all of which has taken place since the early 1970s. This figure is reprinted from Snover et al. 2005.

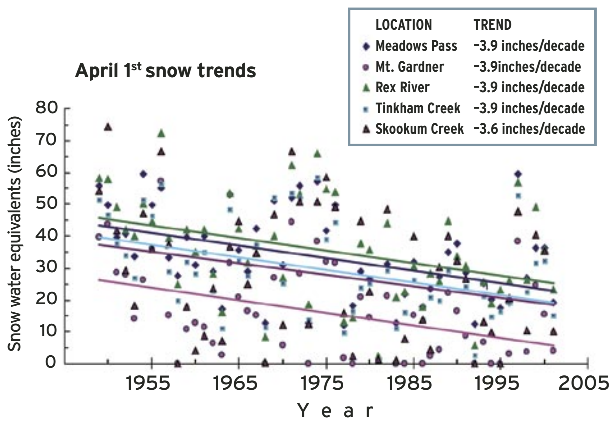

Figure 4.1.2: Historic April 1st snow pack and trends at Snotel sites within the Cedar and South Fork Tolt River basins. This figure courtesy of Matthew Wiley, UW

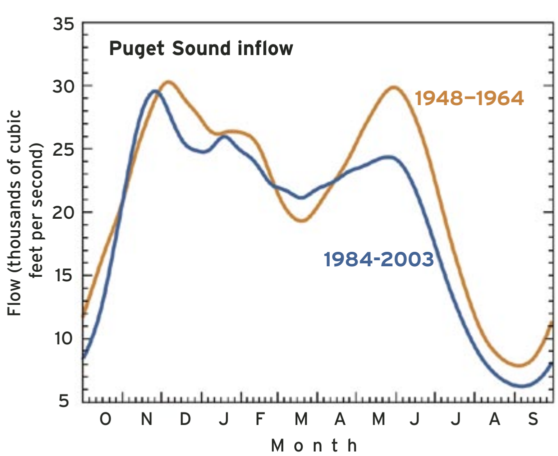

Figure 4.1.3: Average daily freshwater inflow into Puget Sound (found by adding the flow of nine of the largest rivers) for 1948-1964 and 1984-2003. Note the decline in spring/summer flows, and the increased flow in March-April. This figure is reprinted from Snover et al. 2005.

Marine mammals and birds may be directly or indirectly affected by climate changes. Failed breeding success during and limited population increases after El Niño events are exhibited by common murres (Wilson 1991, Carter 2001, Manuwal and Carter 2001). Climate impacts on marine mammals such as killer whales appear to be less direct but climate-altered abundances, distribution and timing of prey sources, especially salmon, could affect killer whale populations (Wiles 2004).

Projected changes for the 21st century

Human activities, primarily the burning of coal, oil, and natural gas, have committed the Earth to a different and warmer climate in the 21st century. Projections for the consequences of future global warming in the Puget Sound region include:

- **Temperatures will continue to rise**. Even the most conservative scenarios show the climate of the Pacific Northwest warming significantly more than was experienced during the 20th century (Figure 4.1.4). Recently run climate models project, on average, a 6°F (3.5°C) warming by 2100 (with a range of +2 to +10°F).

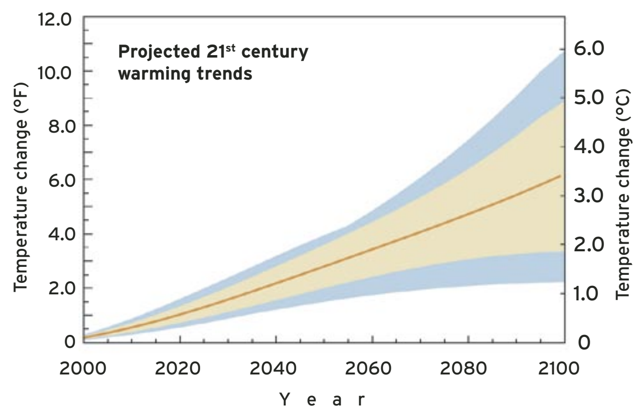

Figure 4.1.4: Projected changes in annually averaged temperature for the Pacific Northwest, compiled by considering climate scenarios for 10 global climate models each using two scenarios of future socioeconomic growth. The orange line shows the average of all the model simulations. The blue shading indications the range from highest to lowest, and the yellow shading indicates the range in which about two-thirds of the scenarios fall. This figure is reprinted from Snover et al. 2005.

- **Water temperatures will continue to rise.** Given the close correspondence between surface air temperature and surface water temperature, the latter is also projected to increase in Puget Sound and in the rivers and streams that feed into it.

- **River and stream flows will be altered.** Warming air temperature in winter and spring will cause earlier snowmelt, and more precipitation falling as rain rather than snow. Puget Sound's typically low summer stream flows are likely to be further reduced, while early spring and winter stream flows are likely to rise.

- **Winter runoff will increase, the amount of water stored as snowpack will decrease in the late spring, and snowmelt runoff will substantially decrease.** This will have the effect of decreasing the natural water storage in many Puget Sound watersheds in the late spring, resulting in earlier exhaustion of the snowpack and lower flows in streams in late spring and summer. This shift in the hydrograph will increase the competition for water resources. It will increase the number of days upon which utilities must rely on water stored behind dams, while decreasing the natural storage in the snowpack. This will make it much more difficult to maintain instream flows for fish and to provide water for municipal uses.

- **River flooding will increase.** With more of the region's annual precipitation falling as rain rather than snow, stormwater runoff and flooding along many of the region's rivers and large streams will likely increase.

- **Puget Sound circulation will likely change.** The sub-tidal circulation of Puget Sound is largely driven by the difference in salinity between fresher waters within the Sound and the saltier ocean waters in the Strait of Juan de Fuca. Circulation is therefore sensitive to the timing and amount of freshwater inflow, mixing within the Sound and the salinity of ocean waters in the Strait. Observed and simulated circulation data for Puget Sound have shown different sensitivities in different sub-basins to varying freshwater inflow. Increased streamflow into Hood Canal increases exchanges, but increased streamflow into Puget Sound's main basin decreases exchanges at Admiralty Inlet. Circulation in Puget Sound's main basin appears to be more sensitive to variations in ocean salinity compared to freshwater inflows. Projected changes for the timing of freshwater inflows will likely alter the circulation of Puget Sound, but changes to the upper mixed layer of the coastal ocean may be at least or more important and the combined effects of these factors will be difficult to predict. At this time, there is substantial uncertainty about global warming impacts on the water properties of Washington's coastal ocean.

- **Sea level will continue to rise,** especially in south Puget Sound (Figure 4.1.5). The rate of rise in the Pacific Northwest is projected to be faster than the global average and is likely to increase both the pace and extent of the erosion and nearshore habitat loss already affecting Puget Sound shorelines.

- **Puget Sound water quality will change.** Marine water temperatures in Puget Sound will continue to increase as a consequence of projected changes in climate due to increases in air temperature and increases in the temperature of freshwater inflows. Changes in streamflow timing will likely produce fresher waters during winter and saltier waters during summer. Stronger stratification in Puget Sound's waters in winter is expected from increased streamflow, while weaker stratification is expected in summer from decreased streamflow. Increased water temperature in summer may partially offset weaker stratification owing to decreased streamflow at some locations, but this is likely to be minimal given the role of salinity in Puget Sound's stratification.

- **Biological productivity in Puget Sound will increase, particularly in surface waters, and warmer water temperature and stronger winter stratification will likely contribute to decreased dissolved oxygen (DO) in deep waters.** The increased number of plants and animals in the water column will result in an increase in the organic material delivered to bottom sediments as they die and sink. Increased decomposition of this organic material will increase the consumption of DO at depth. Because of the numerous factors influencing nutrient levels in Puget Sound and uncertainties as to how these factors interact, it is difficult to predict the impact of projected climate change. Nutrient levels may increase due to rising sea level increasing the likelihood of leakage from septic tanks, but increased utilization of nutrients from increased biological productivity may offset this, particularly in summer. Increased streamflow in

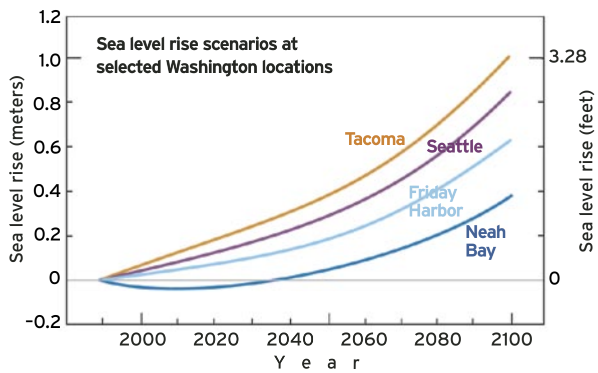

Figure 4.1.5: Mid-range future sea level rise scenarios for locations in Puget Sound. These sea level rise curves account for projected global sea level rise, the increased rate projected for the NE Pacific and the sinking of local land. The degree of sea level rise projected at Tacoma for 2050 (about 1.2 feet or 0.4 m) would not occur at Seattle until around 2060 and at Friday Harbor until around 2080. Depending on the various climate sensitivity factors and response option assumptions, the sea level rise scenarios could be 20 percent to nearly 200 percent of the mid-range scenario depicted. This figure is reprinted from Snover et al. 2005.

winter may also lead to an increase in nutrient levels, and decreased streamflow in summer may reduce them. Future human activity such as agricultural and home gardening practices will likely influence these possible responses. Finally, fecal coliform is also expected to increase due to climate change because increased sea level will increase leakage from septic systems and increased winter rains will increase stormwater runoff and the likelihood of combined sewer overflows. Future waste management practices will also likely influence this response.

- **Nearshore habitat will be lost.** Sea level rise, temperature change and changes in nutrient availability may lead to further declines in critical marsh and coastal wetland habitats.

- **Salt marshes will be at risk.** Projected changes in water temperature, water salinity, and soil salinity could change the mix of plant species in salt marshes and the viability of invertebrates that play a key role in the health of salt marsh systems.

- **Environmental stresses on salmon will increase.** Lower summer flows and warming waters is likely to negatively affect salmon that depend on rivers during the summer months. Increases in fall and winter peak flows will likely have serious negative impacts on Puget Sound Chinook salmon populations during critical spawning and egg incubation periods (see Box: Climate change and recovery planning for Chinook salmon in the Snohomish basin on opposite page).

- **Warmer water could put many species at risk.** Plankton, the foundation of Puget Sound's food web, are sensitive to temperature change. Temperature-driven shifts in plankton could ripple through the food web, changing the composition of invertebrates, fish and mammal communities.

- **Toxic marine algae and toxic shellfish events will likely increase.** The frequency and duration of Harmful Algal Blooms (HABs) in Puget Sound are likely to increase as a consequence of projected climate change. Many HAB species that affect the Puget Sound are seasonal and only impact recreational and commercial shellfish resources during summer and early fall. Expected increases in water temperature will increase the window for growth and encourage earlier and longer lasting blooms. Growth will be favored even further due to expected increases in nutrients. HABs of Paralytic Shellfish Poisoning (PSP) causing algae may also be influenced by expected changes in stratification. For example, increased stratification in winter may further contribute to earlier blooms, but decreased stratification in summer may offset expected increases due to warmer temperatures and increased nutrients. In contrast, HABs of Domoic Acid Poisoning (DAP) causing algae that are favored by a well-mixed water column may be further increased in summer.

- **The productivity and nature of biological resources could be drastically altered from our current system and perception.** While the consequences of climate impacts to Puget Sound's marine fishes and other biota are difficult to predict, there are some clear indications for how marine life will respond to a warming climate. With sustained and increasing ocean temperatures, cold-water species such as Pacific cod and walleye pollock may become unviable in local waters. Some marine bird populations may suffer with continued poor breeding success. While marine mammals may be able to cope with warmer temperatures, their foraging behavior and distributions may be altered in the future to less nutritious species or different feeding areas. With these potential negative consequences, there may be positive aspects such as a different suite of warmer water species like Pacific whiting, mackerels, sea basses, and tunas.

- **Changes in marine life will force changing management frameworks for marine fish and salmon fisheries, and for conducting recovery efforts through endangered and threatened species listings.** Fisheries management will require clever and responsive frameworks to take advantage of unpredictable surpluses in some species, and to limit or close fisheries during run failures. Decisions will need to be made whether to attempt to save species that may simply become unviable in warmer or highly varying climatic regimes.

Key information gaps and uncertainties

Specific characteristics of climate change: There are two primary sources of uncertainty for the climate system's response to human activities (of chief concern here are anthropogenic emissions of greenhouse gases and sulfate aerosols). First is the uncertainty about future emissions, and second is the uncertainty associated with the climate system's sensitivity to changing concentrations of greenhouse gases and aerosols. The former uncertainty is explored by considering a range of future emission scenarios, while the latter is explored by considering the output from a variety of climate models that demonstrate a range of climate sensitivities.

Regional ecosystem responses to climate change: While some aspects of climate change impacts on Puget Sound's ecosystems are well known, many are not, and there are likely to be many ecosystem surprises as a consequence of climate change.

Increasing acidification of marine waters due to the increased uptake and dissolution of CO_2 may have profound impacts on marine food-webs: Calcifying species of plankton like coccolithophores, foraminifera, and pteropods are expected to suffer serious negative impacts of increased ocean acidification. The negative impacts of increased acidity on plankton may lead to negative impacts on many other species—pteropods, for instance, are an important food-source for juvenile salmon, herring, and cod.

Municipal and industrial water supplies: The most important short time uncertainties related to regional water supplies likely are not related to climate change but to regional population growth and per capita water consumption in the future.

Surface winds, coastal upwelling and Puget Sound circulation: It is unclear how regional changes in surface winds will impact Puget Sound directly, and also indirectly via changes in coastal upwelling. The intensity and direction of surface winds over Puget Sound are directly important for driving mixing and advection. Upwelling winds along the coast are important, indirectly, because these winds mechanically pump cold, nutrient rich, subsurface water to the surface and lead to the development of highly productive subarctic habitat along the Pacific coast. Variations in coastal water properties are important for Puget Sound because these typically cold, salty, and nutrient rich waters flow into Puget Sound at depth. In a climate modeling study using a high-resolution (~40km grid) nested regional atmospheric model, Snyder et al. (2003) found a delayed timing for the onset of upwelling winds off the northern California and southern Oregon coasts, and an increase in the intensity of peak and late season upwelling winds, in response to a doubling of pre-industrial concentrations of atmospheric CO_2. Previous climate modeling experiments found no indication of systematic changes in the character of coastal upwelling as a consequence of global warming (Hsieh and Boer 1992; Mote and Mantua 2002).

Climate change and recovery planning for Chinook salmon in the Snohomish basin

Climate change will present significant challenges to recovering and maintaining salmonid populations in Puget Sound. Among the expected regional impacts of global warming are increasing air and stream temperatures, decreasing summer flows, and increasing peak winter flows (Figure 4.1.6). A recent study for the Snohomish River basin used a series of linked models of climate, land cover, hydrology, and salmon population dynamics to investigate the impacts of climate change on the effectiveness of proposed habitat restoration efforts designed to recover depleted chinook salmon populations (Battin et al. in review). The results of this study indicate a large, negative impact on freshwater salmon habitat due to climate change, primarily due to increases in peak water flows during egg incubation periods.

The analysis also asked whether watershed restoration and protection efforts planned in the Snohomish Basin are likely to make a difference in the face of future climate impacts. The modeling suggests that restoration actions and habitat protection can help to mitigate the negative effects of climate change, but that the habitat deterioration associated with climate change will make meeting salmon recovery targets more difficult. Just how difficult reaching salmon recovery will be is hard to predict, but it appears that planned watershed restoration will effectively 'buy time' for riverine systems and salmon, allowing more targeted climate strategies to be designed and implemented before it is too late for the fish. Because the negative impacts of climate change are projected to be most pronounced in relatively pristine high elevation portions of the Snohomish Basin where there are few opportunities for more restoration, climate change and habitat restoration together are projected to cause a spatial shift in salmon abundance in this basin. If climate warming continues as expected, salmon recovery strategies that enhance mid- and lower-elevation river habitats are likely to be more successful than those that rely heavily on salmon production from high-elevation, snowmelt-dominated basins.

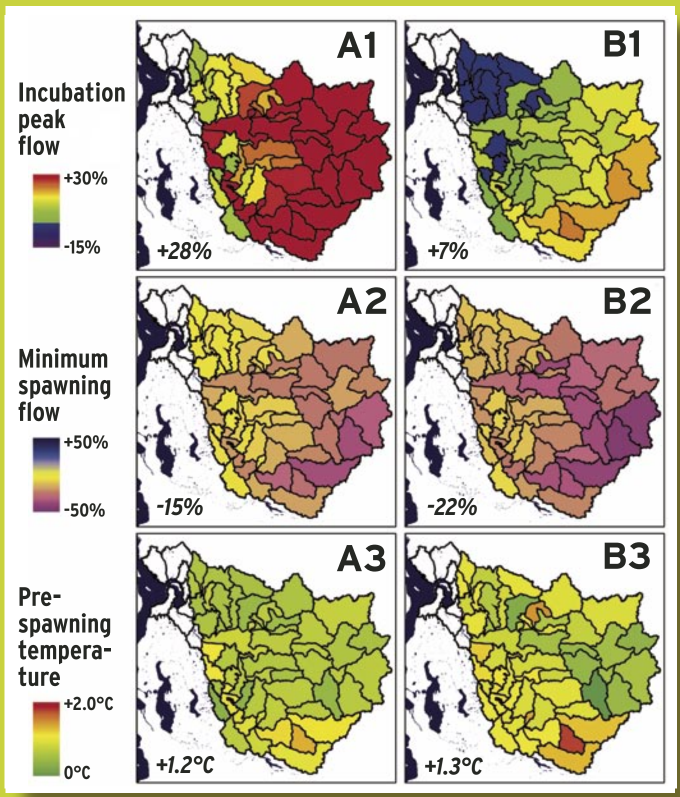

Figure 4.1.6: Climate impacts on three important hydrologic variables for salmon under two different climate scenarios. Row 1 shows percent change in incubation peak flow, Row 2 shows the percent change in minimum spawning flow, and Row 3 shows the change in pre-spawning temperature in degrees C. The number in the lower left corner of each panel indicates the basin-wide average impact. The panels in column A are based in the GFDL R30 modeled climate, column B is based on the HadCM3 modeled climate. This figure courtesy of Matthew Wiley, UW.

References

Battin, J., M.W. Wiley, M.H. Ruckelshaus, R.N. Palmer, E. Korb,, K.K. Bartz,, H. Imaki. (In review): Projected impacts of future climate change on salmon habitat restoration actions in a Puget Sound river

Carter, H.R., U.W. Ulrich, R.W. Lowe, M.S. Rodway, D.A. Manuwal, J.E. Takekawa, and J.L. Yee. 2001. Population trends of the common murre (Uria aalge californica). Pages 33-132 in D.A. Manuwal, H.R. Carter, T.S. Zimmerman, and D.L. Orthmeyer, editors. Biology and conservation of the common murre in California, Oregon, Washington, and British Columbia,Volume 1: Natural History and Population Trends. U.S. Geological Survey, Information and Technology Report USGS/BRD/ITR-2000-0012, Washington, D.C.

Hare, S.R., and N.J. Mantua. 2000. Empirical evidence for North Pacific regime shifts in 1977 and 1989. Progress in Oceanography 47:103-145

Hinch, S.G., M.C. Healey, R.E. Diewert, and M.A. Henderson. 1995. Climate change and ocean energetics of Fraser River sockeye (Oncorhynchus nerka). Climate Change and Northern Fish Populations. Canadian Special Pub. Fish. Aquat. Sci. 121: 439-445.

Hsieh, W.W. and G.J. Boer. 1992. Global climate change and ocean upwelling. Fisheries Oceanography 1(4):333-338

Hollowed, A.B., and W.S. Wooster. 1995. Decadal-scale variations in the eastern subarctic Pacific II. Resposnes of northeast Pacific fish stocks. Pages 373-385 in R.J. Beamish (ed) Climate Change and northern fish populations. Can. J. Fish. Aquat.Sci. 121

Mantua, N.J., S.R. Hare, Y. Zhang, J.M. Wallace, and R.C. Francis. 1997. A Pacific interdecadal climate oscillation with impacts on salmon production. Bull. American Meterological Society 78:1069-1079

Mote, P.W., A.K. Snover, L. Whitely Binder, A.F. Hamlet, and N.J. Mantua, 2005: Uncertain future: climate change and its effects on Puget Sound—foundation document. Climate Impacts Group, Center for Science in the Earth System, Joint Institute for the Study of the Atmosphere and Oceans, University of Washington. 37 p.

Mote, P.W., E.A. Parson, A.F. Hamlet, W.S. Keeton, D. Lettenmaier, N. Mantua, E.L. Miles, D.W. Peterson, D.L. Peterson, R. Slaughter, and Amy K. Snover 2003. Preparing for climatic change: the water, salmon, and forests of the Pacific Northwest. Climate Change 61:45-88
Schoener, A., and D.L. Fluharty. 1985. Biological anomalies off Washington in 1982-83 and other major El Nino periods. Pages 211-225. In: El Niño North, W.S. Wooster, ed. Washington Sea Grant, Seattle

Snover, A.K., P. W. Mote, L. Whitely Binder, A. F. Hamlet, and N. J. Mantua. 2005. Uncertain future: climate change and its effects on Puget Sound. Climate Impacts Group, Center for Science in the Earth System, Joint Institute for the Study of the Atmosphere and Oceans, University of Washington. 35 p.

Snyder, M.A., L.C. Sloan, N.S. Diffenbaugh, and J.L. Bell. 2003: Future climate change and upwelling in the California Current. Geophysical Research Letters Vol. 30, No. 15, 1823, doi:10.1029/2003GL017647

Tyler, A.V. 1995. Warmwater and cool-water stocks of Pacific cod (Gadus macrocephalus): a comparative study of reproductive biology and stock dynamics, Pages 537-545 385 in R.J. Beamish (ed) Climate change and northern fish populations. Can. J. Fish. Aquat.Sci. 121

Wiles, G.J. 2004. Washington State status report for the killer whale. Wash. Dept. Fish and Wildlife, Olympia, WA 106 p.

Wilson, U.W. 1991. Response of three seabird species to El Niño events and other warm water episodes on the Washington coast, 1979-1990. Condor 93:853-858

4.2 The future of Puget Sound habitats

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The Puget Sound region encompasses an enormous variety of habitats and species that not only use those habitats, but also create habitats for other species (see sections 3.5 and 3.6). However, these habitats are not static, but rather, have experienced multiple changes in response to natural variation in climate and other natural processes, local perturbations, and, of course, human actions. These human actions have not been uniform across the landscape, however, but have tended to be concentrated in particular areas. Shorelines, and floodplains, for instance, have been disproportionately affected by human activities, as have saltwater marshes, while alpine areas have received much less human impact. In this paper, we describe the changes in the distribution of Puget Sound habitats and the relatively recent activities that led to those changes. We then discuss an approach to habitat conservation in the Puget Sound region, focusing on protection of high quality habitats and restoration of key areas. Finally, we conclude with information needs that will ultimately support effective habitat conservation, and that should improve our ability to gain the range of ecosystem services from the landscape to support healthy human, wildlife and fish populations.

The History of Habitat Change in the Puget Sound Eosystem

Freshwater, marine, nearshore and upland habitats throughout the greater Puget Sound region have been affected by a variety of economic activities, including agriculture, heavy industry, timber harvest, and the development of sea ports and residential property. The changes brought by these activities have affected, or have the potential to affect dramatically the physical structure of those habitats, the animal and plant communities found there, and the human uses of the region. Their restoration and protection will be key to maintain and support the many uses and benefits we derive from the region.

Washington State has approximately 5,000 km of marine shoreline, of which about 4,000 km border Puget Sound (PSAT 2005). The development of these shorelines began in the mid 1850s as shoreline vegetation was cleared to facilitate the movement of materials between upslope areas and Puget Sound, which served as the main shipping highway through which goods and services moved in and out of the region (Chasan 1981). Since the 1850s, Puget Sound shorelines have been transformed from mostly forested habitats to areas increasingly used by humans.

Development in the nearshore environment, i.e., the area from the top of shoreline bluffs to the depth where light no longer supports benthic plant growth, includes two broad categories: shoreline armoring and construction of overwater structures. Shoreline armoring involves the placement of structures (e.g., bulkheads, seawalls, revetments, groins, and jetties) typically in an attempt to prevent shoreline erosion or to control the movement of beach sediments. The construction of overwater structures such as docks and piers can limit the light available for eelgrass and other aquatic plants. This, in turn, can affect both the substrate and the animal communities in that area. The shallow, nearshore habitats in which this development often occurs are naturally limited in Puget Sound, and they are the main spawning and rearing areas for key forage fish species (herring, surf smelt, and sandlance) that are important food web members.

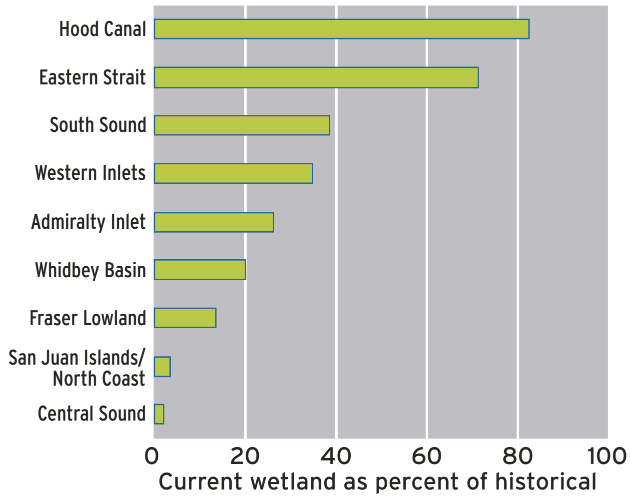


Figure 4.2.1: Percent of tidal wetlands lost by sub-basin (adapted from Collins and Sheikh 2005).

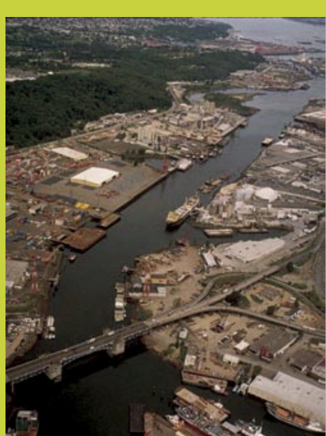
Puget Sound river estuaries, small embayments, and river floodplains have also been dramatically transformed. River deltas provide important and diverse habitats for salmon and a variety of other fishes and birds. Naturally functioning floodplains create an array of unique habitats that historically supported all salmon species, and loss of floodplain habitats has been a major cause of lost salmon production from Puget Sound Rivers. Most delta marsh habitats have been converted to agricultural and industrial uses, with the most intensive modifications focused in South Sound, main basin, and Whidbey basin (Figure 4.2.1: Percent losses). Between the late 1800s and the mid 1900s, several major estuaries of central Puget Sound were transformed into port facilities. The creation of ports typically involved dredging navigational channels, filling shallow tidally influenced habitats such as marshes and flats, and armoring the shoreline with dikes, levees, bulkheads, and other structures (Box 4.2.1: Duwamish changes). At the expense of salmon and other riparian-associated species, floodplains now support a substantial agricultural economy as well as industrial and commercial endeavors. Such tradeoffs have contributed to declines in salmon populations and the listing of Chinook and chum salmon under the Endangered Species Act.

Headwater and high-elevation tributary habitats in the Puget Sound region have been less severely altered than low-elevation floodplains and deltas, in part because many of these areas are protected in Wilderness Areas and National Parks. Mid-elevation rivers are typically located in industrial forest lands, where habitats are altered by forestry activities, but generally the habitat changes are less dramatic than in agricultural or urban areas. Over the last 30 years, 2.3 million acres of Washington forest lands have been converted to other uses, and in the last 50 years more than two-thirds of old growth forest habitat, much of it in the Puget Sound region, has been lost (Washington DNR, 1998). Little is known about changes in open-water and deepwater habitats in Puget Sound. The installation of telecommunication cables, power cables, and fuel pipelines throughout Puget Sound has disturbed deep habitats to an unknown degree, although the magnitude of such disturbance is likely small on an ecosystem scale. Overall, there has been a tremendous degree of alteration to nearly all of the broad habitat types in the Puget Sound region:

- **Shorelines:** Approximately 30% of the Puget Sound shoreline has been modified by humans, most intensely in the heavily populated regions of Puget Sound. Nearly 52% of the central Puget Sound and about 35% of the shorelines of Whidbey Island, Hood Canal and South Puget Sound have been modified (Berry 2000). Nearly 80% of the shoreline from Mukilteo to Tacoma has been altered, largely due to the seawall armoring associated with the Burlington Northern Railroad tracks.

- **Deltas:** Low elevation marsh and flats were isolated by systems of levees and dikes to prevent inundation by flooding river or marine tidal waters. Today, more than 80% of all tidal wetlands have been converted to human dominated land uses (Collins and Sheikh 2005).
- **Floodplains:** Floodplain habitats historically supported diverse habitat types and salmon species in all of Puget Sound's rivers. Extent and diversity of floodplain habitats has been dramatically reduced, mainly by levees that isolate the river from its floodplain (Shared Strategy 2005).

- **Low elevation terrestrial areas:** Most of the low elevation vegetation communities (coniferous forests and grassland-savanna) of Puget Sound have been converted to urban or agricultural uses. Remaining



Box 4.2.1:

Duwamish estuary

The Duwamish Estuary represents the one of the most extreme cases of port development. The lower 9.3 miles of meandering Duwamish River was straightened and shortened to 5.3 miles. Nearly all of the lower 11 miles of tidally influenced river/estuary were modified by dikes, levees and revetments and all tidal swamps, 98% each of tidal forests, marshes, shallows and flats, and 80% of the riparian shoreline have been lost to human development (Blomberg et al., 1988).

forestlands at low elevation are typically managed intensively on 40 –70 year rotations.

- **Freshwater resources:** Water impoundments (dams and their reservoirs) and water withdrawals have dramatically altered instream hydrologic processes that create and maintain riverine and riparian habitat. A total of 21 major dams occur within the anadromous fish zone of rivers and streams that drain into Puget Sound. Many Puget Sound streams also have smaller water withdrawal or impoundment structures–some of which still impede migrating fish.

The Future of Puget Sound Habitats

The future of Puget Sound's habitats depends first and foremost on choices made by its people and how we evaluate the many tradeoffs among the benefits we gain from the widely varying habitats in the region. Many choices remain to be made—and particular care is needed to evaluate tradeoffs between services that support key species in Puget Sound and services that more directly support the human population. While definitive predictions about much of the future of Puget Sound habitats are not possible, we can be certain of two main future pressures on Puget Sound habitats, and we can predict how they might change Puget Sound habitats if current trends continue. First, development and conversion of more natural areas will continue as the population increases. If current development and land use approaches are maintained, population growth will reduce habitat availability and diversity, especially along marine and freshwaters, as well as further fragment and thus reduce quality of remaining undisturbed upland areas as habitat for fish and wildlife. This will have a wide range of impacts on the quality of habitats and the range of species that can be supported (see Section 4.4: Alberti et al.) Second, climate change is likely to reduce the amount and impair the quality and availability of habitats for many species. Global warming is occurring so quickly that many plants may have difficulty adapting to changing conditions. Importantly, many of these plant species comprise habitat for other species. Relatively mobile species may be able to move to higher and colder elevations or to more northern (and colder) latitudes. However, less mobile organisms may be trapped where they currently exist, and those that are on the southern edge of their range may be lost from the Puget Sound region. A few of the predicted future climate impacts are, increases in water temperature, sea level and changes in hydrological processes, all with concomitant changes in habitat forming-processes (see Section 4.1: Mantua et al.).

These two pressures—climate change and human population growth—pose distinctly different challenges for managing the future of Puget Sound habitats. Humans do have considerable control over modes of development and the magnitude and distribution of impact that land uses will have on particular habitats. Managers can thus choose development pathways that conserve and restore Puget Sound's habitats.

However, we have virtually no local control over future global climate and the habitat changes it will cause, putting a premium on actions that conserve Puget Sound habitats despite the influence of climate change. A habitat conservation strategy that is robust to these pressures involves identifying habitat protection and restoration strategies that are adaptable to unexpected climate or land use effects.

Strategies that include the following elements will be more likely to maintain and improve the diversity and quality of habitats available in the Puget Sound region:

1. **A clear description of historical and current changes in the Puget Sound ecosystem.** A clear understanding of the tradeoffs that have led to the current plight of Puget Sound will enable stakeholders and policy leaders to make better decisions that lead to protection and restoration of the ecosystem while allowing for economic and population growth. Although we cannot yet clearly identify which habitat losses have had the greatest impacts on ecosystem goods and services, we can clearly identify which habitat losses have occurred, where they have occurred, and what the causes of loss have been. (See, for example, Box 1). Unfortunately, a comprehensive analysis of habitat loss has not been conducted throughout the region. Completing these analyses and synthesizing the results into a comprehensive narrative describing how human actions and natural factors have altered Puget Sound habitats is a critical first step in setting a vision for the future of Puget Sound.

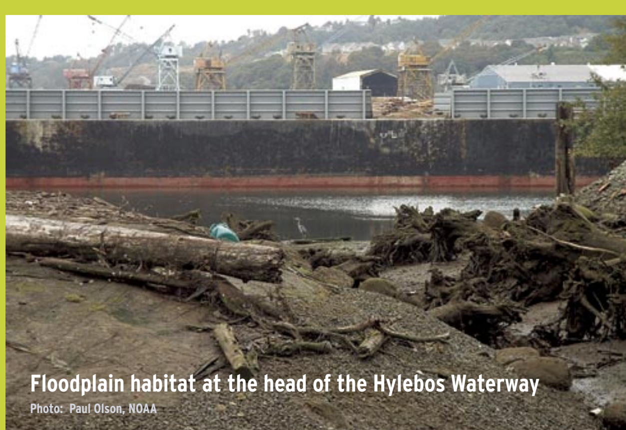
2. **A robust strategy for habitat protection, targeting critical habitat types and highly-functioning habitats.** Maintaining currently high quality habitats is a more effective and less-costly alternative than restoring already damaged systems. However, continued population growth will reduce habitat abundance and diversity unless we have effective strategies for protecting remaining habitats. Habitat protection efforts that emphasize saving rare and threatened habitats, especially those types that were once abundant and supported key species such as floodplain habitats, tidal marshes, and eelgrass beds) will increase the likelihood that such important habitat elements will contribute to robust ecosystem functioning. Some efforts to conduct a categorization of habitat types and identify priorities for protection have been initiated, for example, by The Nature Conservancy.
   Protection of existing functional habitats will likely

Box 4.2.2

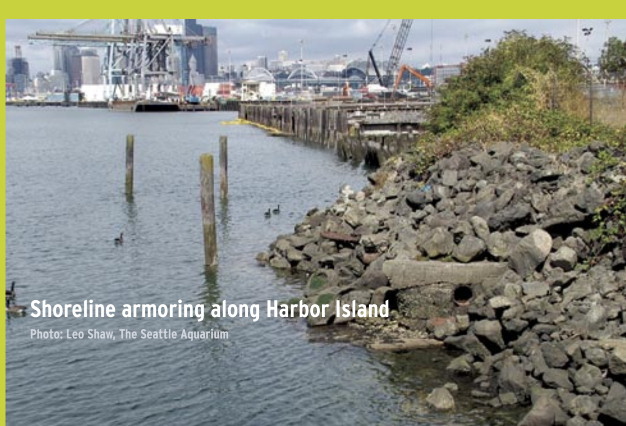
Habitat protection

The decline of Puget Sound habitats continues today as development pressures increase, intensifying the need for an aggressive strategy to protect important and functioning Puget Sound habitats. Unless protective measures focus on rare and threatened habitat types, loss of these habitats today will ultimately lead to more expensive habitat restoration efforts in the future. Key threatened and rare habitat types needing immediate protection include intact riparian habitats along rivers and shorelines (top photo), floodplain habitats in urbanizing areas (middle photo), and nearshore habitats threatened by development and armoring (bottom photo). Mechanisms of habitat protection include land acquisition, purchase of conservation easements, and regulatory protections. Protection of habitat promotes ecosystem function more fully than restoration or mitigation (NRC, 1996), thus a strategy utilizing land acquisition is considered to provide more certainty in the long term than regulatory systems that are subject to changing statutes and uncertain enforcement effort.

Riparian shoreline in Pierce County
Photo: Randy Carman, WDFW



Floodplain habitat at the head of the Hylebos Waterway
Photo: Paul Olson, NOAA



Shoreline armoring along Harbor Island
Photo: Leo Shaw, The Seattle Aquarium

require that urban and suburban development strategies be changed, and measures to ensure that the chemical quality of the water, sediments, and food does not negate the usefulness of these habitats be implemented. Innovative, cross-jurisdictional approaches have the potential to increase opportunities for habitat protection. For example, some of the most important existing areas for conservation of terrestrial biological diversity in urbanizing environments across the US are found on military properties, simply because these areas have been less intensively developed than the surrounding land. Because of the gains in efficiency and effectiveness for habitat conservation, protection measures such as acquisition, conservation easement programs, regulation, and incentives targeting relatively undisturbed habitats would be the highest priority in the near term. (Box 4.2.2).

3. **A process-based approach to habitat restoration.** The current condition of the Puget Sound ecosystem, with its species at risk and declining habitat quality, makes it clear that some restoration beyond the status quo will be necessary to achieve a healthy range of habitat types and quality. Restoration focusing on allowing the natural system to form and sustain habitats is the most sustainable and cost-effective approach to habitat restoration (see Box 4.2.3). Restoration of habitat-forming processes focuses on actions that restore critical functions such as river and shoreline processes (e.g., sediment supply and transport, nutrient and wood supply from stream-side forests, reduction of contaminant sources), and connectivity of upland habitat patches. Such restoration efforts that also account for important biological needs—such as the suite of habitats required by salmon for spawning and rearing in rivers, streams and lakes to transitional habitats at river deltas, and important marine rearing areas—will meet broader ecosystem needs as well.

   Approaches to natural resource management that address ecosystem needs and functions as well as human needs are benefited by shared and clearly stated scientific and policy or social goals. These shared goals will help policy makers and scientists work together to identify the quantity and types of functioning habitats needed to support the growing demands for land and water as human density increases as well as healthy ecosystems. Importantly, functional marine ecosystems are dynamic, and thus it may be impossible to restore the ecosystem to a particular state that can be maintained over long periods. A reasonable goal, therefore, may be to restore ecosystem processes that contribute to a functional, resilient and ultimately healthy Puget Sound ecosystem. In working toward goals, it is important also to recognize that habitat protection or restoration is not always an "all or nothing" proposition. Industrial forestlands, and to a lesser extent agricultural lands, provide important ecosystem services in the form of wood and food products, recreational opportunities, fish and wildlife habitat, and support for locally based economies.

Key Uncertainties and Information Gaps

Achieving these multiple goals for habitats and lands, however, will require approaches that allow us to consider and, when possible, resolve some key information gaps.

- Unknown and unforeseeable policy and social choices make it. difficult to project the Puget Sound habitat characteristics into the future. However, we know enough to evaluate the likely outcomes of alternative futures. That is, while we cannot know what policy makers and citizens will choose to do in the future, we can describe the habitat consequences of several alternative futures based on existing knowledge and models. A good example of such an analysis is the Willamette Alternative Futures project, which evaluated the effect of three possible future scenarios on a variety of aquatic habitat, wildlife, and fish community indicators, as well on the future of agricultural practices and water supplies (Ecological Applications, 2004, volume 14, issue 2. See also Section 4.6, Cullen et al., for further discussion of the methods involved in scenario analysis).

- The outcomes of many restoration actions are not well-characterized. Process-based restoration strategies may be more likely to succeed than single-species restoration programs, and successes are likely to be more durable. However, natural variability and directional changes such as population growth and climate change will influence the outcome of restoration in ways that are not fully predictable. Consequently, a moderate amount of uncertainty exists regarding the outcome of restoration activities. Restoration outcomes will fluctuate naturally, and resulting habitats will be modified by changes associated with increasing human population density, biological invasion, and climate change. For example climate-related changes in hydrology, sea level, storminess, temperature, and pH will influence the physical processes and biological communities that are the subject of restoration. In addition, the ways in which the range and quantity of additional ecosystem services that working lands (e.g. agricultural areas) can provide while still providing more direct human benefits is an area that is ripe for additional scientific investigation.

Box 4.2.3

Restoring habitat-forming processes

Process-based restoration differs from traditional habitat restoration in that it restores processes that form and sustain habitats (e.g., sediment supply, nutrient supply, or river dynamics), rather than attempting to build specific habitat types (e.g., a rearing pond or a beach habitat). It relies on our understanding that freshwater and marine habitats are created and sustained by natural processes such as storms, flooding, erosion, and functions of shoreline forests, and that these processes are required to maintain abundant and diverse habitats through time. Without the natural functioning of these processes, key habitat types disappear and species that depend on those habitats decline in abundance. Thus, by restoring these habitat-forming processes, we can cost-effectively restore the diverse habitats required to support recovery of the Puget Sound ecosystem. Within Puget Sound, process-based restoration is rapidly becoming standard practice for restoration of riverine, shoreline, and marine habitats. Reduction of sediment supply and restoration of streamside forests allow recovery of freshwater spawning and rearing habitats for salmon, and delta habitats are restored by removing dikes and allowing floods and tides to restore and maintain tidal marsh habitats. At Seahurst Park in the city of Burien, reconnecting the bluff-to-beach sediment supply will restore nearshore sediment dynamics, and allow recovery of critical beach habitats (lower photo).

Lockheed Superfund site on the West Waterway of the lower Duwamish River
Photo: Randy Carman, WDFD

Seahurst Park restoration site
Photo: WA ECY Shoreline Web

- Processes operating in deep-water habitats are not well-understood. On-going and proposed activities associated with increased development, such as shoreline modification, wastewater discharge, and energy generation, could potentially have substantial impacts on deepwater habitats through changes in sediment supply, toxic contamination and interruption of marine circulation. Changes in sediment supply are known to affect deepwater habitats, including changes in benthic communities and sediment contaminant concentrations associated with abnormally wet or dry years (Partridge et al., 2005). The magnitude of possible changes in deep water habitats due to human-induced alterations in sediment supply relative to natural changes is unknown. Most treated municipal wastewater is intentionally discharged to open water/deepwater habitats in Puget Sound, and those wastewaters are known to contain trace amounts of pharmaceuticals, personal care products, and other so-called emerging contaminants that may compromise the quality of local habitats. In addition, a number of sites in Puget Sound, including the Tacoma Narrows, Admiralty Inlet and channels in the San Juan Islands, have been identified as favorable prospects for tidal in-stream power production. The potential impacts of such projects to open water/deepwater habitats are largely unknown, as are their effects on habitat-forming processes such as tidal currents and sediment dynamics.

References

Berry, H. 2000. Shoreline modification in Puget Sound: Washington State Department of Natural Resources. Olympia, Washington

Crawford, R.C. and H. Hall. 1997. Changes in the south Puget prairie landscape. In P. V. Dunn and K. Ewing (Editors). Ecology and conservation of the South Puget Sound prairie landscape. The Nature Conservancy, Seattle, WA

Blomberg, G., C. Simenstad, and P. Hickey. 1988. Changes in Duwamish River estuary habitat over the past 125 years. Page 437-454 In Proceedings of the First Annual Meeting on Puget Sound Research, Volume II. Puget Sound Water Quality Authority Seattle, Washington

Chasan, D.J. 1981. The water link: A history of Puget Sound as a resource. University of Washington Press. Seattle, WA

Collins, B.D. and A.J. Sheikh. 2005. Historical reconstruction, classification, and change analysis of Puget Sound tidal marshes. Project completion report to Washington Dept. of Natural Resources, Aquatic Resources Division. Olympia, WA

McDonald K., B. Simpson, D. Paulsen, J. Cox, and J. Gendron. 1994. Shoreline armoring effects on the physical coastal processes in Puget Sound, Washington. Coastal Erosion Management Studies Volume 5. Shorelands and Coastal Zone Management Program, Washington Department of Ecology. Olympia, WA

National Research Council. 1996. Upstream: Salmon and society in the Pacific Northwest. National Academies Press

Partridge V., K. Welch, S. Aasen, and M. Dutch. 2005, Temporal monitoring of Puget Sound sediments: Results of the Puget Sound Ambient Monitoring Program, 1989-2000. Washington Department of Ecology, Publication Number 05-03-016

Puget Sound Action Team. 2005. Puget Sound Action Team website: www.psat.wa.gov/About_Sound/AboutPS.htm

Washington Department of Natural Resources. 1998. Our Changing Nature: Natural Resource Trends in Washington State. Washington Department of Natural Resources, Olympia, WA

Wilhere, G.F., M.J. Linders, and B.L. Consentino. In press. Defining alternative futures and projecting their effects on the spatial distribution of wildlife habitats (Landscape and Urban Planning)

4.3 Species, Food Webs, and Human Impacts on Marine Ecosystems

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At the core of the Puget Sound ecosystem are upland, freshwater, estuarine, and marine food webs—where interactions among species dictate their numbers and distribution. As discussed in Sections 1.1 and 3.6, many species in Puget Sound are showing signs of stress. These imperiled species include our regional icons—Pacific salmon and orca whales—and less charismatic representatives, such as the large-awned sedge, pinto abalone, and the Olympic torrent salamander. The species that help define what "Puget Sound" means to us could be lost, unless we explicitly recognize in our management decisions that the fates of these species are dependent on many other, less visible species in food webs. In this short paper, we use stories from other ecosystems to illustrate why it is important to consider species interactions when managing complex marine ecosystems. A common feature of these stories is that in each case, human actions led to unintended consequences for focal species--and human uses of them–because of changes in their food webs. We close by raising examples where management of Puget Sound species would be wise to consider their broader food web.

Fundamental Concepts in Species and Food Webs

All populations are governed by two basic processes: the rate of successful reproduction and the rate of deaths. Fluctuations in these two processes give rise to the dynamic behavior of populations. To successfully reproduce, animals must mate, and offspring must find necessary conditions to grow and avoid predators. It is this latter process that is thought to be the most important one causing changes in marine populations, because the small offspring that are typical of marine animals require a very particular set of conditions if they are to survive to adulthood. These conditions include availability of the right kinds of food, the right kinds of habitats to occupy, and the ability to avoid being eaten by others. For most marine species, the chances that any single individual will survive this critical time period are very small. For instance, a Pacific cod in Puget Sound may release hundreds of thousands of eggs at a time, with the hope that a tiny fraction of these will survive. In some years, perhaps none of the offspring will survive because the proper conditions are not present. Other years might be "boom years" where the environmental conditions are optimized to promote growth and survival of these vulnerable creatures. Many animals and plants have evolved to cope with this "boom or bust" cycle by having long lives and producing many offspring for many years in the hope that one or two years will result in successful reproduction.

The processes that dictate survival through these critical early stages are influenced by a host of environmental and ecological factors. For instance, most marine species in Puget Sound and worldwide have a life cycle that includes larvae that have limited swimming abilities and whose movements are therefore determined by water currents. Because these water currents are determined by oceanographic processes, there is a tight coupling between the physical environment and the ability of these small larvae to be transported to favorable habitats. Because species exist within the Puget Sound ecosystem filled with several other species, competition, predation, and disease can all affect their ability to survive and reproduce. Competition occurs when two or more individuals require the same resource that is in short supply. Competition may occur between members of the same species or among individuals that are different species. For instance, if two species in Puget Sound both require the same prey to survive (e.g., salmon and spiny dogfish both eat herring), the presence or increased abundance of one of those predatory species could lower the resources available to the other and thereby lower survival of the less abundant species. Predation is a ubiquitous force for early life stages, because individuals are small and easily consumed by a wide range of predators (Bax 1998). It follows then that a high abundance of predators can markedly affect the survival of individuals in these early life stages. Of course, the abundances of these potential competitors and predators are dictated by shared or separate processes operating on their own offspring. Thus, connecting all of the species that might directly or indirectly alter the population dynamics of another species quickly leads to a complex web of interactions (see Figure 3-17, Puget Sound food web). It is this recognition that has lead to an emerging view that management of marine resources needs to focus on more than just one species at a time, and consider the entire interaction web and ecosystem of which that species is a part (Pikitch et al. 2004). This is one of the central tenets of ecosystem-based management.

Human activity affects the survival rates of marine species in Puget Sound in many ways—through direct harvest, removal or alteration of habitat, deposition of contaminants, and alterations to basic ecosystem processes on local, regional, and global scales. The targeted removal of marine life through fishing is an obvious action affecting fish, shellfish and marine mammal populations. Once thought inexhaustible, some of the world's fish stocks have been decimated by overfishing (Pew Oceans Commission 2003). Because fishing often targets the larger-bodied species in a food web (e.g., lingcod, rockfish, and Chinook salmon in Puget Sound) and because these organisms tend to feed on species higher in the food web, the depletion of fished stocks can cause cascading effects throughout the entire community. Marine populations also are impacted by the direct alteration of critical habitats. In some cases alteration is intentional: development of shoreline property often involves purposeful manipulation of the physical environment to facilitate boat navigation and other human uses. Other times, habitat alteration is unintentional: use of high pressure hoses to harvest geoduck clams, for example, disrupts the benthic physical and biological habitat where these clams live (Goodwin 1978). The basic ecosystem processes supporting marine species can also be greatly impacted by human activities around estuaries and coastal areas. Human waste, fish farming and agricultural run-off may enrich the concentration of limiting nutrients, enhancing rates of plant production and changing the composition of those species (Carpenter et al. 1998). Because this production fuels the entire food web, alteration of these basic rates can have widespread impacts on the species that comprise the food web (see Box 3-3, Dissolved oxygen and water quality in Hood Canal and South Puget Sound). Contaminants can enter the food web and persist there for many years, potentially affecting species' basic rates of growth, survivorship, and reproduction (Landahl et al. 1997). Finally, on a global scale, human-caused climate warming is liable to induce widespread changes in marine ecosystems (see Mantua et al. Section 4.1).

Case Studies

Although human impacts to particular species and their habitats are fairly well documented in many cases, the ways in which human actions have re-shaped the food web overall is not well understood. Like those of many coastal and estuarine ecosystems, the basic structure of the food web of Puget Sound, and human alterations to it, are not well known. The following examples illustrate the types of profound changes in species abundances and food webs that result from human activity, and therefore serve as potent reminders of the importance of considering food webs when managing human use of Puget Sound.

Oysters in Chesapeake Bay

The Chesapeake Bay once supported a thriving population of oysters, which were so abundant that they were capable of filtering all of the water of the bay within 3 days. This intense filtering capacity imposed a strong control on the small plants that float in the water column (phytoplankton) and thereby actively regulated the water clarity. Because the water was kept relatively free of phytoplankton, light could penetrate to the bottom of the bay and nourish the plants attached to the bottom surface. By the end of the 1800's, mechanical methods to harvest oysters had been developed, and the oyster population was severely depleted by the beginning of the 20^{th} century.

The impact of widespread oyster removal on the Chesapeake Bay food web was profound. Because the surviving oysters were too few to filter the water, the phytoplankton began to flourish at the expense of plants such as eelgrass that were attached to the seabed. At the same time, agriculture in the Chesapeake Bay watershed intensified and increased the delivery of plant nutrients. Together, fishing and land-use caused a profound shift from a food web that was fueled largely by production along the seabed, to one that was fueled by production in the water column(McCay et al. 2003). Excessive phytoplankton production created an enormous increase in the deposition of organic matter to the seafloor, which when consumed by bacteria, created widespread oxygen depletion. Many forms of marine life such as dolphins, otters, turtles and sharks, once commonly sighted in Chesapeake Bay, are now rarely present (Jackson et al. 2001). These effects have continued to the present day, where the persistent low oxygen condition has stymied efforts to restore oyster populations (Mann 2000).

Atlantic Cod in the Northern Atlantic Ocean

Atlantic cod in the N. Atlantic has long been an important fishery. These populations supported fishing for centuries, but the advent of modern fishing gear and the growth of fishing fleets in the 1980's led to collapses of most Atlantic cod stocks by the mid 1990's. Cod prey responded in nearly all locations by surges in productivity. For example, throughout the North Atlantic, the collapse of cod stocks was followed by a rapid increase in northern prawn populations (Worm and Myers 2003). In the Baltic Sea, a small herring-like species (sprat) became 5-fold more abundant following the collapse of the cod stock (Essington and Hansson 2004). In both of these cases, fisheries have now switched to targeting the prey species that cod used to eat. These effects are also manifest in nearshore kelp ecosystems in the Gulf of Maine: the release of predation pressure by cod on sea urchins allowed the latter to proliferate, and the urchins' intense grazing activities nearly eliminated kelp forests (Steneck et al. 2004). These kelp forests, in turn, supported an enormous diversity of fishes and invertebrates, which suffered from the kelp forests' demise. Relatively recently, humans began directing their harvest on the sea urchins, and in many locations decimated them. Kelp forests have begun to recover as a result, but the entire community of bottom-dwelling invertebrates has been drastically, and potentially irreversibly altered through the proliferation and then collapse of sea urchin populations. Taken together, these experiences with Atlantic cod illustrate the far reaching impacts of overfishing on ecosystems.

Marine Diseases in Australia /New Zealand

Human activities in the marine and nearshore environments can result in massive and rapid disease outbreaks (Harvell et al. 2004; Lafferty et al. 2004). These disease outbreaks, caused by a variety of small parasitic organisms that infect larger animals, are nearly impossible to contain once they occur. For example, pilchards (a type of sardine) in South Australia and New Zealand suffered massive mortality from a rapidly spreading virus (Gaughan et al. 2000). Masses of dead pilchards were found floating on the surface at sea, washed up on beaches, and in the stomachs of benthic fishes. Although the origin of this virus is unknown, the most likely source is the frozen fish that were imported to feed tuna in nearby net pen operations in South Australia. Because pilchards are an important prey item for many fishes, birds and marine mammals, the ecological effects of this disease outbreak were profound. Shortly after the disease outbreak, local penguin populations that feed on pilchards vanished and other predators on pilchard were forced to switch their feeding to other prey items (Chiaradia et al. 2003; Bunce 2004; Taylor and Roe 2004).

General Conclusions

At least three lessons can be derived from these case studies about human impacts on marine food webs. The first is that food webs can undergo rapid transformation in response to human activity. Second, these transformations are often surprising, because the ecological roles of species are often not fully revealed until they have been severely depleted or changed. Thus, our knowledge of species and food webs has derived from a body of work that resembles the practice of human physiology in the nineteenth century, where the function of various human organs was inferred from cases where they were removed from patients. Third, there are important limits to our ability to predict the outcome of human activity on food webs. There are so few "degrees of separation" between species in marine food webs that it is difficult to predict all of the indirect effects that might follow from a human activity that affects any one species. Moreover, the ecological roles of species are not fixed in time and space; a species that serves as a prey species in some conditions might be the predator in others.

Specific Considerations for Puget Sound

Humans have lived in and affected the Puget Sound ecosystem for millenia, yet we have little sense of how our historical or recent activities have shaped the species and food web connections that we presently see. We can, however, begin examining the changes in human demands and ecological conditions in Puget Sound to identify some questions about the future for the Puget Sound food web. Below we list five examples of these questions which are by no means exhaustive but provide a sense of the nature and scope of concerns that we face to ensure effective policy decisions for Puget Sound.

- Harbor seals, once depleted in Puget Sound, have apparently recovered and have reached a stable abundance in many areas. Seals and their relatives the sea lions eat a wide variety of fishes, especially codfishes and herring that once were the basis for thriving fisheries in Puget Sound. These marine mammals may be limiting depressed populations of salmon, especially returning salmon concentrated at river mouths or human-caused restrictions such as the Ballard Locks.

- Pacific cod and rockfish populations have been depleted by overfishing and other factors, but apparently have failed to recover despite large reductions in fishing on them. Might there be a shift in the food web structure that is preventing their recovery? Are recent increases in crab abundance due in part to a release from predation by cod and dwindling numbers of other predators (such as spiny dogfish)? In the few marine reserves in Puget Sound, lingcod have become the dominant fish species and may be limiting the recovery of their rockfish prey in the protected areas. Would an increase in harvest of lingcod promote the recovery of rockfish?

- Presently, the most dominant single fish species in Puget Sound is the ratfish, a medium-sized relative of sharks that feeds primarily on small clams and other small organisms found in the deep seabed. Have ratfish always been so dominant, or has human activity and resulting food web impacts facilitated increases in their populations? Might this large population be consuming and diverting energy that would otherwise support other members of the food web? Or, do these species and others like dogfish hold other species in check to form a balanced and stable ecosystem?

- Dungeness crab is an important species in the Puget Sound food web, occupying habitats ranging from nearshore shallows to the deepest regions. These crabs also have multiple roles in the food web, serving as a predator on small juvenile fishes, bottom invertebrates and other crabs, and as prey for larger-bodied fishes. At the same time, these populations support a lucrative fishery. How this harvest impacts other members of the food web is unknown.

- Growing evidence in Puget Sound and other estuaries suggests that hardened shorelines have reduced the quality of nearshore habitats for plants and animals. Forage fish appear to be among the food web members that are susceptible to shoreline modifications. For example, surf smelt eggs spawned on beaches in Puget Sound that were modified by development had half the survival rates of smelt eggs laid on natural beaches (Rice et al. 2005). Will increased shoreline development in the future result in depressed populations of surf smelt predators, such as salmon and fish-eating birds?

We know that the Puget Sound food web is not immune to the types of changes experienced elsewhere in the world, and that human demands on this ecosystem are only going to increase over the foreseeable future. What then are the policy and scientific priorities that will ensure prudent decisions over the next twenty years that avoid the catastrophic, unexpected and irreversible ecological shifts that have occurred elsewhere? Scientifically, we need to continue and enhance ongoing monitoring on key species in this food web, encourage new initiatives to better understand linkages between species and their dependence on habitat, and also look backwards in time to better understand how the Puget Sound food web has changed historically in response to human activities. More effective policy decisions regarding fishing, contaminants, land use, and nearshore habitat will follow from this improved understanding of the Puget Sound food web, but science will be unable to completely eliminate uncertainty. If policy makers and scientists can work closely to identify some of these key uncertainties and explore the risks associated with them, we can facilitate policy decisions that are more robust to uncertainties about the direct and indirect effects of human activities on the Puget Sound food web.

Harbor seal populations, formerly depleted, have rebounded and may be limiting recovery of other depleted species such as salmon.

Pacific cod, once abundant, is now quite rare in Puget Sound. It is unclear whether the decline is due to climate, fishing, or other human activities.

This strange-looking creature, the ratfish, is the most abundant fish in all of Puget Sound. Has this always been the case, or is this a recent phenomena? Researchers are trying to answer these questions.

Dungeness crab are the focus of a lucrative fishery, but they also occupy an important and middle niche in the food web as both predators and prey.

References

Bax, N. J. 1998. The significance and prediction of predation in marine fisheries. ICES J. Mar. Sci. 55: 997-1030

Bunce, A. 2004. Do dietary changes of Australasian gannets (Morus serrator) reflect variability in pelagic fish stocks? Wildlife Research 31: 383-387

Carpenter, S.R., N.F. Caraco, D.L. Correll, R.W. Howarth, A.N. Sharpley, and V.H. Smith. 1998. Nonpoint pollution of surface waters with phosphorus and nitrogen. Ecol. Appl. 8: 559-568

Chiaradia, A., A. Costalunga, and K. Kerry. 2003. The diet of Little Penguins (Eudyptula minor) at Phillip Island, Victoria, in the absence of a major prey - Pilchard (Sardinops sagax). Emu 103: 43-48

Essington, T.E. and S. Hansson. 2004. Predator-dependent functional response and interaction strengths in a natural food web. Can. J. Fish. Aquat. Sci. 61: 2227-2236

Gaughan, D.J., R.W. Mitchell, and S.J. Blight. 2000. Impact of mortality, possibly due to herpesvirus, on pilchard Sardinops sagax stocks along the south coast of Western Australia in 1998-99. Marine And Freshwater Research 51: 601-612

Goodwin, C.L. 1978. Some effects of subtidal geoduck *(Panope generosa)* harvest on a small experimental plot in Puget Sound, WA. Wash. Dept. Fish. Progress Rep, 1978

Goodwin, C.L. 1978. Study of clam resources and evaluation of harvesting gear. Puget Sound subtidal geoduck survey data. Washington Department of Fisheries. Progress Report Washington Department of Fisheries. Olympia, WA

Harvell, D., R. Aronson, N. Baron, J. Connell, A. Dobson, S. Ellner, L. Gerber, K. Kim, A. Kuris, H. McCallum, K. Lafferty, B. McKay, J. Porter, M, Pascual, G. Smith, K. Sutherland, and J. Ward, J. 2004. The rising tide of ocean diseases: unsolved problems and research priorities. Frontiers In Ecology And The Environment 2: 375-382

Jackson, J.B.C., M.X. Kirby, W.H. Berger, K.A. Bjorndal, L.W. Botsford, B.J. Bourque, R.H. Bradbury, R. Cooke, J. Erlandson, J.A. Estes, T.P. Hughes, S. Kidwell, C.B. Lange, H.S. Lenihan, J.M. Pandolfi, C.H. Peterson, R.S. Steneck, M.J. Tegner, and R.R. Warner. 2001. Historical overfishing and the recent collapse of coastal ecosystems. Science 293: 629-638

Lafferty, K.D., Porter, J.W. and Ford, S.E. 2004. Are diseases increasing in the ocean? Annual Review Of Ecology Evolution And Systematics 35: 31-54
Landahl, J.T., Johnson, L.L., Stein, J.E., Collier, T.K. and Varanasi, U. 1997. Approaches for determining effects of pollution on fish populations of Puget Sound. Trans. Am. Fish. Soc. 126: 519-535

Mann, R. 2000. Restoring the oyster reef communities in the Chesapeake Bay: A commentary. J. Shellfish Res. 19: 335-339

McCay, D. P.F., Peterson, C.H., DeAlteris, J. T. and Catena, J. 2003. Restoration that targets function as opposed to structure: replacing lost bivalve production and filtration. Mar. Ecol. Prog. Ser. 264: 197-212

Pew Oceans Commission. 2003. America's living oceans: charting a course for sea change. A Report to the Nation. Pew Oceans Commission. Arlington, VA

Pikitch, E.K., Santora, C., Babcock, E.A., Bakun, A., Bonfil, R., Conover, D.O., Dayton, P., Doukakis, P., Fluharty, D., Heneman, B., Houde, E. D., Link, J., Livingston, P.A., Mangel, M., McAllister, M.K., Pope, J. and Sainsbury, K. J. 2004. Ecosystem-based fishery management. Science 305: 346-347

Rice, C.A. 2005. Effects of shoreline modification on a northern Puget Sound beach: microclimate and embryo mortality in summer spawning surf smelt (Hypomesus pretiosus). Estuaries and Coasts, 29(1):63-71

Steneck, R.S., Vavrinec, J. and Leland, A. V. 2004. Accelerating trophic-level dysfunction in kelp forest ecosystems of the western North Atlantic. Ecosystems 7: 323-332

Taylor, I.R. and Roe, E.L. 2004. Feeding ecology of little terns Sterna albifrons sinensis in south-eastern Australia and the effects of pilchard mass mortality on breeding success and population size. Marine and Freshwater Research 55: 799-808

Worm, B. and Myers, R.A. 2003. Meta-analysis of cod-shrimp interactions reveals top-down control in oceanic food webs. Ecology 84: 162-173

4.4 Interactions between Natural and Human Systems in Puget Sound

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1. Interactions between ecosystem and human well-being

The health of the Puget Sound ecosystem and its ability to support a growing human population is highly influenced by complex interactions between human and ecological processes. The drivers of ecosystem change include such diverse factors as patterns of human population growth, local and global markets and economies, and climate change; and they both interact and affect different components of the ecosystem simultaneously – influencing the ways humans plan their communities and the range of other species that are supported in those areas, for example. Characterizing these complex interactions is critical for assessing the possible impacts of human activities and the ecosystem responses to alternative management approaches. Importantly, simply adding humans to models of ecosystem change may not be sufficient to understand the interactions between these drivers, and the processes that translate them into impacts that occur at multiple levels (Pickett et al. 2001, Grimm et al 2001, Alberti et al 2003). Studying coupled human-natural systems requires us to recognize the reciprocal interactions and feedback—effects of humans on the environment and effects of the environmental change on human well being.

2. Human Drivers of Ecosystem Change

Key human drivers of change in Puget Sound are human demographics, economics, technology, social organization, and political and governmental structures. Choices humans make about the location of our work, play, and homes, as well as consumption behaviors directly influence the use of land and the demand for and supply of resources. These forces together affect the land cover and ultimately landscape heterogeneity and its natural processes and disturbances. For example, urban development affects ecosystems by fragmenting natural habitat (e.g. land conversion), modifying biophysical processes (e.g. artificial drainage), imposing barriers (e.g. roads), and homogenizing natural patterns (e.g. sprawl often occurs as a regular grid that disregards natural vegetation and topography).

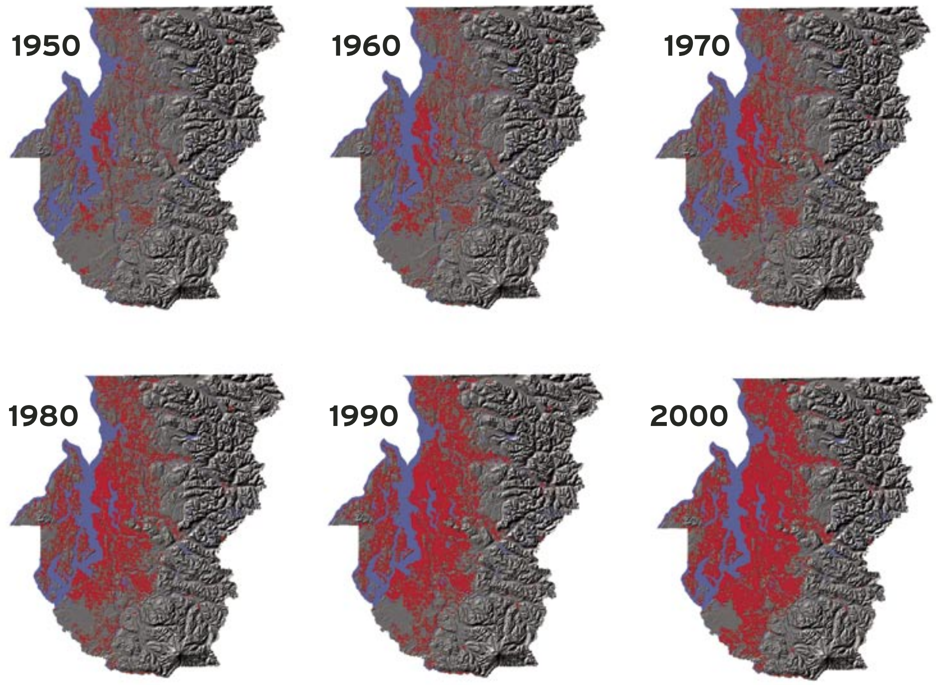
Although a systematic account of the impacts of human and natural drivers, their trajectories, and potential interactions has yet to be developed in Puget Sound, several studies have started to establish linkages between human activities and ecological change in this region.

2.1 Patterns of Human Population and Economic Activities

Dramatic changes in the Puget Sound landscape over the last century have been driven by population growth (Figure 4.4.1). The human population in this region has increased particularly rapidly over the last two decades. In 2005 the Puget Sound Basin housed approximately 4.4 million people, a 25% increase from 1991. Although estimates vary depending on the area encompassed, according to the State Office of Management, our population is expected to grow to 4.7 - 6.1 million residents by 2025. The intermediate projection estimated by the State suggests we will see an additional two million people in the basin within the next 20 years (OFM 2005).

Figure 4.4.1: Land cover change in central Puget Sound between 1950 and 2000.

Changes in developed land between 1950 and 2000 are derived from parcel data that track the year each parcel is developed. These data are contained in County Assessor files and were compiled by the Puget Sound Regional Council. (Source: UW Urban Ecology Research Lab 2005).



Most of the population growth in the Puget Sound region has concentrated in the Central Puget Sound region (which includes King, Kitsap, Pierce, and Snohomish counties), which currently contain 3.4 million people (Puget Sound Regional Council (PSRC) 2006). The central Puget Sound region experienced substantial growth over the last three decades, increasing by over 1.3 million people between 1970 and 2000. In most counties, the population distribution is shifting from large urban areas to outlying areas (OFM 2005). Most of the increases in the region's population come from immigration, meaning that people moving to the area account for 2/3 of the growth in the last decade.

Trends in household size are a good indicator of how population change may affect consumption patterns such as the number of housing units, energy use, vehicle trips, and similar expenditures. According to the 2000 Census, household size in the Puget Sound Basin is declining– dropping to approximately 2.5 people per household from about 3.0 in 1970 (US Census 2000). If trends toward declining household size persist, the number of households will continue to increase faster than population in the next decades, which will have important consequences for land and resource uses.

Economic and employment growth drive population trends and urbanization patterns. The Puget Sound economy has expanded faster than the national economy. Total employment in Central Puget Sound more than doubled between 1970 and 1990, from 740,927 to 1,445,243 jobs. By 2000, total employment had increased to more than 1.7 million. The Puget Sound Regional Council projects that the region will reach 2.0 million jobs by 2010, 2.2 million jobs by 2020, and more than 2.5 million jobs by 2030. As the number of jobs increases, the economy is shifting from a manufacturing base to dominance by service and office industries, including software, retail, biotechnology, tourism, internet services, and telecommunications.

2.2 Changes in Land Cover

A number of environmental changes are associated with human population growth through change in land cover, growing demand for natural resources, and increasing pollution loads. The presence of more people implies even greater demand for goods and services, increased use of land for housing, and expanded transportation and other infrastructure to support human activities.

The land cover of Puget Sound today exhibits a dramatic human presence (Figure 4.4.2). Although an historical account of change in land cover across the entire Puget Sound basin is not yet available, the dramatic changes documented for the Puget Sound lowlands in the recent past show clearly the rapid effects of urbanization (Alberti et al. 2003). Between 1991 and 1999 alone, 1% of the total area in the Central Puget Sound region has been newly developed, and the area designated as forest land decreased by a total of 55% during the same period. Overall, forest cover decreased 8.5 percent between 1991 and 1999. Highly developed land (i.e., land with greater than 75 percent impervious cover) increased by more than 6 percent of total area in the region, and moderately developed land (i.e., between 15 and 75%

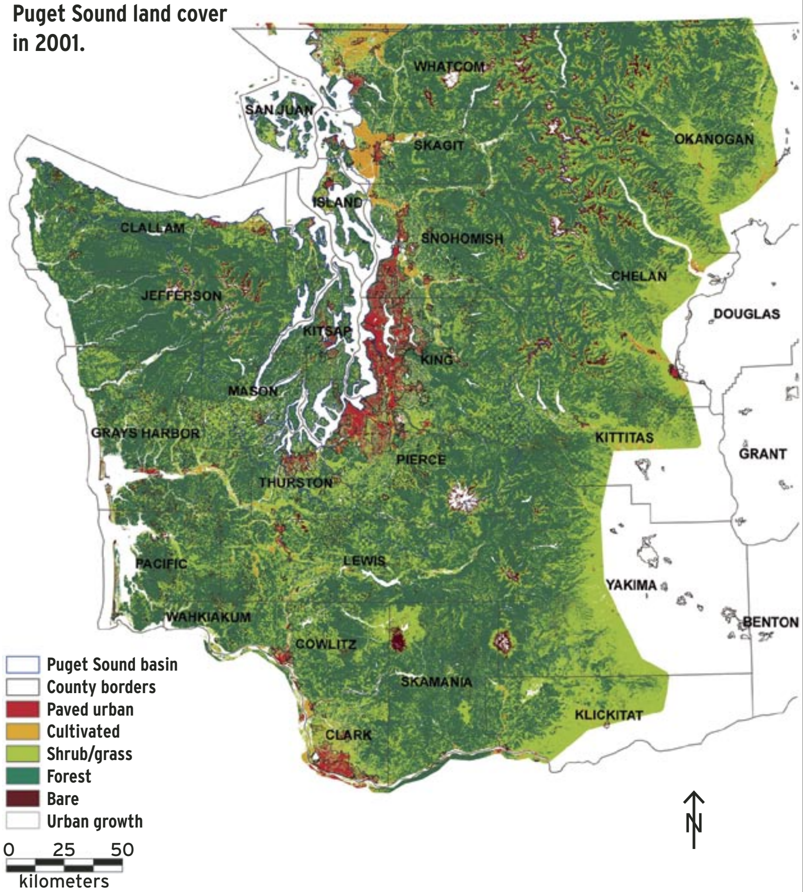


Figure 4.4.2: Puget Sound land cover in 2001.

impervious cover) increased by almost 8 percent. The most intense development has occurred within the Urban Growth Boundary as defined by the State Growth Management Act, where forest cover has declined by 11.1%. Almost half of the land conversion to development has occurred in the Seattle Metro area (Alberti et al. 2003).

2.3 Effects of Urbanization on Ecosystem Attributes

Urbanization is one of the key drivers of land transformation and causes the most persistent ecosystem changes through clearing of vegetation, compacting soil, artificially draining surface water, and covering the land surface with impervious surfaces.

These changes, particularly increases in impervious surface area, affect hydrological and ecosystem function by modifying natural drainage and runoff and by changing the natural habitats that support aquatic organisms. Change in land cover and land use associated with urbanization produce changes in both the type and the magnitude of fluxes of water, nutrients, and sediments within watersheds. Because ecological processes are tightly interrelated with the landscape, changes in the landscape structure resulting from urbanization have also important implications for watershed biotic integrity (Box 4.4.1).

Over the past decade, numerous studies have linked urbanization with aquatic system condition in Puget Sound and elsewhere (Booth and Jackson 1997, Karr 1998, Yoder et al. 1999, Thorne et al. 2000, Alberti et al. 2006). Other studies have linked changes in land use from historical conditions to declines in salmon populations within the Puget Sound region (Frissell et al. 2000, Collins et al. 2005, Bartz et al. 2006, Scheuerell et al. 2006). The biotic integrity of streams exposed to different degrees of urbanization can be compared by examining fish and macroinvertebrate assemblages in those watersheds. Although impervious surface emerges as perhaps the most prominent stressor, it is clear that there is no best single variable that explains complex relationships between urban development and ecological conditions in watersheds (Box 4.4.1A).

Urbanization also clearly affects terrestrial ecosystems, and birds are excellent indicators of its effects in these areas; they respond rapidly to changes in landscape structure and function. Urbanization affects birds directly through changes in ecosystem processes, habitat, and food supply, and indirectly through changes in predation, interspecific competition,and diseases (Marzluff et al. 2001). Change in land cover favors organisms that are more capable of rapid colonization, better adapted to the new conditions, and more tolerant of people than sensitive organisms. Native and nonnative species in urbanizing regions interact in complex ways, resulting in novel combinations of organisms living in unique communities. Diversity may peak at the urban fringe because of the colonization of intermediately disturbed forests by early successional, native species (Box 4.4.1B, Marzluff 2005).

The impacts of rapid landscape changes associated with population growth and urbanization in watersheds and nearshore environments are not restricted to freshwater and terrestrial environments, however. These changes are also degrading marine waters in Puget Sound estuaries, resulting in increased closures of fishing, recreation activities, and shellfish harvesting (PSAT 2002). One-third of Puget Sound's shorelines (about 800 miles) have been impaired by bulkheads, armoring, and dredging. Increasing amounts of toxic and nutrient loads are added to marine waters (PSAT 2004). The effects are reflected by poor sediment quality in a growing number of areas in Puget Sound (DOE 2002, PSAT 2004). Contaminants that bioaccumulate in the food chain, such as polychlorinated biphenyls (PCBs), are among the greatest concern for organisms such as orcas, seals, English sole, and mussels (see section 3.6 and the following issue paper).

Excess nutrients also are associated with increased human activities. In Hood Canal, excess nutrients cause intense algal blooms, contributing to low levels of dissolved oxygen which are contributing to fish and invertebrate kills (Section 3.3). Bacterial contamination is another major threat. Since 1980, the Washington State Department of Health (DOH) has downgraded nearly 20 percent (30,000 acres) of the area once available for commercial shellfish harvest in Puget Sound due to bacterial contamination (DOH, 2004). A steady loss of habitat, decline in some fish and wildlife populations, and closures of shellfish beds are signs that the Puget Sound is threatened. How human activities contribute to many of these threats is not well understood.

Effects of human activities on ecosystems are highly dependent on land use practices. Urban development incorporates a variety of different land-use types, including industrial, commercial, mixed use, single-family residential (SFR), multifamily residential (MFR), and open space, each of which exhibit a different land-cover composition and configuration. These diverse patterns of land cover have different implications for ecosystem health since they vary by the extent of impervious surface, quantity of vehicle use, and the predominant composition of runoff. Unless trends in land use patterns are significantly modified to reduce their impacts, urbanization will continue to place increasing stresses on the land, natural resources, and biodiversity.

Although increasing studies address the effect of urbanization on ecological conditions, few have directly addressed the question of how alternative urban development patterns influence ecological processes. Urban ecological studies will need to assess the ecological consequences of alternative development patterns if they are to answer questions about strategies for achieving more sustainable urban forms.

2.4 Examples of Ecosystem Feedback on Human Values

Ecological changes have important consequences for human well being. They affect the availability of important ecosystem services to the human population such as clean water, productivity of soils, clean food, and the quality of terrestrial and marine habitats on which many human activities depend. Environmental changes also affect the health of the urban environment and human health. The value of urban environments and human health can be estimated by assessing how changes in the environment affect the price of goods and services on which humans depend. While these feedback mechanisms are widely recognized, their economic and social costs in Puget Sound have not been quantified yet. Only recently a few scholars have started to quantify the value that people implicitly place on natural amenities by assessing the

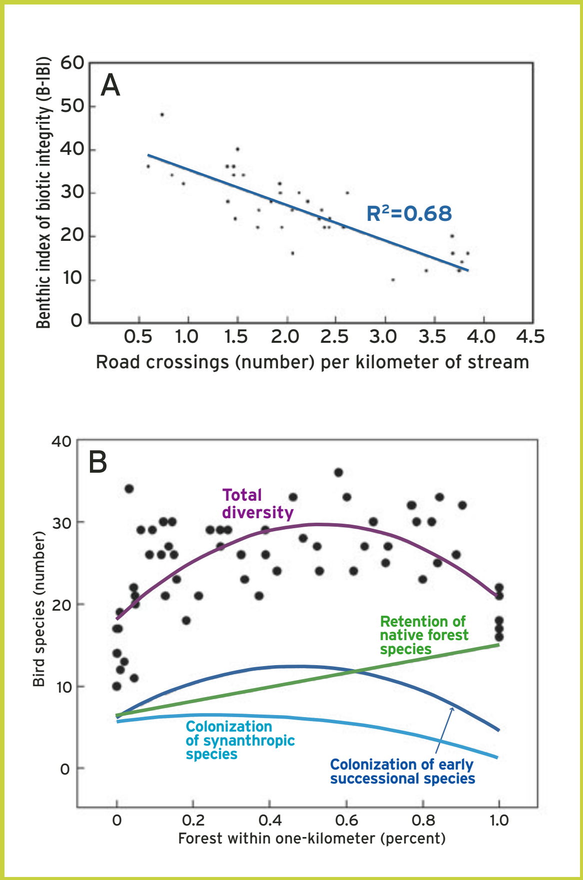
Box 4.4.1

Examples of interactions between urban patterns and ecosystems in Puget Sound—effects on macroinvertebrates and songbirds

The Urban Ecology Team at the University of Washington has conducted a study of the impact of urban development patterns on bird diversity and aquatic macroinvertebrates (Alberti et al. 2002).

A: Effects of urban patterns on macroinvertebrates.
Urban landscape patterns and ecological processes in watersheds are linked in complex ways and there is a strong correlation between urban land cover and stream conditions (Morley and Karr, 2002). Land uses and activities occurring on developed land strongly influence stream ecology. For example, the number of roads crossing streams is highly correlated with the abundance and species presence of aquatic insects (macroinvertebrates) in the stream as measured by the Benthic Index of Biotic Integrity (B-IBI). This index measures the relative health of the aquatic system by examining the number of species present, the proportion of relatively pollution-intolerant species present and the density of these organisms. B-IBI declines as number of road crossings per km of stream increases across 42 sub-basins in Puget Sound. The number of road crossings appears to be more important than other types of impervious surfaces in this area (Alberti et. al. 2006a).

B: Effects of urban patterns on songbird diversity.
The diversity of songbirds in the Puget Sound varies with the amount of natural vegetation in the nearby landscape. Landscapes with intermediate amounts of settlement and forest cover have the greatest diversity of songbirds (20–35) since they still retain some native species and gain synanthropic species (i.e., those species more tolerant of human presence). In contrast, most landscapes with either extensive settlement or no settlement had fewer than 20 species of songbirds (Marzluff 2005). However, those with extensive settlement supported primarily introduced species, such as English sparrows and starlings, while areas with substantial forest cover supported a much higher percentage of native songbirds.



revealed preferences on goods and services. For example, ecological changes such as loss of forest cover will feed back on the choices of households' locations, and availability of land and resources. Mills et al. (in review) estimated the effect of land cover on the real estate sale prices of single family housing in King County (WA). Preliminary results show that percent forest within a 300m radius from a parcel has a significant impact on housing price with an estimated decline of about 2 percent in sale price resulting from 10 percent loss in forest cover on nearby land.

3. Puget Sound Future Scenarios

The health of the Puget Sound ecosystem is vital to economic, cultural, and recreational activities and overall human and ecological well being. While much of the Puget Sound region is still healthy, rapid landscape change associated with population growth and urbanization in watersheds and nearshore environments is degrading ecosystem functions. This degradation has important consequences for the ability of the ecosystem to sustain the increasing human population and its activities in the future. These trends are likely to continue over the next several decades with increasing population growth and conversion of forested land to suburban development (Vitousek et al. 1997).

Assessments of potential impacts of urbanization trends are critical to identify policy priorities for the Puget Sound and to support effective and sound decisions. Several research teams at University of Washington other science entities are working towards developing predictive models and integrated assessments by linking human behaviors to ecosystem change. Recent projections suggest a substantial decline in forest cover and fragmentation associated with increased urban development over the next two decades in central Puget Sound (Figure 4.4.3). These changes, coupled with projected climate change (see Section 4.1) will present a challenge to managers.

Identifying and prioritizing strategies to address potential impacts of future conditions requires improving our ability to develop future scenarios by identifying key drivers and what we can describe about the complex interactions between human and natural systems. Scenario planning can offer a tool to develop alternative plausible futures and their effects on critical ecological and human services. These scenarios paint alternative pictures about what the future might look like, and can then be used to develop alternative strategies, assess the outcomes in terms of human and ecological values and evaluate different costs and benefits under each scenario. For example, by exploring alternative scenarios of climate change and ecological and human responses, strategies can be identified to increase the resilience of ecological and human systems to all range of possible changes in climate conditions.

Characterizing the interactions between human and natural systems both qualitatively and quantitatively is a key information for supporting policy decisions. This will require enhanced and ongoing collaboration across the natural and social sciences to understand both the complexity of human behaviors influencing urban development and the responses and feedbacks to ecological change. It also requires a new partnership between the scientific and policy communities to help define critical questions and make the scientific findings more directly useful in decision making. This collaboration is also critical to develop monitoring strategies and indicators that more directly link ecological change to human well being. The Millennium Ecosystem Assessment has provided a road map to start to draw such links in a way that can effectively help policy making and the public (Carpenter et al. 2006). The challenge for both the scientific and policy communities in Puget Sound is to strengthen their collaboration to develop an integrated regional ecosystem assessment.

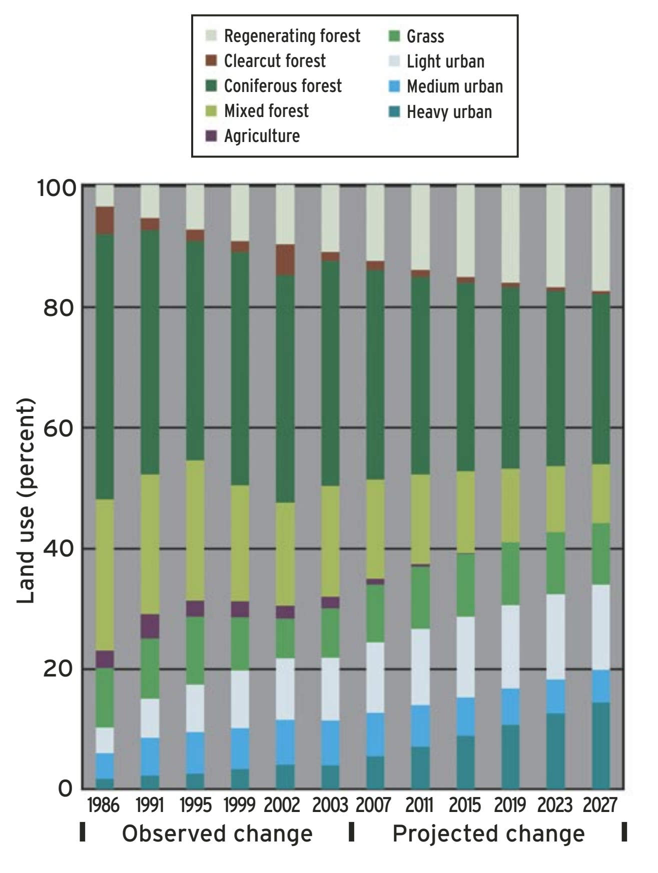


Figure 4.4.3: Observed and projected land cover change 1986-2027 (Central Puget Sound Land Cover Change Model, Alberti et al. 2006b) Previous data and projected changes indicate a continuing increase in the percent of urban land use types at the expense of forest lands.

References

Alberti, M., D. Booth, K. Hill, C. Avolio, B. Coburn, S. Coe, and D. Spirandelli. 2006a. The impact of urban patterns on aquatic ecosystems: An empirical analysis in Puget lowland sub-basins. Landscape and Urban Planning, In Press

Alberti, M., D. Booth, K. Hill, and J. Marzluff. 2002. The impact of urban patterns on ecosystem dynamics. NSF Report Urban Environment Program (DEB- 9875041)

Alberti, M., J. Hepinstall, P. Waddell, J. Marzluff, and M. Handcock. 2006b. Modeling interactions among urban development, land-cover change, and bird diversity. Biocomplexity Report NSF

Alberti, M., J. Marzluff, E. Shulenberger, G. Bradley, C. Ryan, and C. ZumBrunnen. 2003. Integrating humans into ecology: Opportunities and challenges for studying urban ecosystems. BioScience 53:1169-1179

Alberti, M., R. Weeks, and S. Coe. Urban land-cover change analysis in central Puget Sound. Photogrammetric Engineering & Remote Sensing 70:1043-1052. 2004

Bartz, K., K. Lagueux, M.D. Scheuerell, T. Beechie, M. Ruckelshaus. 2006. Translating alternative land use restoration scenarios into changes in stream conditions: a first step in evaluating salmon recovery strategies. Canadian Journal of Fisheries and Aquatic Science. 63: 1578-1595

Booth, D.B. and C.J. Jackson. 1997. Urbanization of aquatic systems—degradation thresholds, stormwater detention, and the limits of mitigation. Water Resources Bulletin 33, 1077–1090

Carpenter, S. R., R. DeFries, T. Dietz., A.H. Mooney, S. Polasky, V.W. Reid, and R. J. Scholes. 2006. ECOLOGY: Enhanced: Millennium Ecosystem Assessment: Research Needs. Science 314 (5797): 257

Department of Ecology, Washington State 2002. http://www.ecy.wa.gov

Department of Health, Washington State. 2004. 2003 Annual growing area reports. Office of Food Safety and Shellfish Programs, Washington Department of Health. Olympia, WA

Grimm, N. B., J. M. Grove, S.T.A. Pickett, and C. L. Redman. 2000. Integrated approaches to long-term studies of urban ecological systems. BioScience 50:571-584

Karr, J.R., 1998. Rivers as sentinels: using the biology of rivers to guide landscape management. In: Naiman, R.J., Bilby, R. (Eds.), River Ecology and Management: Lessons from the Pacific Coastal Ecoregion. Springer, New York, pp. 502–528

Mantua, N. J., and P. W. Mote. 2002. Uncertainty in scenarios of human-caused climate change. In N. McGinn (ed.), Fisheries in a Changing Climate Symposium 32, pp. 263-272, Bethesda, Maryland: American Fisheries Society

Marzluff, J.M. 2001. Worldwide urbanization and its effects on birds. Pages 9–47 in Marzluff JM, Bowman R, Donnelly R, eds. Avian Ecology in an Urbanizing World. Norwell (MA): Kluwer

Marzluff, J. 2005. Island biogeography for an urbanizing world: extinction and colonization may determine biological diversity in human-dominated landscapes. Urban Ecosystems, 8: 157–177

Mills, A., A. Bjorn, P. Waddell, and M. Alberti, (Forthcoming). Relationships between land cover and housing prices in King County

Morley, S.A., and J.R. Karr. 2002. Assessing and restoring the health of urban streams in the Puget Sound Basin. Conservation. Biology. 16, 1498–1509

Office of Financial Management, Washington State, 2005. Washington State Data Book, OFM Forecasting Division. Olympia, WA

Pickett, S.T.A., M.L. Cadenasso, J.M. Grove, C.H. Nilon, R.V. Pouyat, W.C. Zipperer, and R. Costanza. 2001. Urban ecological systems: Linking terrestrial ecological, physical, and socioeconomic components of metropolitan areas. Annual Review of Ecology and Systematics 32:127-157

Puget Sound Action Team 2002. Puget Sound Update, 2002. Puget Sound Action Team. Olympia, WA

4.5
Puget Sound: Marine Ecosystems and Human Health

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Introduction

Human health is unequivocally linked with the marine environment. In a broad sense, the condition of the marine ecosystem impacts human health just as human activity impacts the health of the marine environment. Oceans and estuaries are a source of most of the world's biodiversity, biological activity, and biomass production. Oceans and estuaries also provide sustenance for human populations, and play key roles in controlling greenhouse gases by providing oxygen regeneration through the respiration of phytoplankton and algae, and in the generation of weather patterns. However, oceans and estuaries are also the end repository for the myriad of pollutants released into our waters and atmosphere. Release of natural and anthropogenic compounds by human activities can have serious impacts on marine ecosystems, which in turn impact the health of the living marine resources on which humans rely. Marine factors directly affect human health in three ways– transmission of infectious disease (pathogens), exposure to toxic substances such as chemical contaminants, and the ingestion of marine biotoxins (produced by naturally occurring microscopic organisms such as bacteria and algae species that are toxic to humans in sufficient concentrations). Most human health exposure occurs through the consumption of contaminated fish and shellfish.

The Burden of Growth

Over the past 100 years there has been substantial urban and industrial development within the Puget Sound region resulting in heavy inputs of chemical contaminants at selected sites as well as significant loss or alteration of marine habitat. According to census data from the State of Washington, between 1910 and 1990 the population of the counties bordering on Puget Sound (King, Kitsap, Snohomish, Pierce, Skagit, Island, Mason, Jefferson, Clallam and Thurston Counties) increased nearly six-fold. Moreover, population growth and related urban and industrial development has continued to increase in the Puget Sound region during the 1990s and into this new millennium. The estimated total population in the Puget Sound region in 2003 was 3.8 million, with 86% residing in King, Pierce, and Snohomish Counties where major urban centers including Seattle, Bellevue, Tacoma, and Everett are located. Each of these counties has a major river system and many small stream systems, and numerous industrial and storm water outfalls that convey point and non-point source pollution into Puget Sound. Population trends suggest that population growth and increased motor vehicle use in the Puget Sound region will continue, and the geographical area affected by urban development may expand beyond current population centers. Increased vehicular use and point and non-point source runoff from urban areas is likely to lead to increased and more widespread pollution in the Puget Sound region, a trend similar to what has been observed nationally.

Trends in Marine Toxics

For most marine pollutants, concentrations vary in proportion to numbers of people living in a particular area. If a particular compound is banned or its use is significantly reduced, the concentration in the surrounding environment generally declines over time. As an example, the concentrations of cadmium, copper, and polychlorinated biphenyls (PCBs) have declined nationally in marine coastal environments over recent years, largely because the use of these substances is either banned or significantly reduced. Alternatively, if the quantity of a compound used in a particular area increases over time, the concentration in the surrounding environment increases proportionately.

As an example, the concentration of polybrominated diphenyl ethers (PBDEs), a brominated flame retardant commonly found in household plastic products such as sofa foam and computers, has increased 12-fold in Columbia River whitefish from 1992 – 2000 (Figure 4.5.1, from Rayne et al. 2003). Importantly, the concentration of some types of pollutants can increase within animals through a process called biomagnification. Biomagnification (Box 4.5.1) refers to the tendency of pollutants to concentrate as they move from one trophic level to the next.

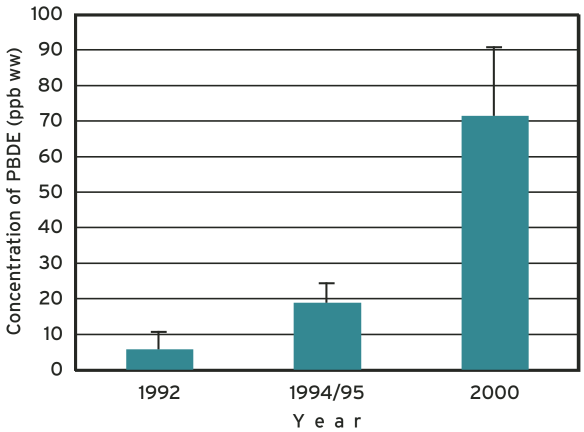

Figure 4.5.1: Concentration of polybrominated diphenyl ethers (PBDEs) in Columbia River whitefish from British Columbia, Canada (Rayne et al. 2003).

The Washington State Department of Fish and Wildlife (WDFW) has collected fish tissue data from Puget Sound since 1989 for the Puget Sound Assessment and Monitoring Program (PSAMP), building on work initiated by NOAA's Northwest Fisheries Science Center in the early 1980s. While PCB levels have declined nationally since their ban in 1977, they persist at significant levels in Puget Sound fish with no clear trend established since sampling began under PSAMP. It is no surprise that PBDEs have also been detected in Puget Sound fish during recent sampling by WDFW. Although only recently added to the list of substances for long term monitoring and analysis, there is obvious concern that Puget Sound fish will not escape the trend towards increasing levels of PBDEs.

Children and the Developing Brain: A Growing Concern

The Washington State Department of Health (DOH) assessed PSAMP fish contaminant data to address potential health impacts to humans who eat marine fish

Box 4.5.1

Definitions

Bioaccumulation: General term describing a process by which chemicals are taken up by aquatic organisms directly from water, as well as through exposure through other routes, such as consumption of food and sediment containing the chemicals.

Bioconcentration: A process by which there is a net accumulation of a chemical directly from water into aquatic organisms, resulting from simultaneous uptake (e.g., by gill or other tissues) and elimination.

Biomagnification: Result of the processes of bioconcentration and bioaccumulation by which tissue concentrations of bioaccumulated chemicals increase as the chemical passes up through two or more trophic levels. The term implies an efficient transfer of chemical from food to consumer, so that residue concentrations increase systematically from one trophic level to the next.

from Puget Sound. Mounting evidence has heightened concern that exposure of the developing fetus to contaminants in fish can result in learning and behavior deficits later in life. This concern has driven local, state and federal health agencies to issue fish consumption advisories that focus on women of child-bearing age and young children. The vast majority of these advisories are based on PCBs and mercury (Jacobsen and Jacobsen 2006, Schanz, 2003, Grandjean et al. 1997, NRC 2000). While no consumption advisories have yet been issued with respect to PBDEs in Puget Sound fish, recent animal studies indicate that PBDEs are yet another contaminant of concern with respect to childhood development (McDonald 2005, Birnbaum and Staskal 2004).

While DOH continues to emphasize that many Puget Sound fish are an excellent part of a healthy diet, consumption advice for specific areas of the Sound has been in place for several years (e.g., Eagle Harbor, Duwamish River, Commencement Bay). More recently, DOH has broadened that advice to include Puget Sound Chinook salmon in response to elevated levels of PCBs and mercury. DOH still encourages consumption of all Puget Sound salmon but increasing levels of emerging contaminants such as PDBEs could impact such advice in the future.

Trends in Marine Biotoxins

It can be argued that no other ecosystem in the nation is faced with a more diverse and increasing number of problems due to harmful algal blooms than Puget Sound. Puget Sound is the only place in the U.S. where blooms of

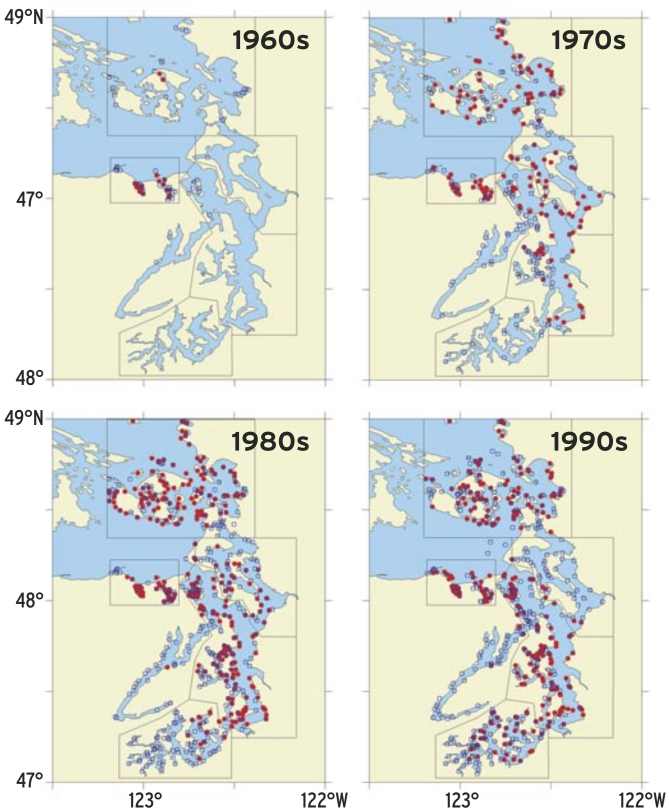

Figure 4.5.2: Movement of paralytic shellfish toxins into south Puget Sound over the past 4 decades (from Trainer et al., 2003). Closed circles indicate at least one shellfish closure at each site.

the alga *Heterosigma* has killed net-penned fish, paralytic shellfish toxins have caused hundreds of closures of shellfish harvest areas each year, elevated levels of domoic acid in shellfish recently have caused closures of shellfish harvesting sites and dinophysistoxins (a tumor promoting toxin) pose a threat. There is clear evidence that certain harmful algal blooms are new or expanding in scope and magnitude. For example, the closures of shellfish beds to commercial, recreational and tribal subsistence harvest due to the type of harmful algal bloom toxin known as paralytic shellfish toxin (PST) are now occurring in more places in Puget Sound than they did in the 1950s when monitoring in shellfish began (Figure 4.5.2). The magnitude, frequency and geographical distribution of these closures due to paralytic shellfish toxin have increased over the past 50 years.

A comparison of maximum PST averages per decade and population estimates of all counties bordering Puget Sound over the last 4 decades shows a high level of correlation (Figure 4.5.3), While this association is not necessarily a cause and effect relationship, it has been suggested that increased nutrient loadings into Puget Sound may contribute to increasing PST. Nutrient sources from land clearing, logging, aerial forest fertilizing by timber companies, direct sewage outfalls, agricultural runoff, and even aquaculture operations, may stimulate the growth of *Alexandrium* cells, which produce PSTs. The *Alexandrium* can concentrate in shellfish and cause paralytic shellfish poisoning in humans. To plan effective mitigation strategies, the linkages between population growth, global climate change, and natural factors and increased toxin levels must be assessed, as these correlations have not yet been closely studied.

Trends in Marine Pathogens

Population growth in the Puget Sound Basin can result in the introduction of disease-causing bacteria, viruses and protozoa (e.g. *E. coli*, norovirus, giardia) from animal waste and malfunctioning sewage systems, thereby directly contaminating beaches and shellfish beds. Increased nutrients in the ecosystem from sewage outfalls and agricultural and storm water runoffs also provide growth conditions favorable for rapid bacterial growth in estuarine waters, including shellfish growing areas. Following National Shellfish Sanitation Standards, commercial and recreational shellfish growing areas are

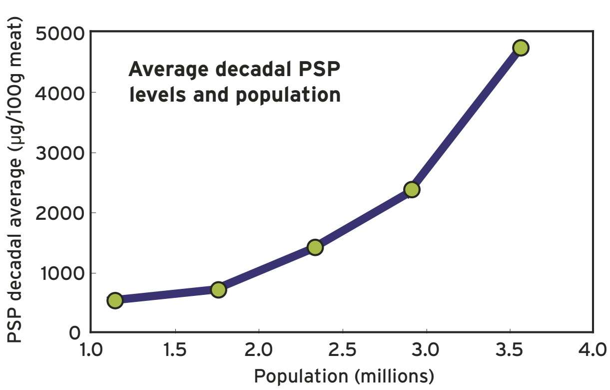

Figure 4.5.3: Maximum paralytic shellfish toxin 10-yr. average versus population estimates (from Trainer et al. 2002). Census data for counties bordering Puget Sound were obtained from the following site: http://www.census.gov/population/cencounts/wa190090.txt.

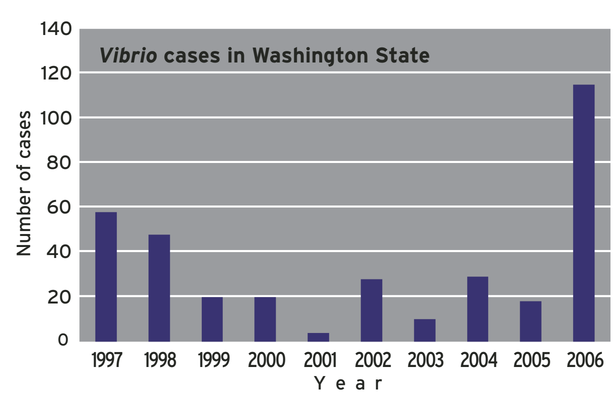

Figure 4.5.4: Number of confirmed cases of *Vibrio parahaemolyticus* infections in Washington State, 1997-2006 (from WA DOH).

monitored by DOH to detect emerging conditions that make shellfish harvesting unsafe, including the presence of potentially disease-causing bacteria. Since 1980 about one quarter of the 140,000 acres potentially available for commercial harvesting have been considered unsafe for shellfish harvesting (Puget Sound's Health 2002).

In the past decade, significant increases in illness due to consumption of raw oysters have been noted in the Pacific Northwest (Figure 4.5.4). Unusually warm water temperatures in the region during the summer months of 1997 and 1998 were responsible for one of the largest documented outbreaks of illness due to consumption of raw oysters contaminated with the naturally-occurring pathogen *Vibrio parahaemolyticus*. Since then, this pathogen has been responsible for several outbreaks in the U.S., including atypical locations such as Prince William Sound in Alaska. These outbreaks have been attributed to warmer than usual water temperatures that contribute to increased proliferation of the bacterium. The latest outbreak that occurred in July 2006, resulted in 115 reported cases of human illnesses in the Pacific Northwest, closure of most oyster harvesting in Washington State, and a national warning about Washington oyster consumption released by the Food and Drug Administration (FDA).

Subsistence consumption of Fish and Shellfish

Some communities are more dependent on fish and shellfish from Puget Sound than the general population. Native American Tribes and Asian-Pacific Islander communities eat more fish and shellfish than the average Washingtonian. This increased consumption has been documented in a number of fish consumption surveys (CRITFC 1994, Toy et al. 1996, EPA 1999, Suquamish 2000). The same could be said for avid recreational fisherman and shellfish harvesters and their families. High-end consumers of fish and shellfish are at increased risk for exposure to toxics, pathogens and biotoxins. While closing of recreational and commercial shellfish areas and the issuance of fish consumption advisories by DOH can serve as a protection, the disproportionate health, cultural and economic impacts on these communities should not be overlooked. DOH has recognized the balance that must be struck between reducing exposure to contaminants and maintaining the benefits associated with a healthy diet of Puget Sound fish and shellfish.

Economic Implications

Noticeable adverse health outcomes, or the perception of unacceptable risk, associated with pollutants in Puget Sound could have profound economic ramifications to the region. The local economy could be potentially impacted by reductions in:

- recreational activity at local beaches
- consumer confidence in the safety of fish and shellfish and associated sales
- tourism
- productivity associated with employee absenteeism
- our overall health and well-being

Assessing Risk: Data Gaps and Uncertainities

The field of risk assessment provides a general framework within which to identify the data necessary to comprehensively assess the impact of pollutants, biotoxins and pathogens in Puget Sound. A generalized risk assessment framework encompasses (1) field studies to assess the level of exposure of members of a population to the contaminants of interest; (2) field and laboratory studies to collect the data necessary to link the dose of contaminant explicitly to specific health outcomes (referred to as responses); and (3) integration of field and laboratory studies to infer population-level impacts over both short- and long-term time periods. Our understanding of the relationship between the Puget Sound marine ecosystem and human health will continue to improve as we implement these studies.

Environmental Monitoring—Assessing the level of exposure to contaminants

Sampling carried out in the Puget Sound (such as that under the Puget Sound Assessment and Monitoring Program, or PSAMP) has provided useful data on a range of contaminants and toxic chemicals at selected sites throughout the Sound. Monitoring could provide better information if it were expanded, with specific focus on (1) increased sampling of fish to confirm assumptions about using existing data as a surrogate for all consumed species, as well as providing a better data set to assess emerging contaminants of concern; and (2) further testing of fish in locations not yet sampled, to confirm or adjust estimates of tissue concentrations based on sediment concentrations of toxic chemicals. Moreover, although indicator organisms partially address regulatory requirements for assuring water quality with respect to shellfish harvesting, the continued improvement of monitoring programs and techniques to identify potentially toxic algae and pathogenic bacteria in water and shellfish (similar to approaches used in Nilsson et al. 2003; Trainer and Suddleson 2005) will allow managers and public health officials to develop risk assessment strategies that are relevant to protect human health and avoid unnecessary closures of shellfish beds.

The ability to maintain long-term data sets such as those compiled under PSAMP will enhance our ability to make linkages between human health and the condition of the Puget Sound ecosystem. Collection of environmental data over time allows for the identification of trends that can be linked to existing health databases such as shellfish disease outbreaks, cancer registries and biological monitoring in human populations. Establishing these linkages will allow Puget Sound restoration efforts to focus on those environmental factors that will have the most positive impact on human health.

Impacts on Neurodevelopment—Linking contaminants to health outcomes

Researchers have long focused on those problems that result in acute or otherwise obvious impacts on human health. While risk assessment techniques address low-dose, chronic impacts to human health (e.g. cancer), our awareness of sub-clinical effects is increasing. Neurodevelopmental impairment of children is of increasing concern. It is currently estimated that 17% of school-aged children suffer from behavior, memory or learning deficits (Szpir, 2006). While linkages with the environment remain unclear, concern has begun to focus on persistent, bioaccumulative toxics (PBTs) including those that are building up in the Puget Sound ecosystem (e.g. PCBs, mercury, PBDEs). By better understanding the sub-clinical effects of toxics in humans, proper regulatory levels can be established for the release of these toxics into Puget Sound.

Understanding the Ecology of the Organisms—Identifying the Triggers for Increases of Naturally Occurring Toxins

A better understanding of environmental conditions that promote biotoxin-forming organisms is needed to assess the relative contribution of human versus natural conditions on biotoxin production. Naturally-occurring toxins, such as those from harmful algae (e.g. *Alexandrium* and *Pseudo-nitzschia*) and bacteria, (e.g. *Vibrio*), are produced at low levels in many parts of the world's oceans without any detrimental effects. However, when the toxins produced by these organisms are concentrated in shellfish, human disease outbreaks can occur. A complete understanding of the ecology of these organisms - the genes involved in toxin production, the environmental conditions under which the highest levels of toxins are produced, and the role of these toxins in the metabolic processes of the host organism—will assist in managing the system in ways that minimize the risks to humans and the ecosystem as a whole.

Next steps: A Holistic Understanding of Impacts to Our Health and Well-Being

Both our physical and mental health can be influenced by the condition of the Puget Sound ecosystem. Our understanding of the impacts of the health of Puget Sound to our physical health is advancing—for example, we better understand the benefits of seafood consumption and conversely, the adverse impacts of contaminants and biotoxins in seafood and waterborne pathogens. Nevertheless, to date little emphasis has been placed on understanding the full range of impacts that the Puget Sound ecosystem can have on our mental health and overall well-being. A number of studies have illustrated the positive effects of natural environments on childhood learning and emotional well being as well as greater recovery from stress, enhanced social connections, increased ability to concentrate, and improved self-discipline. Our efforts to protect and restore the Puget Sound ecosystem are more certain to provide a broad array of benefits to humans if we can understand how the condition of our natural environment affects short- and long-term benefits to our mental and physical health, the mechanisms by which impacts occur, age or developmental stage differences as well as changes over time.

The Puget Sound is fortunate to have two recently created Centers of Excellence in Oceans and Human Health located in Seattle, one under the auspices of the Northwest Fisheries Science Center, and one in the University of Washington. Together with their external partners, these Centers will enhance the understanding required to allow public health agencies to maximize human health benefits derived from the Puget Sound ecosystem.

Summary

It is clear that contamination of Puget Sound waters and biota by chemical contaminants, pathogens and biotoxins has adversely impacted human health. What remains unclear is the magnitude of this impact on human health, economy and culture. Fish consumption advisories and shellfish beach closures have become a necessary response to pollutants in Puget Sound, but these remedies are far from a sustainable solution. These restrictions have obvious consequences on our economy and culture and can even run counter to the goal of protecting public health if they are not properly balanced with the myriad of health benefits associated with a diet of fish and shellfish. In the end, a better appreciation of the relationship between human health and the health of Puget Sound will enhance our societal will to protect and restore this unique ecosystem.

REFERENCES

Birnbaum, L.S. and D.F. Staskal. 2004. Brominated flame retardants: Cause of concern? Environmental Health Perspectives 112(1): 9-17

CRITFC (Columbia River Inter-Tribal Fish Commission), 1994. A fish consumption survey of the Umatilla, Nez Perce, Yakama and Warm Springs Tribes of the Columbia River Basin. CRITFC Technical Report No. 94-3. Portland, OR

EPA, 1999. Asian and Pacific Islander seafood consumption study. EPA Region 10. EPA 910/R-99-003. Available at: http://www.epa.gov/r10earth/offices/oea/risk/a&pi.pdf

Grandjean P., P. Weihe, R. White, F. Debes, S. Araki, K. Yokoyamma, K. Murata, N. Sorensen, R. Dahl, and P. Jorgensen. 1997. Cognitive deficit in 7-year-old children with prenatal exposure to methylmercury. Neurotoxicology Teratology 19(6):417-428

Jacobson J.L. and S.W. Jacobson. 1996. Intellectual impairment in children exposed to polychlorinated biphenyls in utero. N England J Med 335:783-789.
McDonald, T. 2005. Polybrominated diphenylether levels among United States residents: daily intake and risk of harm to the developing brain and reproductive organs. Integrated Environmental Assessment and Management 1(4):343-354

National Research Council (NRC). 2000. Toxicological Eeffects of methylmercury—Committee on the Toxicological Effects of Methylmercury, Board on Environmental Studies and Toxicology, Commission on Life Science. National Academy of Sciences. National Academy Press, Washington, DC

Nilsson, W.B., R.N. Paranjpye, A. DePaola, and M.S. Strom. 2003. Sequence polymorphism of the 16S rRNA gene of Vibrio vulnificus is a possible indicator of strain virulence. J. Clin. Microbiol. 41(1):442-446

Puget Sound's Health 2002. Third report on key indicators of Puget Sound Health. Puget Sound Action Team, Olympia, WA

Rayne, S., M.G. Ikonomou, and B. Antcliffe. 2003. Rapidly increasing polybrominated diphenyl ether concentrations in the Columbia River system from 1992 to 2000. Environmental Science and Technology 37(13): 2847-2854

Schantz, S., J. Widholm, and D. Rice. 2003. Effects of PCB exposure on neuropsychological function in children. Environ. Health Perspect. 111(3):357-376

Szpir M. 2006. New thinking on neurodevelopment. Environ Health Perspect. 2006 Feb;114(2):A100-7
The Suquamish Tribe, 2000. Fish consumption survey of the Suquamish Indian Tribe of the Port Madison Indian Reservation, Puget Sound Region. The Suquamish Tribe. 15838 Sandy Hook Road, Post Office Box 498, Suquamish, WA 98392

Toy, K.A., N.L. Polissar, S. Liao, and G.D. Middelstaedt. 1996. A fish consumption survey of the Tulalip and Squaxin Island Tribes of the Puget Sound Region. Tulalip Tribes, Department of Environment, 7615 Totem Beach Road, Marysville, WA 98271

Trainer, V.L. amd M. Suddleson. 2005. Monitoring approaches for early warning of domoic acid events in Washington State. Oceanography 18(2):228-237

Trainer, V.L., B.T.-L. Eberhart, J.C. Wekell, N.A. Adams, L. Hanson, F. Cox, and J. Dowell. 2003. Paralytic shellfish toxins in Puget Sound, Washington State. J. Shellfish Res. 22(1): 213-224

4.6
Integrating the Sciences: Natural and Social Science Support for Decision-Making

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Both natural causes and human decisions carry implications for ecosystem services and consequently for the well-being of all species on a variety of temporal and spatial scales. For example, human decisions impacting nearshore environments and fisheries, including salmon harvest levels, may lead to severe species and habitat impacts on very short time scales, as well as additional longer term issues. In this paper we apply an analytic framework to two interrelated decisions from the Puget Sound Region—the issue of how to restore an important salmon migratory pathway at McGlinn Island Causeway and the process of setting levels for salmon harvest. These examples require the integration of natural and social science information in multi-attribute decisions that seek to account for biological and economic implications of salmon levels (for both harvest by multiple populations and recreation such as whale watching) and channel navigability.

Context: Relationship of Ecosystem Structure and Function and Human Well-Being

We place this paper in the context of the larger report by reference to Figure 2-1 (adapted from NRC, 2004 and Millenium Eosystem Assessment, 2005). Of the four ovals in the figure, there are two which relate closely to human decision making, *Human Actions* and *Ecosystem Goods and Services*. *Human Actions* are direct decisions and their repercussions. In our examples these would be decisions about salmon harvest levels and about land uses or the alteration of landscapes. In decision analytic terms these are policy and management decisions made in the face of uncertainty about the future, but which should be informed by monitoring, scientific models and expert judgment which embody the state of science relevant to the options being considered. There is a great deal of human control over the care and judgment exercised in every step of these actions, which in turn translates into some human control over the degree of the impacts experienced by the ecosystem for a given level of harvest, or for a given land use agenda. In addition, human decisions are represented indirectly in the *Ecosystem Goods and Services* box - since humans decide the extent to which they will partake of particular ecosystem services, and also are accountable to exert some level of control over how their actions/consumption will affect the capacity and enjoyment of other humans and other species.

There are trade-offs inherent in land use, fish harvest levels, and ecological goods and services. For example, diking and marsh drainage for agricultural land use provide agricultural goods and services, as well as returns to the local economy, but may reduce ecological goods and services, like coastal water quality required for productive shellfish habitat and salinity gradients required for salmon migration to maintain healthy populations. Informed decision-making should consider these trade-offs in light of our best scientific understanding of their relationships and the goals and objectives of the impacted communities.

Decision Analytic Process

Decision analytic frameworks provide a formal structure and tools for looking at human decisions *a priori* and exploring the availability of information, the tradeoffs inherent in each strategy, and the range and likelihood of possible outcomes and impacts. These frameworks structure decisions in terms of the alternatives being considered, preferences over possible outcomes, and the relevant information that describes our uncertainty in which of these possible outcomes will likely occur. These decision tools lay bare the hidden interactions of agenda, the gaps in scientific understanding, and the significance of these gaps in terms of whether they could drive decisions/choices in another direction, *before* prioritizing among the possible alternatives on the table. Decision analytic structures, ranging from simple to extremely complex, organize information and decision processes to help decision makers systematically understand decision consequences, drivers, impacts, sources of uncertainty/variability, and trade-offs. Application of decision analytic tools is often said to improve the decision process, and provide the highest chance of the best outcome, but no process can guarantee an optimal outcome when uncertainty about the future is inherent. Chance always plays a role.

Decision Analytic Tools

Several decision analytic tools may be useful in Puget Sound resource management problems, but we focus here on the influence diagram. Influence diagrams are framing tools used for graphically representing the decision problem in terms of the relations between the alternatives being considered, uncertainties about the consequences of choosing particular alternatives, and the performance measures that describe what decision-makers and stakeholders care about (Howard and Matheson, 1984; Howard, 1990; Labiosa, 2003). The influence diagram can be constructed through a group exercise in decision framing, focusing attention on the physical, economic, and social relationships between the important variables in the decision situation, including decision strategies, uncertain variables describing the state and response of the natural system, and variables related to valuing outcomes. In addition to graphically representing important aspects of the decision problem, the influence diagram can be used to determine information/forecasting requirements and data needs. Sensitivity analysis may be used to determine which, if any, uncertainties can be treated deterministically and which uncertainties are most significant to driving overall variability in the outcomes, thus the influence diagram may evolve during a decision analysis problem. The role of the influence diagram in determining information and modeling/forecasting needs is very important: this approach helps decision makers and technical experts/scientists communicate about what information is important *in terms of the decisions to be made*. "Uncertainties that matter" are defined in this context as those for which a resolution in information could lead to a shift in the preferred alternative.

Puget Sound Examples

We have chosen two interrelated decisions for which the integration of natural and social science tools in a decision analytic process is important to future health and well-being across multiple objectives – setting harvest levels for salmon and restoration of migration pathways, for the multiple objectives of salmon population viability, navigation, recreational opportunities and cost. In both contexts our ability to minimize risks and maximize benefits to multiple species, over scales of space and time are in conflict and require tradeoffs. These risks and benefits are also balanced subject to economic, legal, and political constraints.

Salmon harvest decisions/impacts

Under the Endangered Species Act (ESA) government agencies are responsible for evaluating the long-term viability of individual species in order to decide whether they warrant "listing" as critical or endangered. The goal of the ESA is to ensure that species are viable over the long term (e.g., a 100-year period), consistent with extinction risk time frames for other species. The National Marine Fisheries Service (NMFS) is charged with these duties for marine species such as salmon, an exercise which relies in part on the setting of harvest levels at sustainable levels.

Our traditional approach to managing fisheries is based upon the use of single-species models of population dynamics. The goal of this approach is simply to provide a sustainable harvest of a target species. Such an approach ignores a broad suite of interactions among exploited species and between exploited species and other members of the community.

However, scientists are well aware that these interactions not only exist but have serious implications. For example, the prosecution of the Baltic Sea fishery even at a limited levels results in fundamental shifts in the structure of the community at all trophic levels. In this system, fishing reduces biomass of cod and herring—two important prey species of imperiled seals in the Baltic Sea. While "sustainable" fishing will allow for the recovery of cod and herring stocks, it appears that this level of fishing reduces fish biomass to the point that it inhibits recovery of seal populations. We can learn important lessons from this example which apply directly to management of the fisheries of Puget Sound which are characterized by complex webs linking marine species, and special relationships involving humans as well.

The goal of the sustainable fishery of a single species is simply different than, and in some cases may be difficult to reconcile with, the goal of maintaining marine communities in state that optimizes such ecosystem services as tourism or biodiversity. A prime example of such a trade-off may be the potential indirect effect of salmon fishing on whale watching. In Puget Sound, salmon fishing is clearly important economically, socially and culturally. As a result salmon populations are closely monitored, and sophisticated models have been developed to ensure that sufficient numbers of fish escape harvest so that salmon populations are sustained. With careful management of fishing (and other human impacts on salmon) sustainable tribal, commercial and recreational salmon fisheries is an achievable goal.

However as mentioned above, salmon harvest is accompanied by externalities and additional ecological and economic costs, e.g., substantial interaction with the viability of the recreational and tourism economy around whale watching. Salmon are the major prey item of Southern Resident Killer Whales (orcas). In 2003 there were approximately 37 active commercial whalewatching companies in the region, with 73 boats and passenger levels estimated at 450,000 in both 2001 and 2002. Puget Sound waters also attract large numbers of private boaters private floatplanes, helicopters, and small aircraft taking advantage of opportunities to view whales. A pivotal step in setting salmon harvest levels has been the establishment of the minimum number of individuals that constitutes a viable population. Still, number of salmon is only the beginning of the process since it does not account for other objectives such as the relationship between salmon and whales, and this expansive economy around whale watching. And this becomes extremely important if the maximum sustainable yield of a population is well below the size of the unfished population. As stated above, shifts can occur in the communities within which target species are embedded. An example of this is the impact on whale communities of shifts in salmon populations, which in turn imply shifts in recreational and economic opportunities that depend on the whale populations.

Taking a step backward, a further set of challenges related to integration of natural and social science is posed by the nature of the information available for making harvest decisions in the first place. A combination of quantitative and qualitative information is used to estimate the minimum viable population in light of abundance, productivity, diversity and spatial structure. As a result of severe limits in available data, the population calculations and requirements rely heavily on models describing the life cycle and robustness of salmon. Competing models lie at the heart of disputes about such habitat altering developments as management of near shore environments, hydropower generating dams and other hazards to fish. Some of the models rest on the assumption that simple proportions may adequately describe the rate of survival of fish faced with a barrier such as a dam, as they head to their spawning waters. Others use complex systems of equations to describe multiple life cycles and interactions in predicting survival under habitat challenges. All this complexity aside, the models only account for objectives specified by the analysts running them, which in some cases means only salmon population viability, rather than other objectives such as whale watching as noted above.

Even beyond these limitations of model structure the absence of adequate quantitative information for determining critical population parameters often leaves researchers in qualitative territory. Nevertheless, the number of fish constituting a viable population with respect to these parameters must be estimated for each population, and also in light of the characteristics of the overall ESU. This process is complicated in that the right number can never be known with certainty, and there is a small but finite probability of species extinction even with relatively large populations. A working assumption is that a 5% risk of extinction within 100 years should correspond to the viable population estimate. This assumption lies at the margin between scientific assessment and policy/ management decision making. The development of a distribution reflecting uncertainty in the magnitude of the extinction risk versus population size would enable the decisions about the acceptable risk of extinction to be shifted from the shoulders of the scientists to those of policy makers, but distribution construction is itself very complex. These decisions rest at the intersection of natural and social science. How should acceptable risk be established in this case? Is it more appropriately dictated by the values of society or is it a purely scientific issue based on the history of species robustness in the face of challenge? Who is in the best position to decide?

Breaching McGlinn Island Causeway

On-going decisions about breaching McGlinn Island Causeway illustrate the potential use of decision analysis to integrate the social and natural sciences in support of restoration decisions, in this case for restoring an important salmon migratory pathway. The project involves the restoration of a portion of the Skagit River delta, a specific decision and location on a relatively small scale which represent many related decisions all around the Puget Sound. The analysis that follows is intended to be illustrative and does not reflect the input of stakeholders or decision-makers.

The filling of sloughs in the 1930s and the emplacement of the Skagit jetty near McGlinn Island in the 1950s to control flooding and sedimentation in Swinomish Channel interrupted principal hydrologic connections between the North Fork Skagit River and the Swinomish Channel (Figure 4.6.1). These developments, in turn, disrupted salmon migration by physically prohibiting their passage and by stopping freshwater intrusions into the region. Today, juvenile Skagit Chinook salmon can only access Swinomish Channel on their way to Padilla Bay through a small fish passage in the jetty at high tide (Figure 4.6.2) or by circumnavigating the jetty. However, high salinities at the end of the jetty are thought to impose physiological barriers to salmon smolt and exacerbate mortality rates. Heavy ship navigation-related dredging of the Swinomish Channel also prohibits salmon passage.

There are a range of alternatives currently under consideration by the Skagit River Watershed Council which will submit proposals to the Salmon Recovery Funding Board. Restoration plans of the lost migration pathways near McGlinn Island call for breaching the causeway (Figure 1) to connect the N. Fork Skagit River to the Swinomish Channel for fish access and freshwater input, to mimic the historical role of sloughs. Alternatives are currently being devised and must consider the number and placement of connections with respect to multiple objectives: (1) enable juvenile Skagit River Chinook salmon to effectively access their migration path to the Swinomish Channel, Padilla Bay, and beyond; (2) enhance the low-salinity gradient along Swinomish Channel to Padilla Bay; and (3) mitigate sediment inputs that necessitate excess dredging for navigation purposes.

The causal relationships between the important uncertainties (or variables) identified for this decision problem are shown as an influence diagram (Figure 3). The uncertainties include future regional climate change and its effects on discharge in the North Fork of the Skagit River; the effects of the causeway breaching alternatives on the salinity gradient, salmon habitat availability, and sediment inputs to Swinomish Channel; the effects of sediment inputs on channel navigation; and the effects of habitat availability on salmon survival. Several of these uncertainties are also performance measures, as indicated by arrows into the multi-attribute utility node, “Restoration Success” (Figure 4.6.3). These performance measures are of direct interest to decision participants and can be monitored to quantify the degree of future restoration progress.

The influence diagram (Figure 4.6.3) may be applied to the McGlinn Island causeway breaching decision by assessing the conditional probability distributions for each variable and eliciting a suitable multi-attribute utility model from decision-makers and stakeholders. Probability assessment would involve simulation models that reflect what is currently known about the causal relationships between stream flows and structure, habitat, fish behavior, and fish population dynamics. The required simulations would include the considerable uncertainty in these relations as stochastic error terms to generate conditional probability distributions that reflect both the knowledge and uncertainty of experts.

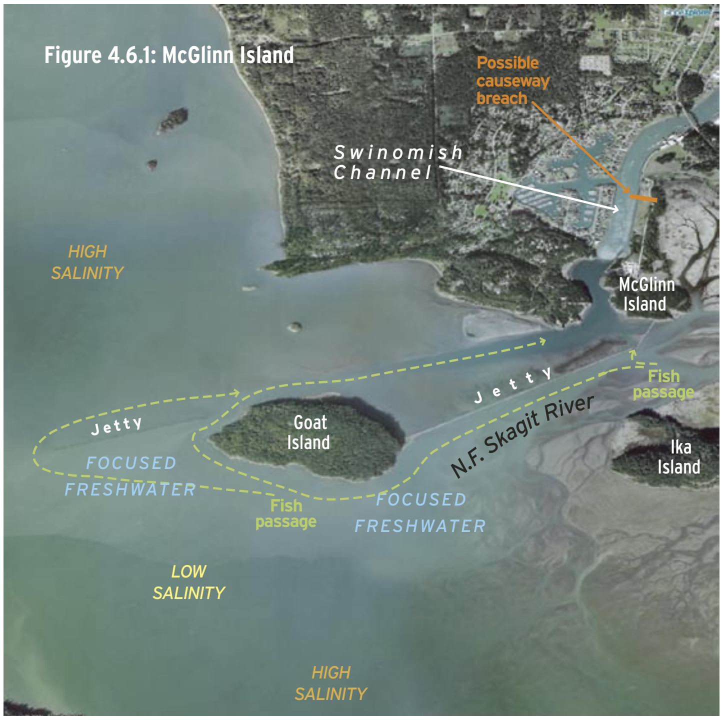

Figure 4.6.1: McGlinn Island

A multi-attribute utility model represents the many objectives, some perhaps conflicting, involved in complex decisions. In decisions under uncertainty, decision-makers and stakeholders do not know exactly what will happen if a particular alternative is chosen. However, given a set of possible outcomes, decision analysts can work with decision-makers and stakeholders to elicit their preferences and to establish possible trade-offs and compromises. In this framework, the best restoration alternative maximizes the multi-attribute utility value, providing the highest probability of the best outcome. The robustness of the best alternative to changes in the underlying uncertainties may be tested using sensitivity analysis. Since stakeholders can be expected to have different preferences, sensitivity analysis of the chosen utility weightings on the choice of the best alternative could be performed to explore trade-offs and to identify the underlying sources of disagreement.

Figure 4.6.2: Fish passage is possible only at high tide


Photo: Eric Grossman, USGS

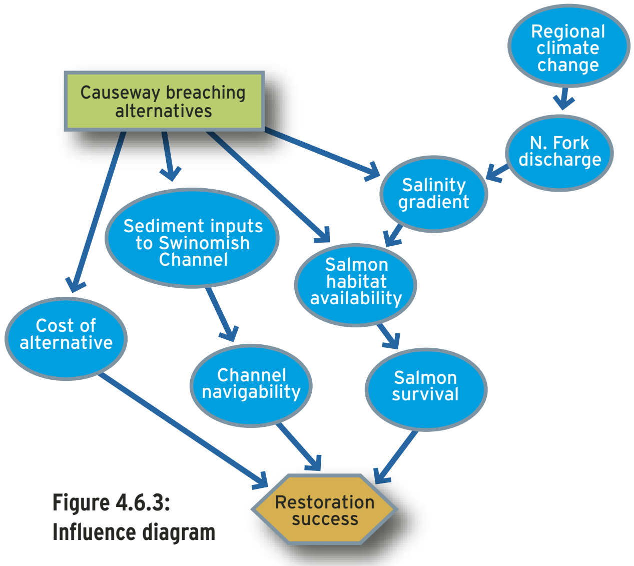

Figure 4.6.3: Influence diagram

Section 5
Key Findings for the Future of Puget Sound

Scientists resoundingly agree that an ecosystem-wide perspective is essential to ensure that a healthy and viable Puget Sound will remain as the legacy for future generations. Importantly, this ecosystem perspective includes humans and the forces that affect human behavior and choices. We have been an integral part of the Puget Sound ecosystem for millennia and have now become one of the driving forces of ecosystem change. Understanding the interactions and linkages among species, habitats, and the processes that support them, as well as the interactions between human and natural systems is thus critical to our ability to anticipate the response of the ecosystem to future natural perturbations and management actions. Adopting such an ecosystem-wide approach will improve delivery of the goods and services the Puget Sound ecosystem provides.

To achieve and maintain healthy ecosystems requires that we change our perspective . . .

– Pew Oceans Commission 2003

The Puget Sound ecosystem exhibits several indicators of severe degradation such as listed species, a fragile food web, diminishing habitats, and persistent and toxic contaminants and these have been elaborated on in Section 3. Scientists stress the importance of concerted and immediate action that will allow the Puget Sound region to take advantage of opportunities to halt or reverse continued declines. These opportunities include preventative strategies, as they are one of the most ecologically and cost-effective solutions for the future. While change is an inherent feature of any ecosystem, the complexity of Puget Sound and projected changes in climate and population growth, point to the need for a broader outlook using ecosystem management.

1. An ecosystem-wide view of Puget Sound will improve our ability to choose cost-effective actions and predict long term results.

- Cumulative pressures on terrestrial, freshwater and marine processes have widespread, interactive, and long-term impacts across the species and habitats of Puget Sound. Regional and local decisions that are made in the context of the connections and tradeoffs among Puget Sound ecosystem goods and services will increase the likelihood that the ecosystem can be managed in a sustainable way.
- An ecosystem-wide framework can be used to identify human and ecosystem linkages and assist policy-makers with the choice of cost-effective management actions that safeguard the environment to the extent possible. Modeling tools recently have advanced beyond single-species forecasts, and may be useful for land-use planning, marine zoning, and other management decisions.
- An ecosystem-wide perspective can help us understand why Puget Sound's water quality, water quantity, species and habitats respond the way they do to existing management activities. Understanding how ecosystem processes such as nutrient loading, freshwater input, marine circulation and climate interact and are connected to upland management will help identify solutions to complex problems. The cleanup of Lake Washington (Box 2-1) is one success story that used such an ecosystem perspective effectively.
- Monitoring strategies that assess connections, cumulative changes to ecosystem components and their interactions will allow measures of progress towards ecosystem goals. For example, managers may be able to predict and monitor how the combination of salmon harvest levels, shoreline armoring, the availability of spawning sites

for herring and other forage fish, and oceanographic conditions will affect the presence and quantity of other species such as orcas and marine bird populations.

- A wide perspective that includes estimating how human actions affect ecosystem goods and services allows managers, elected officials and the public to explicitly weigh potential tradeoffs in alternative management strategies. This allows for more transparent and informed decision-making, with greater likelihood of reaching societal goals.

2. Freshwater tributaries and marine receiving waters are under stress, which is likely to be exacerbated by future climate impacts.

2.1 Future climate impacts in the region are likely to result in reduced summer freshwater flows, increased winter peak flows and warmer stream temperatures.

- Seasonal and year-round freshwater quantity has already been identified as a factor impairing several threatened species in Puget Sound lakes, rivers, and nearshore environments (e.g. Shared Strategy, 2005). A number of other ecosystem services including domestic, municipal, and agricultural water supplies and recreation are also affected by low stream flows. Improved water use efficiency through conservation, re-use or storage will help moderate potential negative impacts of climate change on Puget Sound species, habitats and ecosystem services.
- The amount and timing of freshwater flows affects temperature in streams, lakes, and estuarine waters. Freshwater flows also influence rates of delivery of nutrients, toxics, and pathogens into streams and the marine environment. Forecasted future increases in winter peak flows may increase the rates at which toxics, nutrients and pathogens are introduced to freshwater, estuarine and marine environments.
- The range of introduced species, including novel pathogens, able to flourish in the Puget Sound region may change as a result of physical alterations. The range of native species may also be adversely affected, particularly forspecies located at the southern end of their range that cannot tolerate increased stream temperatures or changing flow regimes.

2.2 Future climate impacts in the region are likely to result in sea level rise in Puget Sound—increases in sea level could be up to 1 meter higher in South Puget Sound within the next 100 years.

- Current and future uses of low-lying areas could be compromised and could affect the quality, quantity and functioning of nearshore, estuarine and lower river habitats.
- Rising sea levels may be beyond the control of Puget Sound decision-makers. However, land use plans and protection and restoration strategies can take into account possible increases in sea level for nearshore, estuarine and lower river habitats as well as commercial, residential and municipal development.
- Zoning, land use and protection (e.g. marine reserves) strategies that consider the likely future distribution and abundance of habitats vulnerable to sea level increases will have greater long-term success than those that do not.

3. Puget Sound's food web has been substantially altered but the nature and strength of interactions among species in Puget Sound food webs is not well understood.

3.1 The focus on single "iconic" top level predator species such as Puget Sound Chinook and orcas is beneficial for energizing public awareness of ecosystem issues. It also is essential to consider competition among predator species and the value of detrital, benthic and other so-called lower trophic organisms in maintaining the food weband for developing sustainable recovery strategies.

- Efforts to recover top-level predators like birds and whales will benefit from concurrent actions aimed at sustaining and recovering species that serve as their food, or that serve as food for their prey.
- Management strategies designed to recover populations of top level predators like orcas, bald eagles and salmon can conflict unless impacts to other predator, competitor, and prey species are considered.

3.2 Life history details such as where species live during some life stages, what they eat, and how long they live are not well known for many marine species in Puget Sound.

- Collecting basic life history information will benefit species recovery and improve our ability to estimate ecosystem responses to diverse types of management actions such as modifying harvest levels or decisions about where to permit construction of private docks.
- Incorporating climate impacts on marine food webs—through affecting the distribution and abundance of native and non-native species—will improve the likelihood of success of recovery strategies.

3.3 Despite their foundation at the base of the food web, we have a poor understanding of the role of phytoplankton, other primary producers such as eelgrass and seaweeds, and zooplankton populations in Puget Sound food webs and how they respond to environmental conditions.

- Actions designed to improve water quality or reduce shellfish contamination problems that include hypothesized effects of plankton communities on nutrient and toxics cycling are more likely to be successful.
- Modeling and understanding changes in the food web will benefit from a more complete understanding of role of plankton and other primary producers in the region.

3.4 Some economic sectors of Puget Sound, such as fishing, commercial and recreational shellfish harvest, aquaculture, and eco-tourism, are completely and directly dependent on ecosystem function and productivity, and in turn have immediate effects on ecosystem goods and services.

- Management incentives and consideration of where these activities occur can improve the chances that operations of resource-based sectors are sustainable and increase the chances that they can continue to benefit from the ecosystem in the face of an increasing human population.
- Addition and removal of substantial quantities of single species through harvest, hatchery and shellfish culture activities likely is having wide ramifications throughout the Puget Sound food web. Assessing the potential impacts of activities directly dependent on ecosystem function on other ecosystem elements (such as habitats and species) will improve the chances that multiple uses of the ecosystem will be supported. For example, how do Pacific oyster aquaculture practices affect the status of native oysters and their predators?
- The introduction and expansion of invasive species in Puget Sound has the potential to severely disrupt food webs or habitats on which these economic sectors depend.

4. Projected increases in human population growth in the Puget Sound region will increase pressure on ecosystem goods and services.

4.1 Shoreline modifications are already extensive enough in the main Puget Sound basin that natural habitat-forming processes have been disrupted, and the distribution of habitat types has been affected.

- The pattern and extent of shoreline hardening and other modifications throughout the Sound affect the success of strategies to protect and recover beaches, eelgrass habitats, kelp forests, and natural shorelines.
- Analysis of the effects of development activities using quantitative or conceptual models can assist decision-makers in assessing broader, cumulative impacts to the Puget Sound ecosystem.

4.2 Focusing shoreline and upland development and other land uses into strategic locations in Puget Sound can allow achievement of a diversity of ecosystem services that are consistent with ecosystem goals.

- The loss of salt marsh and other important habitat types has been regionally significant in Puget Sound and severe in specific areas. Habitat-forming processes such as beach nourishment and bank stabilization, and the maintenance of eelgrass and kelp habitats require an ecosystem-wide approach for planning, protection and restoration to insure diversity and connectivity of habitats. The availability of habitat for forage fish spawning in Puget Sound has been substantially impacted by shoreline armoring. The conservation and restoration of critical habitat for forage fish is a crucial consideration for land use policies and enforcement, as the productivity of these areas will affect ecosystem services throughout Puget Sound.
- Land conversions from forests and prairies to commercial timber production and agriculture and later to associated urbanization impacts are increasing throughout the Sound. While some land use planning and regulatory efforts are having positive effects on species, habitats, and services, these remain largely small scale and localized. Achieving desired ecosystem services for an increasing human population in Puget Sound is possible with explicit balancing of alternative land uses, reduction of impacts of human activities, and careful attention to the locations of impacts and uses.
- Strategies that maximize the range of ecosystem benefits that can be gained from a mixed landscape of agriculture, timberlands and less disturbed ecosystems will help to alleviate impacts associated with urbanization and contribute to goals for human well being.

4.3 Toxics entering Puget Sound accumulate in sediments, marine waters and organisms; and excess nutrients and pathogens negatively impact biological populations, ecosystem integrity, harvest availability, and human health.

- Stormwater runoff in Puget Sound is causing water quantity and quality problems. Increases in impervious surface cover can lead to increases in peak flows, which in turn alter habitat formation in urban and rural river systems. Strategies to reduce the magnitude of stormwater runoff events or the toxics and excess nutrients they deliver during winter high flows could reduce their negative impacts on the health of commercially, recreationally and ecologically important species like shellfish.
- Toxics introduced into Puget Sound lands and waters are showing up as high concentrations in upper-level predators such as salmon, seals and orcas, even though some of these substances were banned decades ago. The number of acres of

highly contaminated sediments in Puget Sound has been reduced due to clean-up efforts. However, contaminants such as polychlorinated biphenyls (PCBs) are declining slowly, if at all, and levels of polycyclic aromatic hydrocarbons (PAHs) have increased in long-term sediment monitoring stations in Puget Sound (PSAT, 2005). Reduction of inputs of toxic compounds to the Sound will benefit ecosystem and human health overall.

- Quantification of rates and amounts of toxic substances entering Puget Sound can be used to assess sources and deposition Sound-wide; leading to an overall strategic approach including a combination of reducing further inputs and cleaning up existing sites to address the most pressing toxic sources first. For example, remediation and restoration actions designed to clean up specific locations where "legacy" toxics are concentrated and known to be entering the ecosystem can help to reduce the amount of toxins that move back into the food web.
- Human population growth has the potential to result in greater levels of pathogens, pharmaceuticals, chemical toxics and nutrients being discharged into freshwaters and the Puget Sound. Revisions to water quality standards and new technologies to remove these emerging contaminants from freshwaters will help alleviate their negative impacts on the Puget Sound ecosystem.
- Both natural and human-induced changes in environmental conditions such as water temperature and density of individual species are likely to result in more disease outbreaks from naturally occurring (e.g., paralytic shellfish poison or PSP) and artificially introduced pathogens affecting many species.
- Artificially high levels of nutrients, introduced through agriculture, stormwater or septic tank drain-off can affect the primary productivity of the system locally or regionally, leading to non-normative blooms of algae and concomitant problems associated with low dissolved oxygen and fish die-offs.
- Human health increasingly is put at risk due to the state of the Puget Sound ecosystem. Difficult decisions face consumers weighing the relative benefits and risks associated with eating fish that contain both high concentrations of beneficial omega-3 fats and toxics.

4.4 Human population growth is likely to result in increased demands for freshwater in general and potable water in particular.

- Implementation of actions that affect water quality and quantity that considers population growth should have smaller long-term impacts than those that do not.
- Some watershed planning groups are explicitly considering patterns of future human development and climate impacts—and models suggest that wise land use, water management, and restoration planning can go a long way towards alleviating pressures on watersheds to provide services for humans and wildlife.

5. Approaches exist for explicitly illuminating tradeoffs between different uses of the Puget Sound ecosystem so that better, more rational and publicly transparent decisions about its future can be made.

- Capturing connections between such valued ecosystem elements as fish (for harvest and food web function) and water flows (for people and maintenance of nearshore habitats) in decision frameworks can support a frank discussion of relative benefits and cost effectiveness of alternative management actions.
- Linking social and economic drivers and responses to ecosystem conditions is a key element of evaluating tradeoffs between alternate management strategies.
- Regular communication between scientists and policy-makers as decision frameworks are implemented can help ensure that results are communicated and used effectively and appropriately.

Conclusions—Key Findings

In summary, the scientific community has emphasized an ecosystem management approach that emphasizes connectivity among parts of the ecosystem. Such linkages take many forms, including the relationship of fundamental drivers such as climate change to our ecosystem, the connection between upland and shoreline activities and the function of marine processes and habitats, the complex web of species in Puget Sound, and the potential implications of past and future perturbations. Finally, connections between scientists and decision makers are considered to be crucial in achieving a broader perspective and sustainable strategy for the future of Puget Sound.

Glossary of Frequently Used Terms

Anthropogenic	Caused by humans.
Attenuation	A decrease in the energy of light due to absorption and scattering in the water column.
Bathymetry	Measure of depth of a body of water.
Benthic	Pertaining to the ocean bottom, especially organisms that dwell on or in bottom sediments.
Bivalve	A mollusk such as an oyster or clam that has two shells hinged together.
Copepod	A sub-class of minute marine or freshwater crustaceans.
Demersal	Ocean zone comprising the water that is near to and significantly affected by the coast or sea floor.
Detritus	Decaying matter from fragments and waste from organisms.
Ecosystem	Ecological + system: A group of interrelated plants and animals together with their inanimate surroundings.
Epibenthic	That which occurs on the surface of sediments on the bottom of water bodies.
Estuary	A semi-enclosed body of water which has free connection to the open ocean and within which sea water is measurably diluted with fresh water derived from land drainage.
Euphotic	The uppermost layer of a body of water that receives sufficient light for photosynthesis.
Eutrophication	An increase in the external nutrient supply to a system, generally resulting in the excessive growth of organisms.
Gastropod	A class of mollusks typically with a shell, including snails, slugs and limpets.
Geomorphology	The structure of land forms and the processes that form them as parts of a system.
Hypoxia	Deficiency of available oxygen.
Macrophytes	An individual alga or plant large enough to be seen with the naked eye.
Microalgae	Diverse group of small algae visible only with a microscope.
Nutrient	Chemical elements and compounds found in the environment that plants and animals use to survive and grow. In water quality investigations, the major nutrients of interest are forms of nitrogen and phosphorus. High concentrations of nutrients in water bodies can cause eutrophication and hypoxia.
Pathogen	Any disease-producing agent, especially virus, bacteria, or fungi.
Pelagic	That part of the ocean that comprises the water column; open water.
Phytoplankton	Microscopic floating plants, including algae, that drift in large numbers in freshwater or saltwater bodies.
Pycnocline	A depth zone at which seawater density changes appreciably.
Taxa	A grouping of organisms that have been given a formal taxonomic name such as species, genus, family, etc.
Thermocline	A layer in a large body of water where there is an abrupt difference in temperature.
Trophic level	A group of organisms that occupy the same position in a food chain.
Vascular plants	A plant containing tissue that conducts water and nutrients throughout the plant.

More glossaries are located at:

http://www.st.nmfs.gov/st4/documents/FishGlossary.pdf
http://www.ecy.wa.gov/programs/sea/swces/products/glossary.htm
http://www.epa.gov/glossary/

References

Armstrong, J.W., C.P. Staude, R.M. Thom, and K.K. Chew. 1976. Habitats and relative abundances of the intertidal macrofauna at five Puget Sound beaches in the Seattle area. Synthesis 9:277-290

Beechie, T.J., M. Liermann, E.M. Beamer, and R. Henderson. 2005. A classification of habitat types in a large river and their use by juvenile salmonids. Transactions of the American Fisheries Society 134:717-729

Ben-David M., T.A. Hanley, D.M. Schell. 1998 . Fertilization of terrestrial vegetation by spawning Pacific salmon: the role of flooding and predator activitiey. Oikos 83: 47-55

Berry, H.D., T. F. Mumford Jr., P. Dowty 2005. Using historical data to estimate changes in floating kelp (*Nereocystis luetkeana* and *Macrocystis integrifolia*) in Puget Sound, Washington. Proceedings of the 2005 Puget Sound Georgia Basin Research Conference. http://www.engr.washington.edu/epp/psgb/2005psgb/2005proceedings/Papers/F7_BERRY.pdf

Bilby, R.E., B.R. Fransen, and P.A. Bisson. 1996. Incorporation of nitrogen and carbon from spawning coho salmon into the trophic system of small streams: Evidence from stable isotopes. Canadian Journal of Fisheries and Aquatic Sciences 53: 164-173

Bilby R.E., B.R. Fransen, J.K. Walter and W.J. Scarlett. 2001. Preliminary evaluation of the use of nitrogen stable isotope ratios to establish escapement levels for Pacific salmon. Fisheries 26 (1): 6-14

Bill, B.D., F.H. Cox, R.A. Horner, J.A. Borchert, V.L. Trainer. 2006. The first closure of shellfish harvesting due to domoic acid in Puget Sound, Washington, USA. S. Afr. J. Mar. Sci.

Bisson, P.A., J.L. Nielsen, R.A. Palmason, and L.E. Grove. 1982. A system of naming habitat types in small streams, with examples of habitat utilization by salmonids during low streamflow, pp. 62-73. In Neil B. Armantrout, ed., Acquisition and utilization of aquatic habitat inventory information, Proceedings, Oct. 28-30, 1981. Western Div. Am. Fish. Soc., Portland, OR.

Bisson, P.A., K. Sullivan, and J.L. Nielsen. 1988. Channel hydraulics, habitat use, and body form of juvenile coho salmon, steelhead, and cutthroat trout in streams. Trans. Am. Fish. Soc. 117: 262-273

Bower, J.L. 2004. Assessing southern Strait of Georgia marine bird population changes since 1980: what we know and what we need to know. In T.W. Droscher and D.A. Fraser (eds). Proceedings of the 2003 Georgia Basin/Puget Sound Research Conference. CD-ROM or Online. Available: [February 2004]

Brennan, J.S., K.F. Higgins, J.R. Cordell, and V.A. Stamatiou. 2004. Juvenile salmon composition, timing, distribution, and diet in marine nearshore waters of Central Puget Sound in 2001-2002. King County Department of Natural Resources and Parks, Seattle 164 pp.

Canning, D. and H. Shipman. 1995, Coastal erosion management studies in Puget Sound, Washington: Executive Summary, Coastal Erosion Management Studies, Volume 1, Shorelands Program, Washington Dept. of Ecology, Olympia, DOE Report 94-74

Cederholm, C.J., D.B. Houston, D.L. Cole and W.J. Scarlett. 1989. Fate of Coho salmon (Oncorhynchus kisutch) carcasses in spawning streams. Canadian Journal of Fisheries and Aquatic Sciences 46 (8): 1347-1355

Cederholm C. J., M.D. Kunze, T. Murota, A. Sibatani. 1999. Pacific salmon carcasses: Essential contributions of nutrients and energy for aquatic and terrestrial ecosystems. Fisheries 24: 6-15

Chappell, CB. 2006. Upland plant associations of the Puget Trough ecoregion. Natural Heritage Report 2006-01. WA Department of Natural Resources, Natural Heritage Program, Olympia, WA. http://www.dnr.wa.gov/nhp/refdesk/communities/pdf/intro.pdf

Climate Impacts Group and University of Washington, 2005. Uncertain future: Climate change and its effects on Puget Sound. http://www.psat.wa.gov/Publications/climate_change2005/climate_home.htm

Cohen, A.N., C.E. Mills, H. Berry, M.J. Wonham, B. Bingham, B. Bookheim, J.T. Carlton, J.W. Chapman, J.R. Cordell, L.H. Harris, T. Klinger, A. Kohn, C.C. Lambert, G. Lambert, K. Li, D. Secord and J. Toft. 1998. Report of the Puget Sound Expedition, September 8-16, 1998; A rapid assessment survey of nonindigenous species in the shallow waters of Puget Sound. Washington State Department of Natural Resources, Olympia WA and United States Fish and Wildlife Service, Olympia WA

Collins, B.D. and A.J. Sheikh. 2005. Historical reconstruction, classification, and change analysis of Puget Sound tidal marshes. Final project report to Washington Department of Natural Resources Aquatic Resources Division, Olympia, WA 98504-7027. Available at: http://riverhistory.ess.washington.edu/ project_reports/finalrpt_rev_aug12_2005.pdf

Crawford, R.C. and H Hall. 1997. Changes in the south Puget prairie landscape. ***In*** P. V. Dunn and K. Ewing (Editors). Ecology and conservation of the south Puget Sound prairie landscape. The Nature Conservancy, Seattle WA

Dethier, M.N. 1990. A marine and estuarine habitat classification system for Washington State. Natural Heritage Program, Washington Department of Natural Resources. 60 pp.
Downing, J., 1983, The coast of Puget Sound: Its processes and development: University of Washington Press, Seattle, 126 p.

Ebbesmeyer, C.C. and G.A. Cannon. 2001. Review of Puget Sound physical oceanography related to the triple junction region. Report for King County Dept. of Natural Resources, 34 pp.

Edmondson, W.T. 1991. The uses of ecology: Lake Washington and beyond. University of Washington Press. 329 p.

Environment Canada, US Environmental Protection Agency, PSAT. Spring 2002 and Fall 2006. Transboundary Georgia Basin-Puget Sound Working Group on Environmental Indicators report. www.env.gov.be.ca/spd/gbpsei/documents/gbpsei.pdf http://www.epa.gov/region10/psgb/indicators/

Floberg, J., M. Goering, G. Wilhere, C. MacDonald, C. Chappell, C. Rumsey, Z. Ferdana, A. Holt, P. Skidmore, T. Horsman. 2004. Willamette Valley-Puget Trough-Georgia Basin ecoregional assessment. The Nature Conservancy. Arlington, VA

Forest Ecosystem Management and Assessment Team. 1993. Forest ecosystem management: An ecological, economic and social assessment. USDA Forest Service

Franklin, J.F. and C.T. Dyrness. 1973. Natural vegetation of Oregon and Washington. USDA Forest Service, Pacific Northwest Region - General Technical Report PNW-8

Fresh, K., C. Simenstad, J. Brennan, M. Dethier, G. Gelfenbaum, F. Goetz, M. Logsdon, D. Myers, T. Mumford, J. Newton, H. Shipman, C. Tanner. 2004. Guidance for protection and restoration of the nearshore ecosystems of Puget Sound. Puget Sound Nearshore Partnership Report No. 2004-02. Published by Washington Sea Grant Program, University of Washington, Seattle, Washington. Available at http://pugetsoundnearshore.org

Gaeckle, J., P. Dowty, B. Reeves, H. Berry, S. Wyllie-Echeverria, T. Mumford, and M. Hannum. 2006. Puget Sound submerged vegetation monitoring project: 2005 monitoring results. Washington Department of Natural Resources, and Puget Sound Assessment and Monitoring Program, Puget Sound Action Team, Olympia, WA. (in draft)

Gelfenbaum, G., Mumford, T., Brennan, J., Case, H., Dethier, M., Fresh, K., Goetz, F., van Heeswijk, M., Logston, M., Myers, D., Newton, J., Shipman, H., Simenstad, C., Tanner, C., and Woodson, D. 2006. Coastal Habitats in Puget Sound: A research plan in support of the Puget Sound Nearshore Ecosystem Restoration Program, in press

Georgia Basin-Puget Sound Indicators (See Environment Canada et al.)

Goetz, F., C. Tanner, C.S. Simenstad, K. Fresh, T. Mumford and M. Logsdon, 2004. Guiding restoration principles. Puget Sound Nearshore Partnership Report No. 2004-03. Published by Washington Sea Grant Program, University of Washington, Seattle, Washington. Available at http://pugetsoundnearshore.org

Goodwin, C.L. and B. Pease. 1989. Species profiles: life histories and environmental requirements of coastal fishes and invertebrates (Pacific Northwest)–Pacific geoduck clam. U.S. Fish. Wildl. Serv.Biol. Rep. 82(11.120). U.S. Army Corps of Engineers, TR EL-82-4. 14 pp.

Gustafson R.G., W.H. Lenarz, B.B. McCain, C.C. Schmitt, W.S. Grant, T.L. Builder, and R.D. Methot. 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, 275 p. http://www.nwfsc.noaa.gov/publications/techmemos/tm44/environment.htm

Horner, R.A., L. Hanson, C.L. Hatfield, and J.A. Newton. 1996. Domoic Acid in Hood Canal, Washington, USA. In: Harmful and Toxic Algal Blooms. Yasumoto T [Ed.], UNESCO

Horner, R.A., D.L. Garrison, F.G. Plumley. 1997. Harmful algal blooms and red tide problems on the U.S. west coast. Limnol. Oceanogr. 45:1076-1088

Hutchinson, I. 1988. The biogeography of the coastal wetlands of the Puget trough - deltaic form, environment, and marsh community structure. Journal of Biogeography 15:729-745

Kline, T.C., J.J. Goering, O.A. Mathisen, P.H. Poe, P.L. Parker. 1990. Recycling of elements transported upstream by runs of Pacific salmon. 1. Delta-N-15 and Delta-C-13 evidence in Sashin Creek, southeastern Alaska. Canadian Journal of Fisheries and Aquatic Sciences 47: 136-144

Kozloff, E.N. 1983. Seashore life of the northern Pacific Coast. University of Washington Press, Seattle

Kruckeberg, A.R. 1991. The natural history of Puget Sound country. University of Washington Press, Seattle

Lance, M.M., and C.W. Thompson. 2005. Overlap in diets and foraging of common murres (*Uria aalge*) and rhinoceros auklets (*Cerorhinca monocerata*) after the breeding season. The Auk 122:887-901

Litzow, M.A., J.F. Piatt, A.A. Abookire, and M. Robards. 2004. Energy density and variability in abundance of pigeon guillemot prey: support for the quality-variability tradeoff hypothesis. Journal of Animal Ecology 73: 1149-1156

Manuwal, D.A., T.R. Wahl, and S.M. Speich. 1979. The seasonal distribution and abundance of marine bird populations in the Strait of Juan de Fuca and Northern Puget Sound in 1978. National Oceanic and Atmospheric Administration, Technical Memorandum ERL MESA-44

Manuwal, D.A., H.R. Carter, T.S. Zimmerman, and D.L. Orthmeyer. Editors. 2001. Biology and conservation of the common murre in California, Oregon, Washington, and British Columbia. Volume 1: Natural history and population trends. U.S. Geological Survey, Biological Resources Division, Information and Technology Report USGS/BRD/ITR–2000-0012, Washington, DC 132 pp.

Millennium Ecosystem Assessment (MA). 2004. Ecosystems and human well-being: scenarios, Volume 2. Island Press, Washington, D.C. (For an overview of the MA reports 2003-2006 see www.maweb.org)

Montgomery, D.R. and J.M. Buffington. 1997. Channel-reach morphology in mountain drainage basins. Geological Society of America Bulletin. 109(5):596-611

Mote, P.W., A.F. Hamlet, M.P. Clark, and D.P. Lettenmaier. 2005. Declining mountain snowpack in western North America. Bullet in of the American Meteorological Society 86:39

Moulton, L. 2006. The San Juan Archipelago forage fish protection project. San Juan County Marine Resources Committee. http://www.sjcmrc.org/programs/foragefish.htm

NOAA/National Marine Fisheries Servic. 2005. Preliminary draft conservation plan for southern resident killer whales (*Orcinus orca*). www.nwr.noaa.gov/mmammals/whales/preliminkwconsplan.pdf

NOAA. 1984. Tidal current tables, 1985, Pacific Coast of North America and Asia, U.S. Department of Commerce, Rockville, MD, 270 pp.

NOAA/NMFS/NWFSC Tech Memo 44 (See Gustafson et al.)

NOAA/NMFS/NWFCS Tech Memo 45 (See Stout et al.)

Naiman, R.J., D.G. Lonzarich, T.J. Beechie, and S.C. Ralph. 1992. General principles of classification and the assessment of conservation potential in rivers. In P. J. Boon, P. Calow, and G. E. Petts (eds.), River conservation and management, p. 93-124. John Wiley and Sons, New York

National Research Council (NRC). 2004. Valuing ecosystem services: Toward better environmental decision-Making. Committee on Assessing and Valuing the Services of Aquatic and Related Terrestrial Ecosystems, Washington, DC

Newton, J.A. "Low dissolved oxygen in Hood Canal – a science primer." http://www.hoodcanal.washington.edu/aboutHC/scienceprimer.jsp

Nysewander, D.R., J.R. Evenson, B.L. Murphie and T. A. Cyra. 2001. Status and trends for a suite of key diving marine bird species characteristic of greater Puget Sound, as examined by the marine bird component, Puget Sound Ambient Monitoring Program(PSAMP)

Peterson, C.H. and J. Lubchenco. 1997. "Marine ecosystem services," in Nature's services: societal dependence on natural ecosystems, G.C. Daily, ed. Island Press, Washington, DC

Pew Oceans Commission. 2003. America's living oceans: charting a course for sea change. A Report to the nation., Arlington, Virginia

Postel, S., and S. Carpenter. 1997. "Freshwater ecosystem services," in Nature's services: societal dependence on natural ecosystems, G.C. Daily, ed. Island Press, Washington, DC

Puget Sound Action Team (PSAT). 1996. Report/workshop Puget Sound intertidal habitat inventory 1996: Vegetation and shoreline characteristics classification methods

Puget Sound Action Team. 2005. Puget Sound conservation and management plan 2005-2006. Olympia, WA

Puget Sound Action Team. 2005. State of the sound 2004. Office of the Governor (Washington State). www.psat.wa.gov Publication No. PSAT 05-01

Puget Sound Nearshore Ecosystem Restoration Program (See Fresh et al., 2004; Gelfenbaum et al. 2006; and Goertz et al. 2004)

Puget Sound Water Quality Action Team, 2002, Puget Sound Update: Eighth Report of the Puget Sound Ambient Monitoring Program. Olympia, Washington. 144 pp.

Reisewitz, S.E., J.A. Estes and C.A.Simenstad. 2006. Indirect food web interactions: Sea otters and kelp forest fishes in the Aleutian archipelago. Oecologia (2006) 146:623-631

Rensel, J.E. 1993. Severe blood hypoxia of Atlantic salmon (*Salmo salar*) exposed to the marine diatom *Chaetoceros concavicornis*. In: T. J. Smayda and Y. Shimizu (eds.) Toxic phytoplankton blooms in the sea. Elsevier, Amsterdam. Pp. 625-630

Ritter ,et al. 1996. Puget Sound intertidal habitat inventory 1996: Vegetation and shoreline characteristics classification methods http://www2.wadnr.gov/nearshore/textfiles/pdf/skagit96.pdf

Rosgen, D. L. 1994. A classification of natural rivers. Catena 22:169-199

Ross P.S., S.J. Jeffries, M.B. Yunker, R.F. Addison, M.G. Ikonomou, J. Calambokidis. 2004. Harbor seals (Phoca vitulina) in British Columbia, Canada, and Washington, USA, reveal a combination of local and global polychlorinated biphenyl, dioxin, and furan signals. Environ Toxicol Chem 23:157-165

Schwartz, M.L., R.S. Wallace, and E.E. Jacobsen. 1989. Net shore-drift in Puget Sound. Engineering Geology in Washington. Olympia, WA: Washington State Dept. of Natural Resources, Division of Geology and Earth Resources, 1989. 1137-1146

Schwartz, M.L. 1991. Net shore drift in Washington State. (Ecology report series by County). http://www.ecy.wa.gov/services/GIS/data/shore/driftcells.htm

Shared Strategy 2005. 2005. Draft Puget Sound Salmon Recovery Plan. Shared Strategy, Seattle WA. Available at http://www.sharedsalmonstrategy.org/plan/index.htm

Shipman, H. 2004. Coastal bluffs and sea cliffs on Puget Sound, Washington, In: M.A. Hampton and G.B. Griggs, eds., Formation, evolution, and stability of coastal cliffs-status and trends, 1693, US Department of the Interior, U.S. Geological Survey, Denver, CO., 123 p.

Simenstad, C.A., W.J. Kinney, S.S. Parker, E.O. Salo, J.R. Cordell, and H. Buechner. 1980. Prey community structure and trophic ecology of outmigrating juvenile chum and pink salmon in Hood Canal, Washington: a synthesis of three years' studies, 1977-1979. Final Rep. Fish. Res. Inst., University of Washington, Seattle, WA. FRI-UW-8026. 113p.

Solomon, C. 2003. An underwater ark. True Nature. National Audubon. http://magazine.audubon.org/truenature/truenature0309.html

Snover, A.K., P.W. Mote, L. Whitely Binder, A.F. Hamlet, and N.J. Mantua. 2005. Uncertain future: Climate change and its effects on Puget Sound. A report for the Puget Sound Action Team 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)

Strickland, R.M. 1983. The fertile fjord. University of Washington Press, Seattle, 145 pp.

Stout, H.A., R.G. Gustafson, W.H. Lenarz, B.B. McCain, D.M. VanDoornik, T.L. Builder, and R.D. Methot. 2001. Status review of Pacific Herring in Puget Sound, Washington. U.S. Dept. Commer., NOAA Tech. Memo. NMFS-NWFSC- 45, 175pp.

Taylor F.J.R. and R.A. Horner. 1994. Red tides and other problems with harmful algal blooms in Pacific Northwest coastal waters. In: Review of the marine environment and biota of Strait of Georgia, Puget Sound and Juan de Fuca Strait. Can. Fish. Aquat. Sci. Tech. Rep. 1948:175-186

The Nature Conservancy (see Floberg et al. and Crawford and Hall)

Thom, R.M., J.W. Armstrong, C.P. Staude, K.K. Chew and R. Norris. 1976. A survey of the attached marine flora at five beaches in the Seattle, Washington area. Syesis 9:267-275.

Thom, R.M., D.K. Shreffler, and K. Macdonald. 1994. Shoreline armoring effects on coastal ecology and biological resources in Puget Sound, Washington: Coastal Erosion Management Studies, Volume 7, Shorelands Program, Washington Dept. of Ecology, Olympia, DOE Report 94-80

Trainer, V.L., B.-T.L. Eberhart, J.C. Wekell, N.A. Adams, L. Hanson, F. Cox, and J. Dowell. 2003. Paralytic shellfish toxins in Puget Sound, Washington State. J.Shellfish Res. 22(1): 213-224.

Transboundary Report (See Environment Canada)

U.S. Commission on Ocean Policy (USCOP). 2004. An Ocean Blueprint for the 21st Century. Washington, DC

USDA Forest Service, Pacific Northwest Region. 1985. Management of wildlife and fish habitats in forests of western Oregon and Washington. Publication No. R6-F&WL-192-1985. Portland, OR

U.S. Geological Survey; Washington Water Science Center. Streamflow data. http://wa.water.usgs.gov/data/realtime/rt_latest_map.html

Van Cleve, F. B., C. Simenstad, F. Goetz, and T. Mumford. 2004. Application of "best available science" in ecosystem restoration: lessons learned from large-scale restoration efforts in the USA. Puget Sound Nearshore Partnership Report No. 2004-01. Published by Washington Sea Grant Program, University of Washington, Seattle, Washington. Available at http://pugetsoundnearshore.org

Warner, M.J., J.A. Newton, and M. Kawase. 2001. Recent studies of the overturning circulation in Hood Canal. In: Proceedings of the 2001Puget Sound Research Conference. Puget Sound Action Team, Olympia, WA, 9 pp.

Washington Department of Ecology, 1978. Coastal zone atlas of Washington, Jefferson County: WA Department of Ecology Shorelands Division, DOE Pub. No. 77-21-11. http://www.ecy.wa.gov/programs/sea/SMA/atlas_home.html

Washington Department of Ecology. 2003. Chemical contamination, acute toxicity in laboratory tests and benthic impacts in sediments of Puget Sound: A summary of results of the joint 1997-1999 Ecology/NOAA survey. http://www.ecy.wa.gov/biblio/0303049.html

Washington Department of Ecology. 2005. Temporal monitoring of Puget Sound sediments: Results of the Puget Sound Ambient Monitoring Program, 1989-2000 http://www.ecy.wa.gov/biblio/0503016.html

Washington Department of Fish and Wildlife. 2006. Aquatic nuisance species. http://wdfw.wa.gov/fish/ans/ans1.htm

Washington Department of Fish and Wildlife. 2006. Species of concern in Washington State. http://wdfw.wa.gov/wlm/diversty/soc/soc.htm

Washington Department of Natural Resources. 1998. Our changing nature: Natural resource trends in Washington State. Washington Department of Natural Resources, Olympia, WA

Washington Department of Natural Resources. 2006. Washington natural heritage program. http://www.dnr.wa.gov/nhp/refdesk/lists/plantrnk.html

Williams, G.D., R.M. Thom, J.E. Starkes, J.S. Brennan, D. Woodruff, P.L. Striplin, M. Miller, M. Pedersen, A. Skillman, R. Kropp, A. Borde, C. Freeland, K. McArthur, V. Fagerness, S. Blanton, and L. Blackmore. 2001. Reconnaissance assessment of the state of the nearshore ecosystem: central Puget Sound including Vashon and Maury Islands (WRIAs 8 and 9). J.S. Brennan, editor. Prepared for King County Department of Natural Resources, Seattle, WA. 266 pp.

Wunderlich, R.C., B.D. Winter, and J.H. Meyer. 1994. Restoration of the Elwha River ecosystem. Fisheries 19(8):11-19

Major timeline sources:

Ecology. Puget Sound Shorelines. History. http://www.ecy.wa.gov/programs/sea/pugetsound/tour/history.html

Milestones for Washington State History. http://www.historylink.org/essays/output.cfm?file_id=5380

Key Agencies Contributing to Sound Science

King County Department of Natural Resources and Parks
The Department's mission is to be the steward of the region's environment and strengthen sustainable communities by protecting our water, land and natural habitats, safely disposing of and reusing wastewater and solid waste, and providing natural areas, parks and recreation programs.

National Oceanic and Atmospheric Administration (NOAA)
NOAA's mission is to understand and predict changes in the Earth's environment and conserve and manage coastal and marine resources to meet our nation's economic, social and environmental needs.

Northwest Indian Fisheries Commission
The Northwest Indian Fisheries Commission supports wise natural resource management for 21 native American tribes in western Washington.

People for Puget Sound
A non-profit organization committed to protecting and restoring Puget Sound and the Northwest Straits, including our living waters, the land, and a common future.

Puget Sound Action Team
The Puget Sound Action Team defines, coordinates and implements Washington state's environmental agenda for Puget Sound.

The Nature Conservancy
The mission of The Nature Conservancy is to preserve the plants, animals and natural communities that represent the diversity of life on Earth by protecting the lands and waters they need to survive.

US Environmental Protection Agency
The mission of the Environmental Protection Agency is to protect human health and the environment. Since 1970, the EPA has been working for a cleaner, healthier environment for the American people.

US Geological Survey
The USGS serves the Nation by providing reliable scientific information to describe and understand the Earth; minimize loss of life and property from natural disasters; manage water, biological, energy, and mineral resources; and enhance and protect our quality of life.

University of Washington
The primary mission of the University of Washington is the preservation, advancement, and dissemination of knowledge.

Washington State Department of Ecology
The mission of the Washington Department of Ecology is to protect, preserve and enhance Washington's environment, and promote the wise management of our air, land and water.

Washington Department of Fish and Wildlife
The mission of the Department of Fish and Wildlife is to provide sound stewardship of fish and wildlife. It manages fish and wildlife species based on the best available science and the scientific process that generates new information for informed, future decision making.

Washington State Department of Health
The Department of Health works with its federal, state and local partners to help people in Washington stay healthier and safer. Its programs and services help prevent illness and injury, promote healthy places to live and work, provide education to help people make good health decisions and ensure the state is prepared for emergencies.

Washington State Department of Natural Resources
The purpose of the Department of Natural Resources is to protect public resources such as fish, wildlife and water, and to manage state trust lands, including forests, farms, commercial properties and underwater lands.

View the report online (under documents) at:
http://www.nwfsc.noaa.gov/research/shared/sound_science/index.cfm