Sound Science: Synthesizing Ecological and Socio-economic Information about the Puget Sound Ecosystem

Observable, widespread declines in the status of species, habitats, and ecosystem function in marine and terrestrial environments have led to calls for ecosystem-scale management strategies as a solution for what ails watersheds and our coastal oceans (Pew 2003, USCOP 2004). At the core of most descriptions of system-wide approaches to natural resource management is the fundamental importance of considering both factors that drive human behavior and the choices we make regarding our use of natural resources, and a full range of potential consequences of human actions on the natural system. It is clear that implementing such an approach in coastal communities will require understanding not only the biology of terrestrial, estuarine, and marine ecosystems, but also how humans fit into the system as consumers, competitors, and producers. Such a perspective facilitates strategies designed to explicitly consider how biological, social and political factors cumulatively affect the goods and services provided by watershed and coastal ocean environments.

In Puget Sound, we have an exciting opportunity to apply the principles encouraged by the national ocean commissions due to the leadership of Governor Christine Gregoire. The Puget Sound Partnership established by the Governor will set goals for Puget Sound "…..to ensure that the Puget Sound forever will be a thriving natural system, with clean marine and fresh waters, healthy and abundant native species, natural shorelines and places for public enjoyment, and a vibrant economy that prospers in productive harmony with a healthy Sound." In particular, the Governor asks that the Partnership develop recommendations for what actions are needed to"…preserve the health, goods and services needed by the year 2020 to ensure that the Puget Sound's marine and fresh waters will be able to support healthy populations of the native species, as well as water quality and quantity to support both human needs and ecosystem functions."

This document is designed to provide a broadly supported characterization of the Puget Sound ecosystem. This characterization can support the development of an action plan for achieving ecosystem-based goals for Puget Sound. It can also provide a foundation upon which prioritization of funding for research and monitoring in Puget Sound can be conducted. Because of Governor Gregoire's leadership in Puget Sound, we are in the enviable position of having a motivated, intelligent and action-oriented audience for this document. The messages we include here are supported by a broad scientific community, which increases greatly the odds that the decisions made by the Puget Sound Partnership will be based on sound science.

Purpose and Scope

The Puget Sound is one of the defining natural features of Washington State (Figure 1). However, with over 40 species currently listed as threatened, endangered, or as candidates for state and federal endangered species lists, declining populations of food fishes, birds, and over a dozen Superfund sites within the Sound, it is clear that this area has suffered many insults. These impacts are likely to increase, as the human population in the Puget Sound region is expected to double within the next 20 years. Past and ongoing impacts to the ecosystem affect not only our recreational enjoyment of the region, but also human health, fishing, shoreline development, and other economic pursuits (PSAT 2005; Table a).

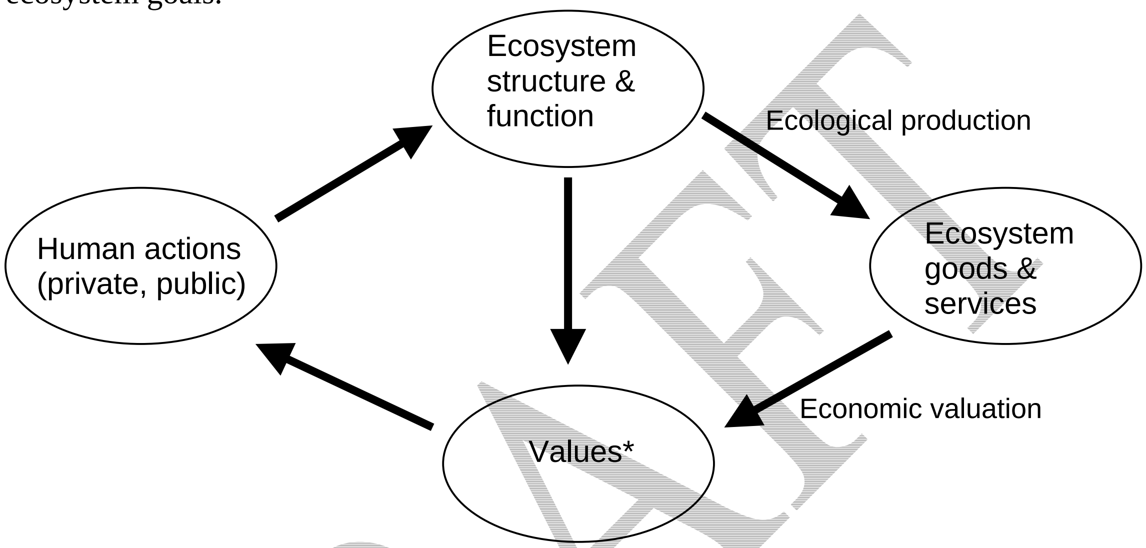
Figure 1. Insert map of Puget Sound region Table a. Insert table with list of major impacts from PSAT, other assessments

In order to meet the Puget Sound ecosystem goals of economic and environmental health, a system-wide perspective is needed. Achieving these multiple goals requires both that they be clearly articulated and that policy-makers have access to assessments of indirect or potentially unanticipated impacts of management actions on the ecosystem (Box 1—urchin barrens), and of potential biological, social and economic tradeoffs between potential management strategies. Science can be instrumental in informing wise decisions in both of these areas. For example, effects of management actions can be translated into "ecosystem goods and services" resulting from ecosystem structural elements such as species and habitats (Box 2). These goods and services can be used as common currencies for comparison among alternative sets of ecosystem-scale actions, allowing the public and policy makers to explicitly consider how changes in ecosystem attributes translate into changes in the services provided by the system. Such a framework also allows consideration of trade-offs among multiple ecosystem objectives and ways to achieve them. In addition, scientists can develop decision support tools that can help organize information to explore ecosystem-level consequences of management actions. By combining ecological estimates of how ecosystem structure and function maintain services with economic estimates of the services' values to humans (e.g., commercial and recreational fishing, shoreline stabilization, cultural heritage, existence of wild species), ecosystem management strategies can be developed so that human actions serve to maintain those values.

Box 1--Insert Box showing pictures of urchin barrens and kelp forests—brief story of the role of otters and other top predators in structuring food webs and habitats.

Box 2--Include list of examples of ecosystem services and how they are just more formal statements of human visions for coastal ecosystems.

The Figure below is from the National Research Council (2004) and shows conceptually how human actions can cause changes in the ecosystem structure and function, which in turn result in different outputs of goods and services from the system. Valuing the ecosystem services and looking at the cost-effectiveness of alternative approaches to achieving ecosystem objectives can inform wise management strategies for achieving ecosystem goals.



*e.g., harvesting, water supply, recreation, transportation, aesthetics, flood, erosion, and pollution control, human health, cultural heritage, species and biodiversity preservation.

The multiple goals of thriving natural systems and vibrant human communities in the Puget Sound region suggests a more integrated approach to managing Puget Sound. We are fortunate to have a wealth of existing scientific work, assessments and planning that already have been done—together, this base of information already can start us on a path towards an ecosystem-scale action plan for achieving Puget Sound goals. As a first step toward supporting ecosystem goals and strategies to achieve them in the Puget Sound region, we provide here an overview of the Puget Sound ecosystem, key science needs for more effective management and currently identifiable threats to the system.

In the first section, we describe the components of the Puget Sound ecosystem, including humans and their effects as part of the system, and characterize linkages between those components. This section summarizes what we know about the Puget Sound ecosystem—its structure, function, and the goods and services it could provide. We know a lot about some parts of the ecosystem—the species, habitats upon which they depend and the processes that maintain those habitats. For some species, habitats, and processes, we have a fairly good understanding of how human actions threaten their persistence and function. However, we know less about the complex food web relationships among species and how the cumulative effects of human actions interact to impact the ecosystem. Our understanding of how Puget Sound produces ecosystem goods and services, and how to assign values to those goods and services is in its infancy. In this section, we also highlight those key threats that clearly have a significant impact on ecosystem elements. We also identify key information needs, defined as gaps that, if filled, would substantially improve our ability to anticipate ecosystem responses to environmental variation and human actions, and therefore our ability to manage for specific ecosystem goals.

In the second section of the document, we summarize how both biological and social science tradeoffs can be assessed in decision frameworks for ecosystem approaches to management in Puget Sound. We illustrate these ideas with a transparent and clear decision framework that can be used to organize what we know about the natural and socio-economic systems to develop short-term management strategies for achieving ecosystem goals. These decision frameworks are designed to adapt strategies over time as our understanding improves of how the ecosystem functions, the relative cost effectiveness of alternative actions and how changes in ecosystem functions lead to changes in the goods and services.

Finally, in the last section, we identify key findings that can contribute to developing both short and long-term action plans and ultimately to achieving Puget Sound goals identified by the region. This section highlights the conclusions from this synthesis and points towards how these findings might inform the charges facing the Puget Sound Partnership.

The Puget Sound Ecosystem: Biological, Physical and Human Components

Overview

The U.S. Puget Sound includes the waters that extend from the mouth of the Straits of Juan de Fuca east including the San Juan Islands and south to Olympia (Figure 2). It is a large, complex estuary that covers an area of approximately 2,330 km^2, includes about 3,700 km of shoreline, and is fed by thousands of streams and rivers that drain a total land area of about 35,500 km^2. Based primarily upon geomorphology, extent of freshwater influence and oceanographic conditions, Puget Sound can be sub-divided into five major basins: North Puget Sound, the Main basin, Whidbey Basin, South Puget Sound and Hood Canal. Each of these basins differs somewhat in such features as temperature regimes, water residence and circulation, biological conditions, depth profiles and contours, processes, species, and habitats. On average, the Puget Sound has a depth of 62.5m, but ranges to nearly 300m 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 physical features of the Puget Sound support a diverse array of plants and animals. There are at least 100 species of birds, 26 species of marine mammals, 200 species of fish, and thousands of species of plants and invertebrates that can be associated with the waters of Puget Sound. While some of these species are biological invaders (e.g., *Spartina*), most of the species of Puget Sound are native species that include both residents and transient or migratory species.

Both physical and biological features of the landscape have changed in response to ongoing settlement and increased population in the area. Land use changes have continued to convert the natural landscape to residential, commercial and industrial use. Between 1991 and 1999 alone, 73 more square miles of land was developed and 241 square miles of forested lands were lost (PSAT 2005). Approximately 1/3 of the shoreline of Puget Sound has been impacted with bulkheads or overwater structures, much of it as a result of residential development. A wide variety of contaminants can be found in the waters, sediments, and biota of Puget Sound ranging from metals (copper) to organic chemicals (PAHs, PCBs). Some areas are so contaminated (e.g., Eagle Harbor and portions of the Puyallup and Green river estuaries) that they have qualified for SuperFund cleanup.

In this section we describe the Puget Sound ecosystem in more details. We address six elements in particular: 1) habitats and physical factors that drive habitat types and distribution; 2) global processes, such as climate; 3) local, marine physical and chemical processes, including circulation; 4) interactions between freshwater or terrestrial systems and the marine system; 5) food webs, species interactions and individual species' biology; and 6) socio-economic factors influencing the ecosystem. These elements are linked in a conceptual model of the system (Figure 2). Global processes, and marine and freshwater or terrestrial processes all affect habitat distribution and availability as well as food webs and other species interactions. All can be affected by external natural or anthropogenic mechanisms, either directly or indirectly. Finally, the interaction of all these elements provides tangible or intangible “goods” that are valued by humans. For each element, we also identify “key” science needs or gaps – those pieces of information, that if obtained, would allow more effective management of the system -- and, where currently available information allows, key threats to that element.

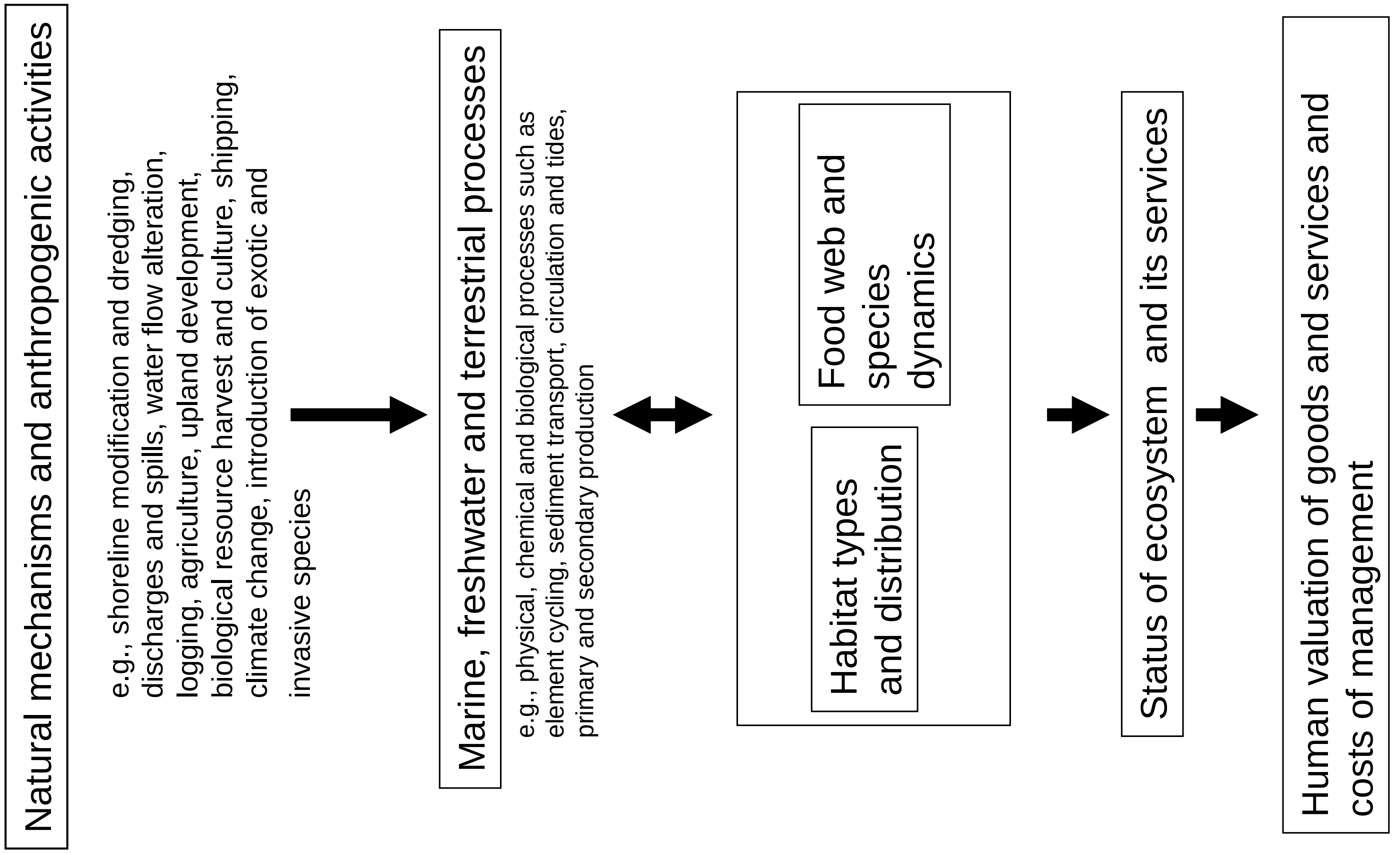


Figure 2. Natural and anthropogenic drivers of changes in ecosystem processes, structure & function; and the resulting ecosystem goods and services

Puget Sound Habitat Types and Distribution

The marine ecosystems of Puget Sound are distributed across a mosaic of habitat types that support a rich array of species. In our conceptual model (Figure 2), Puget Sound habitat types and distribution are influenced by physical and chemical processes in the marine and freshwater realms, and both influence and are influenced by species interactions. Habitat types and their distribution also mediate many of the goods and services valued by humans. In this section, we provide an overview of habitats and species typical of Puget Sound for use as a general reference throughout this document. The goal of this section is not to develop a detailed taxonomy or typology of habitat types, but instead to provide a framework for discussing major habitat types and linking them to the physical and biological processes that have the potential to shape or modify them. We first identify several key physical attributes of marine habitats in Puget Sound, and then briefly describe some of the species characteristic of each habitat and impacts of the human activities that take place in each. Several more complete treatments of habitat exist, for example, Dethier's Habitat Classification Scheme. More comprehensive treatments of the marine flora and fauna can be found in Kozloff 21983). The natural history of the region is described in Kruckeberg (1991).

Key physical attributes of marine habitats in Puget Sound include depth and factors such as light and temperature that are correlated with depth, substrate type, water properties (temperature, salinity, nutrients), and hydrodynamic regime. A primary division in our characterization is those habitats that exist in the water column vs. those that are associated with a substrate. Depth and its correlates influence both benthic and pelagic community composition through physical (e.g., light, temperature), and biological (e.g., food web) processes. Within both water column and benthic habitats, we further distinguish between habitat types found at different depths. Finally, substrate type is a primary determinant of community composition, and we identify areas of different substrate. Water properties throughout the Sound influence planktonic communities and the food webs they support. Hydrodynamic regimes, especially those driven by tidal forcing, interact with other physical and biological attributes to shape habitats and their characteristic biological communities Disturbance events, both natural and anthropogenic, also exert control over species interactions, habitats, and ecosystem form and function.

We first describe characteristics of the pelagic realm, defining the water column as habitat, then proceed to describe several key benthic habitats.

The Water Column

The water column comprises the aqueous habitat in which planktonic and demersal organisms exist. For convenience, the water column often is divided into the euphotic (lighted) and aphotic (unlighted) zones. The bulk of primary production occurs within the euphotic zone, which extends to variable depths, depending on water clarity and penetration of sunlight. Phytoplankton are most abundant in the euphotic zone, where they form the basis of marine food webs. Areas of upwelling or vigorous tidal mixing can support blooms of large centric diatoms that can lead to trophic intensification that supports dense feeding aggregations of fish, birds, and mammals. In other areas, for example Hood Canal and Port Susan, injection of nutrients can cause phytoplankton blooms that lead to hypoxia or anoxia, in some cases causing mortality among fish and invertebrates. Where it occurs, hypoxia is generally a characteristic of deeper waters.

Nearshore waters are tightly linked to upland areas via freshwater inputs. Terrigenous sources of sediment, toxicants, and pollutants all are delivered to nearshore waters in suspension or solution via fluvial, stormwater, or municipal inputs. These can remain entrained in surface layers until the lower-salinity surface waters are mixed with deeper waters. Tidal forcing causes nearshore low-salinity water masses to mix with those further from shore to form water masses of intermediate characteristics. Mixing occurs in both horizontal and vertical dimensions, through the formation and dissipation of tidal eddies and through upwelling at sills, and results in redistribution of terrestrially-derived particles and solutes throughout the water column. Some particles—for example, terrigenous sediments carried in the Fraser River plume—influence pelagic ecosystems via attenuation of light in the upper water column, with consequent impacts on primary productivity. Conversely, terrestrially-derived solutes tend to impact pelagic ecosystems via physiological or metabolic pathways that can have negative consequences for marine organisms. PCBs, dioxins, and other endocrine disruptors can act in this fashion to increase the incidence of disease in vertebrates within Puget Sound.

Trophic webs link nearshore pelagic areas to those further offshore and in deep basins. For example, middle trophic species such as herring, surf smelt, and sandlance use nearshore areas for feeding and reproduction; they in turn are preyed upon by piscivorous fish which ultimately are consumed by birds and mammals. Ontogenetic shifts, for example transitions from larval or juvenile to adult phases, also serve to link shallow nearshore areas with deeper offshore areas. For example, larvae of some rockfish (*Sebastes spp*) species appear to spend a portion of their planktonic life history in surface waters. Juveniles recruit to shallow (<20 m) benthic areas, while adults inhabit deeper areas. Detrital and microbial food webs provide additional important linkages between shallow nearshore areas and deeper offshore areas.

Benthic habitats

<u>Beaches</u>

Puget Sound's beaches are formed from sediment supplied by the erosion of coastal bluffs and redistributed by wave action and littoral drift. They are composed of mud, sand, gravel, or cobble, or a mixture of these. Sandy beaches tend to be unstable and typically support relatively few species and relatively low biomass. Among the more conspicuous species on sandy beaches are beachhoppers, small amphipods that consume drift algae deposited by tides and which are themselves consumed by shorebirds. Like sandy beaches, gravel beaches tend to be unstable and support relatively few species. Stability tends to increase as grain size increases and cobbles become larger and more numerous.

In such areas, epibenthic algae and small invertebrates become more abundant, and infaunal invertebrates become more numerous and diverse. In northern regions of Puget Sound, mixed-substrate beaches support opportunistic algal species, for example, the sea lettuce *Ulva*, as well as epibenthic barnacles and littorine snails, and infaunal polychaetes, arthropods, and molluscs. In southern regions of Puget Sound, epibenthic barnacles, snails, and the Pacific oyster dominate such beaches. Edible clams occupy the low intertidal zone on some beaches.

Humans interact with beaches in many ways. Beaches are preferred sites for many recreational activities, including beachwalking and clamming, and they offer staging areas for activities such as SCUBA diving and kayaking. Upland areas adjacent to beaches are preferred for residential development; in many areas of Puget Sound, residential development has led to beach hardening in efforts to protect homes and other buildings.

<u>Rocky habitats</u>

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. Rocky substrates tend to be more stable than sediment-dominated habitats, and the biological communities that develop on rocky shores reflect this. Some species are very long-lived, reaching ages of several decades or more; other species create highly persistent patches composed of multiple, short-lived individuals. Still other species are short-lived and highly opportunistic, taking advantage of space opened through physical disturbance or by mortality of longer-lived individuals. The rockweed *Fucus gardneri* is abundant on rocky shores throughout the region, where it grows mixed among several species of barnacles. *Fucus* communities 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 that support a different but equally rich community of grazers and predators. Urchins and abalone are among the species found in association with kelp communities; both species have declined sharply due to human removals for food, and abalone now are a conservation target in rocky areas where they once were abundant.

Deep rocky habitats are characterized by the absence of kelps and other large seaweeds, and by the presence of benthic suspension feeders and multiple species of fish, including several species of rockfish (*Sebastes spp.*). Adult rockfish tend to associate with emergent rocky substrates (bedrock, boulders), to which they appear to have high site fidelity. Site fidelity, coupled with characteristics of delayed reproduction, extreme longevity, and susceptibility to fishing-induced embolism, combine to make rockfish highly vulnerable to overfishing. Populations of most species of rockfish in Puget Sound have declined sharply, and most now are conservation targets.

Humans interact with natural communities on rocky shores through recreation and through shoreline development. Both can have negative impacts where the disturbance is frequent or severe. For example, beachwalkers unintentionally can cause mortality of seaweeds and invertebrates through trampling, and the construction of docks, piers, and beachfront homes can modify the physical environment in ways that reduce habitat quality for rocky-shore organisms.

Estuaries, Deltas, and Bays

In an oceanographic sense, the entire Puget Sound constitutes a single large estuary, characterized by fluvial forcing that establishes an estuarine circulation pattern typified by the efflux of low-salinity water at the surface and influx of more saline oceanic water at depth. In a more vernacular sense, Puget Sound is comprised of multiple smaller estuaries, each created by one of the numerous rivers that drain into Puget Sound. These smaller estuaries contribute disproportionately to the overall productivity of Puget Sound. Their shallow expanses of well-lighted water promote the growth of phytoplankton, seagrass, and seagrass epiphytes. These form the basis of important nearshore food webs, provide habitat essential to juveniles of several important species (e.g., out-migrating salmon smolt), and export particulate and dissolved organic matter to offshore areas.

Deltas are formed in areas where rivers deposit large amounts of sediment in nearshore areas. Deltas are characterized by their soft sediments and brackish waters, both of which influence the species that occupy deltaic areas. Rooted vegetation—for example, 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. Marsh plants are important to the development of nearshore food webs, including those important to migratory birds.

Bays share several important characteristics with small estuaries—they tend to be shallow, well-lighted, and highly productive, and they often support the growth of eelgrass and associated communities. Not all bays are supplied by rivers, however, and bays therefore can differ from small estuaries in their physiographic and oceanographic characteristics. Although many bays are characterized by soft-sediment habitats, some bays in the northern and western areas of Puget Sound are rocky, or are a mixture of soft-sediment and rocky habitats.

Estuaries, deltas, and bays all are highly desirable and heavily utilized for a variety of human activities. Recreational uses include boating and fishing (including crabbing and clamming). Commercial uses include aquaculture, fishing, and the construction of facilities (e.g., docks) and the modification of habitat (e.g., dredging) to support such activities.

Figure 3. A panel figure with photos of several different habitat types.

Interactions between Habitats and Other Ecosystem Elements

Aquatic organisms have adapted to variability in the natural environment by evolving life history strategies that reduce their reliance on a particular habitat or optimize their opportunities for successful reproduction (Gross 1987). As an example, Pacific salmon integrate habitats and ecosystems from headwater streams and uplands to the estuary, Puget Sound, and thousands of miles into the ocean by active migration and homing. During this migration the salmon transition through various food webs (Keeley and Grant 2001) initially feeding on aquatic and terrestrial invertebrate drift (or zooplankton) in freshwater, benthic and epibenthic taxa such as amphipods and copepods as well as mysids, cumaceans, isopods, polychaetes, and shrimp in shallow nearshore waters (Kaczynski et al. 1973, Simenstad et al. 1982, Duffy 2003), and planktonic and neustonic taxa such as crab larvae, larvacean, Euphausiids, and fish in deeper nearshore waters (e.g., Simenstad et al., 1980; summarized in Duffy 2003).

Other species such as the bull trout and coastal cutthroat trout are also anadromous, but have a much more limited seaward migration and much greater reliance on the nearshore waters of Puget Sound. Marine birds such as seabirds, waterfowl, and shorebirds similarly integrate habitats over a wide geographic expanse and ecologic range through their migrations. Habitat or ecosystem change in one of the connected habitats therefore affects the other connected habitats through its impact on the condition or behavior of migratory species. Loss of estuary habitat, poor ocean conditions for salmon, or excess harvest result in fewer spawners returning to streams, reduced contribution of marine nutrients from salmon carcasses to the streams and associated riparian and terrestrial community, and lower productivity in these habitats and communities. Reduced numbers of salmon also have a direct effect on their predators including orcas, pinnipeds, and bears.

The nearshore of Puget Sound provides very important habitat to shorebirds, waterfowl, shellfish, finfish, and numerous other biota. Armstrong et al. (1976) found hundreds of species of invertebrates and Thom et al. (1976) found 157 species of algae in the intertidal zone of five beaches within the central Puget Sound. Community studies for eelgrass, saltmarshes, tidal channels, and coastal sand dunes reveal that numerous species use nearshore habitats for part or all of their lives (Canning and Shipman, 1995). Many of the animals that spend some time on or in beaches are there to feed, reproduce, rear, or rest.

Physical processes also influence habitat distribution and abundance. Currents, including tidal currents, affect substrate and determine whether particular areas are depositional or erosional habitats, and thereby affect the structure and productivity of the biotic community. Winds affect water column mixing. Upland watersheds have distinct effects on many estuarine and marine habitats and species through flow (hydrograph and effect on salinities downstream), turbidity, and temperature, and delivery of sediments, nutrients, and contaminants and these effects vary among seasons and basins. For example, two-thirds of the freshwater reaching Puget Sound enters the main basin through the Skagit and Snohomish rivers via the Whidbey Basin with smaller amounts contributed by Lake Washington and Duwamish and Puyallup rivers (Strickland 1983). The amount of freshwater delivered into the Sound is determined by runoff and snowmelt which vary seasonally.

Dams have disrupted the natural connectivity within watersheds and between watersheds and the estuary/ocean in Puget Sound as in other parts of the PNW and the world. Two dams on the Elwha River (Strait of Juan de Fuca; dams slated for removal within the next few years) starved the lower river, estuary, and associated nearshore areas of sediment for nearly a century, reducing gravel and finer substrate habitats in these downstream areas and correspondingly depleting salmon and bivalve populations (Wunderlich et al. 1994). Forage fishes, marine birds, marine mammals, and other species no doubt also have been affected but the effects are unquantified. Monitoring to evaluate dam removal should shed light on the former impacts on these other biota (Triangle Associates, Inc. 2004).

Current and Potential Threats to Puget Sound Habitats

Coastal Development

Coastal development has fundamentally changed the landscape of the Puget Sound. Shorelines have been converted to commercial or residential uses; wetlands have been dredged or filled; hydrological systems disrupted by diking or channeling. Since European settlement, Puget Sound had lost 58% of its intertidal habitat (Hutchinson 1988); the Duwamish, Lummi, Puyallup, and Samish River deltas have lost 92% of their intertidal marshes (Simenstad et al. 1982, Levings and Thom 1994); and at least 76% of the wetlands around Puget Sound have been eliminated, converted to industrial uses in urban areas and to farmland in rural areas. The mudflats associated with the deltas of these estuaries have also substantially declined. About 30% of Puget Sound's beaches now are armored; in some areas, nearly 100% of the shoreline is armored. Armoring reduces the supply of sediment to beaches, leading to narrowing and coarsening, increased scour, and erosion of adjacent areas. These physical changes have negative consequences for littoral species and for ecosystem health.

Invasive Species

Non-native invasive species (NIS) cause negative impacts to receiving environments via habitat alteration, resource competition, food web interactions, and pathogenesis. Among the known NIS in Puget Sound are vascular plants (*Spartina spp.*, *Sargassum muticum, Zostera japonica*) and marine invertebrates (several sea squirts, bivalves, drilling snails and zooplankton). Other non-native species are present but not yet obviously invasive (e.g., Atlantic salmon and American shad), and still others are cryptogenic (of unknown origin, e.g., some sea lettuce species). Alteration of habitat by NIS already has occurred, for example conversion of tidal flats to vegetated meadows via sediment accretion by *Spartina spp*.; loss of native understory kelp species due resource pre-emption by *Sargassum*; and loss of intertidal *Fucus* due to interactions with Pacific oysters. Evidence from San Francisco Bay and other west coast estuaries suggests that NIS will increase in Puget Sound, with increasing negative consequences for native systems.

Additional threats to be fleshed out:

- Contamination of water and sediment
- Anthropogenic hydrological modifications in watersheds affecting both water and sediment

- Human population growth (and concomitant impacts to habitats and habitat-forming processes)
- Changes in physical habitat-forming processes (e.g. currents, sediment delivery) due to changes in climate

Key Science Needs

- Data to describe and quantify linkages between ecosystem processes, habitat structure and organism response.
- Characterization of deep benthic and pelagic habitats, including their biota and human impacts.
- Understanding of likely effects of climate change on habitat-forming processes and habitat distribution
- Description and quantification of single and multiple stressor effects on habitat quality, quantity and distribution (including habitat modification, invasive species, etc.)

Note to reviewers: Both key threats and science needs will require greater description, and will be modified in response to reviewer comments.

Influence of Climate and Other Global Processes on the Puget Sound Ecosystem

That climatic variation underlies the dynamics of many populations, communities and ecosystems is hardly a new idea. In our conceptual model (Figure 2), we include climatic variation as a natural process influencing these elements. Inter-annual (e.g., El Niño events) and inter-decadal climate variability (e.g., climate regimes) generate substantial changes in precipitation and winds that effect changes in primary production, which in turn propagate throughout. In marine systems, climatic processes like El Nino Southern Oscillation (ENSO) have substantial ecological and fisheries consequences in the short term, while climate regimes described by the Pacific Decadal Oscillation (PDO) have longer lasting consequences. To better manage Puget Sound marine resources and anticipate indirect consequences of our actions, or respond effectively to natural variation in the system, we need to understand the mechanisms through which climate affects these systems and incorporate that knowledge in to our prediction and management.

Climate and oceanography are clearly linked through coupling and positive feedback in the overall processes of global heat redistribution. The two are also linked in their effects on marine ecosystems. Large-scale climate patterns effect changes in physical oceanography that in turn influence population dynamics and ecosystem function. Since oceanography is the mechanism through which climate affects marine populations, it is appropriate to investigate jointly their impact on Puget Sound ecosystems. Better understanding the influence of climate on marine populations is important for making better short and long-term predictions, evaluating the past effects of human impacts, determining remediation approaches to current problems, and defining our expectations. In this endeavor defining the mechanisms through which climate affects population and ecosystem dynamics is essential.

The El Niño Southern Oscillation (ENSO) and Pacific Decadal Oscillation (PDO) – Key ecosystem drivers

A primary oceanographic mechanism through which ENSO and the PDO regimes influence marine ecosystems is through the disruption of coast upwelling, which influences water temperature and nutrient availability. Wind-driven coastal upwelling in the eastern margins of the world's oceans results in highly productive fisheries. El Nino events and warm regimes disrupt this upwelling through both the weakening of upwelling favorable winds and the deepening of the thermocline due to relaxed traded winds, resulting in reduced nutrient availability and consequently lower primary productivity. These oceanographic effects propagate through the biological side of the system devastating fisheries yields. The ramifications are more complex than simple changes in abundance or biomass based on productivity. They include changes in assemblage structure and the distributions of species in depth, latitude, on-shore vs. off-shore location as well. For example, changes in the strengths of the Alaska and California currents under different PDO conditions affect the relative abundance of northern and southern copepods, which in turn influences recruitment success of some of their predators.

Climate Change and its potential effects on Puget Sound

There is a strong consensus that human activities have induced and will continue to cause profound climate change through global warming. This change has and will continue to impact marine ecosystems, and the challenge that we face is to manage marine resources in the face of this change. Climate change may manifest as increases in the frequency and intensity of extreme events like El Nino, submarine eruptions that cause fish kills, and anoxic events due to changes in ocean circulation. Changes may also occur as the result of more general changes in the ocean system like a general warming and changes in productivity. Predicting the impacts of these changes on the ecosystem and related fisheries is an important task and requires an understanding of the mechanisms though which climate and oceanography affect fish stocks.

The Climate Impacts Group at the University of Washington published two important reports (Snover et al. 2005; Mote et al. 2005) for the Puget Sound Action Team that document the evidence that climate change has and will continue to occur. Further, these reports document a number of potential impacts that climate change may have on the Puget Sound ecosystem. Here, we highlight several of their key findings.

Based on extensive review of climate records, the UW Climate Impacts Group 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. On average temperature increased about 2.3^{o}F from 1900 to 2000. While changes temperature shows a clear warming trend, changes in precipitation are more variable—so variable that, to date, any trend in precipitation cannot be distinguished from the recorded long-term variability in the system.

Climate models predict an average rate of warming of 0.34°C per decade through 2040 (with some models projecting a rate as low as 0.2°C and as high as 0.5°C per decade). Even though projected changes in precipitation are presently unclear, changes in temperature will have significant impacts on snowpack and stream flow, thus altering freshwater input into Puget Sound. The UW Climate Impacts Group work shows that the timing of water input into the Sound has changed substantially with more water entering the Sound earlier than historically. For instance, with warmer temperatures and less snowpack, the amount of water currently entering Puget Sound between June-September has declined by 18% as compared to the historical record. Additionally, most of the glaciers in the region have been retreated for 50-150 years, affecting flow rates in some systems. Overall, we can expect reduced spring snowpack, earlier spring snowmelt, increased winter flow and decreased summer flow.

Water temperature, salinity, density, dissolved oxygen, and nutrients are influenced by climate-related fluctuations in the Pacific Oceans, freshwater input and local weather. While human activities around Puget Sound clearly affect these attributes of water quality, climate change may potentially exacerbate these problems. For instance, rises in sea level associated with climate warming could affect nutrient levels in surface waters via increased leakage from septic systems.

Such changes can have significant impacts on the Puget Sound system. For example, changes in flow along with changes in temperature, solar radiation, winds can affect density gradients within the water column and thus promote or inhibit stratification (layering)in Puget Sound. Any factor that mixes water masses (e.g., winds, tidal circulation) will decrease stratification, and factors that increase density differences (e.g., fresh water input to the surface, high solar radiation) produce or maintain stratification. A typical model of estuarine stratification is of two layers: relatively warm, fresh water overlying colder, more saline water with separation marked by a distinct pycnocline (region of highest density gradient).

The intensity and persistence of the density stratification of a water column is a key factor with wide–ranging effects. The development of stratification within the water column is significant because of the physical barrier it presents with respect to vertical water movement. Turbulent eddies, driven by winds and tides, cause vertical mixing of phytoplankton, DO, nutrients, etc. If, however, the water is stratified, that is, its density increases significantly with depth, then the ability of turbulent eddies to accomplish vertical mixing will be greatly decreased. This is particularly true at the pycnocline, the region of greatest density change, which is often observed 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 be affected: surface waters can become depleted of nutrients (dissolved nitrogen and phosphorus) and bottom waters can become depleted of oxygen. This is due to phytoplankton growth in the surface water that will deplete ambient nutrients, with no re-supply from nutrient-rich deep waters, and to the decomposition of the organic material in the bottom water that will consume oxygen, with no re-supply from oxygen-rich surface water.

While reduced river input to Puget Sound–Georgia Basin could be hypothesized *a priori* to increase salinity of the receiving marine waters, marine water properties are affected by weather–related forcing on a substantial scale. For example, the 2000–2001 drought period and its associated increase of estuarine salinity lead to higher density surface layers and weaker stratification, with a percent reduction in stratification averaging ~50% for Puget Sound–Georgia Basin and the outer Washington coast estuaries. Furthermore, a result of the higher salinity surface waters and weaker vertical density gradient is a decreased outflow velocity through the Strait of Juan de Fuca. In fact, flow was affected by a factor of four between drought and normal flow years; the reduced seaward flow presumably translates to longer residence times in the estuary. Implications of this could be substantial to ecosystem–level processes. First, marine water quality conditions, such as low dissolved oxygen concentrations, which are maintained by density stratification, could be affected. A reduction in stratification could lead to less probability of low oxygen because of increased mixing (less of a seawater density gradient to overcome). Alternatively, the reduced exchange velocity and an increased water residence time in the estuary could lead to lower oxygen concentrations because of increased time when respiration dominates before exiting the system.

Although stratification is necessary for phytoplankton growth it also optimizes the chances for low DO concentrations. Conditions favorable for phytoplankton growth are sufficient light and nutrients and some degree of stratification (i.e. to prevent mixing out of the euphotic zone). Under such conditions, phytoplankton biomass increases in the upper layer of the water column and nutrients are consumed as growth continues. Without a replenishing source, surface nutrient concentrations decrease and can limit phytoplankton growth, causing a decrease in their biomass. When a nutrient source is available to surface waters, however, phytoplankton production will never reach a nutrient-limited state. Nutrient input can occur naturally through mixing, but the mixing also causes light limitation thus preventing significant population increase. Eutrophication (external increase in nutrient supply to system) of nutrient-limited stratified waters can result in very large algal blooms and, after these sink, a correspondingly large DO debt in bottom waters. However, the physical stratification of the water receiving the nutrient input is important, as inputs to well-mixed water columns have no immediate effect.

Attributes of the saltwater in Puget Sound are a function of climate conditions in the coastal ocean. As discussed above, coastal waters are highly influenced by coastal upwelling, and thus any affect of global climate change on upwelling can have profound influences on the ecosystem of Puget Sound. Exactly, how global warming will affect the crucial wind patterns that drive upwelling is currently unclear.

One of the best understood and most predictable components of climate change is sea level rise. Globally sea level has been increasing at a rate of abut 1-2 mm per year. How this global average is translated to Puget Sound is the by-product of a host of geological factors. For example, land in some regions of south Puget Sound land are sinking more than 2mm per year, while land does not appear to be sinking in regions of north Puget Sound. Thus, we might expect net sea level rise in south Puget Sound to be greater than the global average. Additionally, some climate models predict shifts in winds that could increase sea level rise by an additional 20cm in some regions of the Sound.

Consequences of climate change for the Puget Sound Ecosystem.

While a number of human activities clearly have had profound impacts on the ecosystem in the Sound, climate change probably has had little impact on the ecosystem relative to other risk factors. However, the consequences of future climate change are significant.

Warmer temperatures may increase the productivity of plankton in surface waters. As discussed above this could lead to decreases in dissolved oxygen (DO). Depletion of DO in the water column can have a serious impact on marine ecosystems. The degree of impact will be dependent upon the intensity of the DO depletion as well as the temporal and spatial stability/persistence of the depressed DO levels. In addition, the effects of DO depletion are both organism and habitat-specific. Certain species of fish are stressed by environmental conditions of DO concentrations just under 5 mg/L. Other species may not exhibit stress at 2.0 mg/L. Benthic infauna and, particularly, molluscs are more resistant to hypoxia.

Continuous or even intermittent hypoxic events may result in a shift in species composition. Fish may move away from the depleted area, or have higher susceptibility to disease. Motile species that are affected will attempt to leave the hypoxic area. Sedentary species may be killed outright, or exhibit significant changes in reproductive rates and larval recruitment. The species composition of a given area may also shift in response to changes in predator-prey relationships. Hypoxic conditions can initiate behavioral changes and physiological stresses. The diel pattern of vertical migration exhibited by some zooplankton to avoid predation can be interrupted. Copepods have been found to remain in the pycnocline in an attempt to avoid a bottom layer of low-oxygenated water. Hypoxia may also inhibit the hatching of zooplankton eggs, thereby reducing larval recruitment, and suppress metabolic rates.

Thus, the net effect of oxygen depletion in marine waters may be a shift in species composition, a decrease in population numbers and species diversity with a resulting decrease in amount and type of biomass, a disruption of the usual predator-prey interaction, and a shift in the expected trophic pathways. These combined effects can result in reduced availability and subsequent harvest of marine resources.

Rising sea level will also contribute to significant ecosystem changes. Salt marshes, for example, are among the world's most productive habitats and support a number of important species and provide important ecosystem services. As discussed elsewhere, salt marshes in Puget Sound have declined dramatically as the result of a number of human activities. To date, climate has had little impact on remaining marshes because the rate of accretion of sediments in salt marsh has kept pace with the modest rise of sea level. However, as the rate of sea-level rise increases, accretion in salt marshes will not be able to match the pace resulting in their flooding and subsequent demise.

In addition to salt marshes, other nearshore biogenic habitats such as eelgrass and bull kelp are at risk. Because optimal eelgrass productivity occurs within a narrow band of temperature and salinity, climate change is likely to affect the spatial extent of eelgrass meadows. For instance, if winter temperatures warm, then eelgrass productivity might increase; unless temperatures become too high in which case eelgrass would become stressed. Similarly, bull kelp may be negatively affected by increased water temperature. On the other hand, increased levels of CO_2 may increase growth of kelp.

How climate change will affect upper trophic levels in the Puget Sound ecosystem is complex and not well understood. Fish, seabirds and marine mammals can be affected by climate change though changes in the metabolic budget of animals, changes in habitat, availability of food, or changes in patterns of circulation that affect larval dispersal.

Growth and reproduction in fish is governed by how much energy they require to maintain their basal metabolism and available food resources. When temperatures rise, the energy required to simply stay alive increase and thus the amount of energy available to growth and reproduction will be less. Lower rates of growth and reproduction means that the resiliency of these populations to perturbations (including fishing) is reduced. This is compounded since many fish species directly or indirectly use habitat such as kelp or seagrass beds that may also be declining.

Many marine fish and invertebrates produce pelagic larvae that are dispersed by currents. Since these small larvae have limited swimming abilities, changes in patterns of circulation may affect where and when offspring are delivered.

Certainly, changes in the food web as a consequence of climate change can be expected, but exactly how such changes will be manifested is unclear. We know that shifts in the PDO are accompanied by large shifts in the flow of energy through food webs, but how global climate change will affect food web dynamics is still a matter of speculation.

Using climate information in natural resource management

While climatic variability may be viewed by some as simply background noise, the twists and turns in the ongoing dialogue between the ocean and marine species has important implications for how we manage resources in Puget Sound. For example, scientists frequently determine the maximum sustainable yield of fish stocks based on average conditions over a number of years. Clearly, conditions during El Niño episodes are not average, making predictions based on average environments error prone. What do we need to do to better manage Puget Sound's marine resources in the face of the irregular climatic rhythms such as El Niño or the PDO? We first require accurate predictions of climate events, and we then need to understand how different fish species respond to changing marine conditions so that we can alter our management schemes accordingly.

Although we are not there yet, scientists have made great strides in recent years. Climatologists now use computer models to predict what ocean conditions will prevail several years into the future. The results of such models are by no means perfect, but they do give a better indication of the conditions that fish will face, rather than simply assuming conditions will be average. The Peruvian anchoveta provides a good example of how such El Niño forecasts might be used in marine resource management. Since 1983, El Niño forecasts have been issued in Peru. Typically, these forecasts would predict one of four possibilities: (1) average conditions; (2) a weak El Niño with some disruption of the upwelling system; (3) a major El Niño that strongly interferes with upwelling, or (4) cooler than normal waters offshore (also known as La Niña). Once the forecast is issued, fisheries scientists and government officials can decide on the appropriate levels of harvest.

The ability to use forecasts to alter management requires some understanding of the mechanisms by which climate affects the marine species or habitats being managed. The response of managers to an impending El Niño would certainly vary if the effects of the El Niño were based on changes in DO, food resources, migratory patterns, juvenile survival, etc.. While there is a copious literature describing the impacts of climate on the productivity of marine species, much of this work has simply described patterns, but not the underlying processes producing the patterns. Clearly, the management of Puget Sound for species affected by climate needs to be tuned to the biology of the species of interest. Attention to such biological processes in concert with accurate climate models will begin to give resource managers the tools they need to protect the ecosystem of Puget Sound.

Key Science Needs

1. We know very little about how and why Puget Sound species are affected by climate. Detailed studies of how climatic variation affects such parameters as rates of growth, reproduction, survival, migratory patterns, feeding habitats is crucial.
2. Thus far, the effects of climate on ecology have focused on single-species effects. That is, how does climatic variation affect patterns of abundance of one species. We have very little understanding of how climate will affect ecological communities. For instance, how does climate affect the strengths of food web linkages or competitive interactions.
3. While models predict changes in the timing of freshwater input into Puget Sound, less well documented are studies of how these changes in flow may affect marine water properties in the Puget Sound–Georgia Basin and, in turn, what effects on circulation, timing of phytoplankton blooms, and water quality might be anticipated. We lack a comprehensive and quantitative understanding of how variation in forcing by rivers, ocean, and local weather affect physical and biological processes, as well as their coupling, in the Puget Sound–Georgia Basin region.

Physical and chemical processes in the Puget Sound Ecosystem

The goods and services provided by marine ecosystems rely on maintenance of processes that are described by highly dynamic and interacting physical, chemical and biological elements of the freshwater/terrestrial and marine environments. Structural elements of the ecosystem, such as food webs and the distribution of habitat types, are affected by how well processes such as nutrient cycling, sediment supply, and fresh- and saltwater flows are functioning (Fig. 2). In order to protect or restore key food web elements and habitat types in Puget Sound, we must understand how processes contribute to the underlying causes of species and habitat dynamics (Beechie et al. 2003, Gelfenbaum et al. 2006). If we skip over understanding these mechanistic linkages, we run the risk of designing restoration strategies that will not be sustainable. For example, adding gravel to streams or planting new eelgrass meadows in nearshore areas often do not result in habitat improvements if upstream or up-current flow and sediment delivery problems are not addressed. To avoid unsuccessful band-aid approaches to achieving Puget Sound ecosystem goals, we need to understand how these processes affect food web linkages and habitat distributions, and to identify sources of impaired processes. In this section, we briefly define what we know about physical and chemical processes in the marine waters of Puget Sound, key sources of their impairment, and important science gaps that, if filled, will improve our ability to design protection and restoration strategies for the Puget Sound ecosystem. We focus here on marine processes, since a discussion of how freshwater and terrestrial processes affect the functioning of the Puget Sound ecosystem is covered in the next section.

Figure 4. Include a map of Puget Sound showing marine sub-basins and drift cell locations.

Summary of processes

Circulation and Upwelling

Water movement plays an important role in shaping both the beaches and the health of Puget Sound. Studies of Puget Sound circulation have indicated that the important characteristics of the flow include estuarine circulation, wind and tidal influences, and bottom water intrusions. Topography and variations in the amount and density of saltwater coming into the entrance of the Strait of Juan de Fuca also affect circulation characteristics.

Numerous rivers flow into Puget Sound, diluting the ocean waters and creating gradients of fresh and salt water. The irregular bottom topography, tides, and winds cause mixing and complex currents in the Sound. Superimposed on the tidal currents is estuarine circulation caused by the surface outflow of fresh water from river runoff and deep inflow of salt water from the ocean. The average flow in most of Puget Sound is characterized by a typical two-layer estuarine circulation, where dense oceanic water flows inland to replace salt water diluted by river water flowing on the surface back out to the ocean (Figure 5). Deep, dense salt water enters Puget Sound through Admiralty

Inlet, and part flows south into the Main Basin and part flows 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 outflowing surface water flushes Puget Sound. The amount of water in each layer depends on amount of salt- and freshwater entering the Sound and the degree of mixing caused by tidal and wind forcing. Mixing over the Admiralty Inlet sill plays a major role in this process. A conceptual flow model of Puget Sound suggests that considerable seaward-flowing surface water from the Main Basin is mixed downward into the bottom water entering at the southern end of the Admiralty Inlet sill. This process returns the downward mixing surface water back into Puget Sound, but as part of the deep water below the sill. This process, known as refluxing, means that some fraction of the water and its dissolved and suspended constituents will not leave the basin immediately, but will make additional trips through Puget Sound.

The fresh water flows reaching each of the four major sub-basins of Puget Sound differ because of the size and nature of the watersheds. Sixty percent of the total fresh water entering the Sound flows into the Whidbey Sub-basin from the drainages of the largest rivers in the area--the Skagit, Stillaguamish, and Snohomish watersheds. These rivers collectively drain about 50 percent of the Sound. The main Sub-basin receives 20 percent of the fresh water entering the Sound from the Puyallup, Green/Duwamish, Sammamish, and Cedar rivers. Hood Canal receives 10 percent of the fresh water entering the Sound through a number of minor rivers (i.e., Skokomish, Dosewallips, Duckabush, and Hamma Hamma). The Southern Sub-basin receives less than 10 percent of the drainage into the Sound even though it has a large drainage area. It is fed mostly by small rivers and streams (the only major rivers are the Nisqually and the Deschutes) (PSAT, 1988).

Two major forces, winds and bottom water intrusions, can cause significant variations in the circulation observed in Puget Sound. Northward winds augment the outflowing surface water, and southward winds impede and sometimes reverse the surface flow. These effects at the surface result in compensating flows in the opposite direction. Bottom water intrusions appear as denser salt water crossing the Admiralty Inlet sill replaces the deep water in the Main Basin. The intrusions propagate southward along the Main Basin and also displace the bottom waters of Whidbey Basin as they move northward along Possession Sound.

The characteristics of saltwater coming into Puget Sound are determined in large part by climate conditions along Washington's Pacific Ocean coast. Summertime winds from the north drive coastal upwelling along the Pacific coast, bringing cold, salty and nutrient-rich deep water to the surface. Periods of weak or southerly winds following upwelling events frequently sweep the upwelled waters along the coast into the Strait of Juan de Fuca. The strength and timing of coastal upwelling varies considerably from weeks to decades and has an effect on circulation and water quality within Puget Sound (Snover et al., 2005).

Changes in Puget Sound circulation patterns can have important implications for the exchange of water between Puget Sound and the ocean. Exchange helps flush the deep basins of the Sound and prevents the depletion of dissolved oxygen from organic decay. Exchange also plays a critical role in governing the fate and effects of contaminants that enter Puget Sound. A recent study (Newton et al, 2003) found that, during the 2000-2001 drought in the Puget Sound region, the reduced river flows led to a significant decrease in the exchange between Puget Sound water and the Pacific Ocean. This had consequences for larval and plankton dispersal, as well as water quality.

More on implications of changes in circulation and upwelling: effects on species, habitats, ecosystem services; influences of human activities on circulation and upwelling.

<u>Element Cycling and Stratification</u>

Element cycling in Puget Sound is driven by physical processes and such processes interact with species that use and generate chemical elements of the water. Nutrient concentrations in the upper layers of the ocean tend to be lower than in the deeper waters due to the utilization by phytoplankton in the euphotic (i.e., sunlight-rich) zone. Increased concentrations of nutrients occur in deeper waters due to the release of nutrients back into solution during the decay of detrital material sinking from the upper layers. Replenishment of nutrients in the upper layers can be accomplished through upwelling, vertical diffusion from other areas, and contributions from land through rivers and streams. Certain nutrients, including nitrogen and phosphorus, are necessary for phytoplankton growth. Low nitrogen levels typically limit phytoplankton growth in marine waters, and phosphorus tends to limit plant growth in freshwater.

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. Ambient air temperature, solar radiation, fresh water input from both precipitation and river flow, surface winds, internal waves, and tidal circulation are some of the factors that influence stratification in a water column (Newton et al. 2002). Water density increases with decreasing temperature or with increasing salinity. Any factor that mixes water masses (e.g., winds, tidal circulation) will decrease stratification, and factors that increase density differences (e.g., fresh water input to the surface, high solar radiation) produce or maintain stratification (Fig. 5).

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, DO, 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 observed 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 be affected: surface waters can become depleted of nutrients (dissolved nitrogen and phosphorus) and bottom waters can

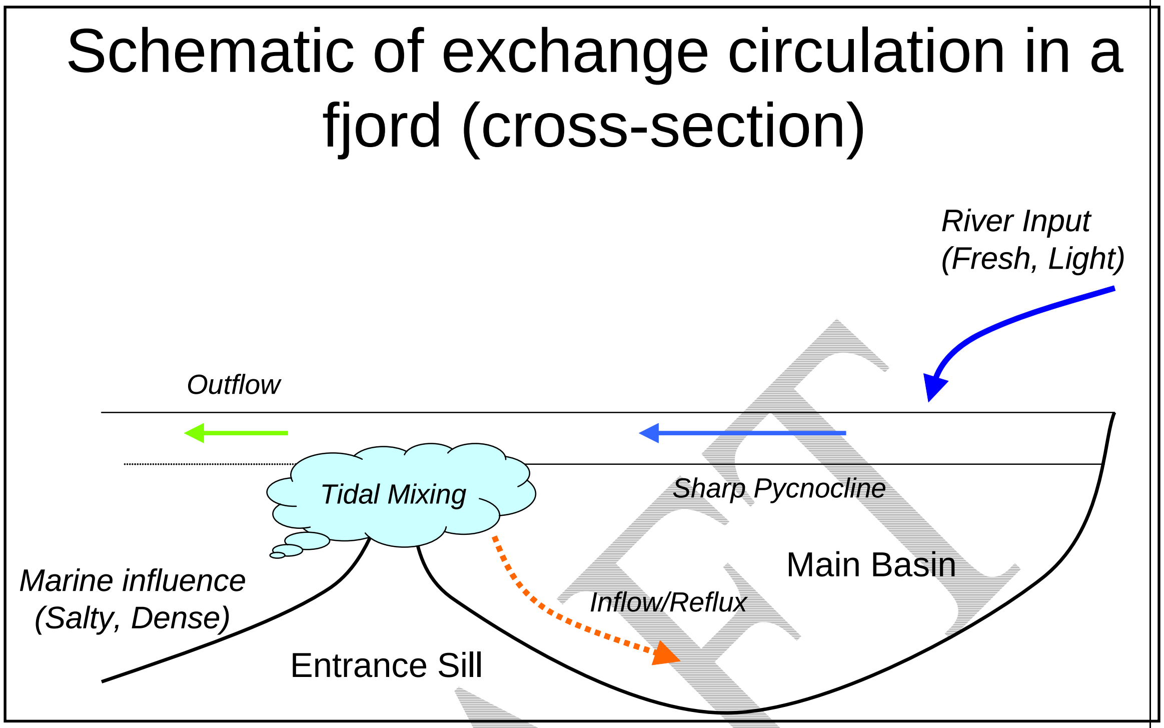


Figure 5: Simplified representation of two-layer circulation and tidal mixing in Puget Sound (courtesy of Mitsuhiro Kawase, University of Washington). The pycnocline is a transition layer between higher-salinity waters at depth and lower- salinity waters on the surface.

become depleted of oxygen. Conditions favorable for phytoplankton growth are sufficient light and nutrients and some degree of stratification (i.e. to prevent mixing phytoplankton out of the euphotic, or light-rich, zone). Under such conditions, phytoplankton biomass increases in the upper layer of the water column and nutrients are consumed as growth continues. Without a replenishing source, surface nutrient concentrations decrease and can limit phytoplankton growth, causing a decrease in their biomass. When a nutrient source is available to surface waters, however, phytoplankton production will never reach a nutrient-limited state. Eutrophication (an increase in external nutrient supply to system) of nutrient-limited stratified waters can result in very large algal blooms and, after the algae sink and decay, a correspondingly large DO debt in bottom waters (Box 3).

Box 3. Dissolved Oxygen and Hood Canal

Hypoxia (dissolved oxygen concentrations <2-3 mg/L), or even anoxia, in Hood Canal is not a new phenomenon, but considerable evidence suggests that this problem has increased in severity, persistence, and spatial extent (Curl and Paulson, 1991; Newton, et al., 1995; 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 1930-1960's with data from 1990-2000's analyzed using the same methods 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 (Collias et al., 1974; Newton et al., 2002) Inventories of deepwater oxygen in the southern main-stem of Hood Canal (Dabob Bay to Great Bend) for these time periods show that while variation is evident, in general the modern data are lower; levels measured during 2004 were at the historical low point for any recorded observations (Warner; http://www.hoodcanal.washington.edu/observations/historicalcomparison.jsp). Similar historical comparisons in lower Hood Canal (Sisters to Lynch Cove) show that while oxygen typically reached hypoxia or even anoxia during summer throughout the record, the recent data show that hypoxia is lasting longer, and of late, throughout the entire year.

Although records of fish kills in Hood Canal date as far back as the 1920's, repetitive fish kills during 2002, 2003, and 2004 indicate that the increasing hypoxia may be having biological consequences. Two fish kill events in Hood Canal during 2003 galvanized public awareness of the water quality challenges faced by this system. 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. The Washington Department of Natural Resources found that Hood Canal is only region in Puget Sound to have consecutive years of eelgrass losses since they started annual monitoring within the Puget Sound Ambient Monitoring Program in 2000. For this reason WDNR identified Hood Canal as an area of concern. Initial findings from 2005 suggest eelgrass declines are more severe in Hood Canal than previously seen, particularly in southern Hood Canal.

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) availability, which can come from both natural and human sources; and other carbon loads from both natural and human sources. Like classic fjords, Hood Canal is prone to hypoxia because deep-water 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). Vertical density stratification in the canal due to freshwater inputs or warm temperatures inhibits vertical mixing. In addition, the effect of ocean boundary conditions, specifically the seawater density, may play a large role in flushing of the canal, determining its residence time or "age" and thus its resultant oxygen content. Experimental evidence has demonstrated that Hood Canal, due to its persistent stratification, has phytoplankton growth limited by nitrogen (N) availability (Newton et al., 1995). Anthropogenic sources of N, such as septic system and hatchery discharges, fertilizers 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 Hood Canal basin is generally low, shoreline development is intensive in a number of regions of the canal and may influence oxygen conditions.

At issue is that all of the mechanisms explained above are involved in determining the observed increase in hypoxia. 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. This need pairs scientists with the capability to make quantitative observations and modeling assessments with local, tribal, state, and federal decision makers through the HCDOP. The multi-year HCDOP-IAM study, begun in 2005, is primarily financed through federal funds secured by Congressman Norm Dicks. This study is administered by the Applied Physics Lab of the University of Washington, through a contract with the US Navy but involves scientists from federal, state, and local agencies, tribes, NGO's, as well as UW and WWU. It is co-managed by APL-UW and the Hood Canal Salmon Enhancement Group. For more information on the HCDOP-IAM study, check out www.hoodcanal.washington.edu.

The effects of DO depletion are organism and habitat-specific. Benthic infauna--particularly mollusks--are more resistant to hypoxia than are most fish species. Continuous or even intermittent low DO events may result in a shift in species composition due to mortality or reduced reproductive success of sedentary species, movement away from depleted areas by more mobile species, or greater susceptibility to disease. The species composition of a given area may also shift in response to changes in predator-prey relationships. The daily pattern of vertical migration exhibited by some zooplankton to avoid predation can be interrupted. Copepods have been found to remain in the pycnocline in an attempt to avoid a bottom layer of low-oxygenated water. In sum, the net effect of oxygen depletion in marine waters may be a shift in species composition, a decrease in population numbers and species diversity with a resulting decrease in amount and type of biomass, and a disruption of the usual predator-prey interactions. These combined effects can result in reduced availability and subsequent harvest of marine resources.

Sources and sinks of nutrients can be from either natural processes or anthropogenic activities. Understanding the impact of human activities (e.g., sewage input, agricultural and domestic fertilizers, freshwater diversion, creation of impervious surfaces) on water quality is complex because the concentrations of important variables (e.g., DO and nutrients) in the water column are the net result of many dynamic input and uptake processes. Sources of nutrients in Puget Sound include dissolved and particulate matter carried by rivers, bacterial nutrient processing (e.g., nitrification), upwelled deep waters, treated and untreated waste from onsite sewage systems and sewage treatment plants, discharges from boaters and other recreational activities, agricultural and stormwater runoff, and wood waste. These nutrients reach the Sound through outfalls, groundwater, rivers, and from the ocean. Nutrient uptake processes include consumption by phytoplankton, bacterial uptake, and possibly the adsorption of nutrients to particulates that eventually settle out.

Examples of oxygen sources are photosynthetic production, diffusion of oxygen from the atmosphere through the water column, and advection or mixing of highly oxygenated waters into lower saturated waters (e.g., downward mixing of surface waters). Examples of oxygen sinks are respiration (especially by bacteria which decay organic matter), chemical oxidation-reduction reactions such as the oxidation of metals (e.g., rusting of iron) or sulfides, and advection/mixing of deeper, oxygenated waters into shallower, saturated waters (e.g., upwelling of deep waters).

Insert brief discussion of specific stratification, eutrophication/DO problems in Puget Sound; and how management can affect such processes (State of the Sound 2004)

Tides and Currents

Tides in Puget Sound are of a mixed, semidiurnal (i.e., approximately once every 12 hours) type with large tidal ranges and, in channels such as Deception Pass, impressively large currents. The shape of the Sound affects the tide as it moves through channels and inlets. Tides are characterized by rapid changes of amplitude and phases in the narrower, shallower reaches of the Sound and slowly changing amplitudes and phases in the deeper, broader regions. Daily tidal ranges of 2.6, 3.4, and 4.4 m occur at Port Townsend, Seattle, and Olympia, respectively (Mofjeld and Larsen, 1984). In the Strait of Juan de Fuca, a 2.2 meter tide at Cape Flattery will reach Port Townsend three hours and forty minutes later and will increase in magnitude to 2.4 meters. The tide will reach south Puget Sound one hour later and increase to 4.1 meters by the time the tide waters reach Olympia. Extreme high tides of 5.5 meters have been recorded in Olympia.

Tidal currents dominate the circulation observed in Puget Sound—movement of water due to tides is about 5-10 times larger than the estuarine circulation seen throughout Puget 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 m/s. 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).

Insert short paragraph linking processes to biological impacts….what food webs or habitat types are affected by tides? What human actions may have impaired circulation patterns? Is there any evidence of changes in circulation over time?

Drift Cells and Sediment Transport

Puget Sound consists of over 4000 km (2500 miles) of shorelines, and this interface between terrestrial and aquatic environments plays an important role in the overall health of the Puget Sound ecosystem (see also *Terrestrial and marine linkages*). Fresh water, sediments, and nutrients are transported across the shoreline interface helping to create critical nearshore habitats. Nearshore habitat attributes, like the shoreline itself, vary tremendously across the Sound. Physical riverine, tidal and wave-driven processes, along with inherited topography and coastal geology (sediment type), determine the coastline habitat types observed in Puget Sound (see *Habitat types*). If sediment delivery and transport processes are disrupted, the habitat types we expect to see along Puget Sound shorelines and at greater depths (e.g., beaches, eelgrass meadows, mud flats) are more difficult to maintain.

A useful way to organize the coastline is in terms of drift cells or littoral cells. Drift cells are landscape-scale units (10s – 1000s meters) that delineate the boundaries of beach sediment transport. Drift cell boundaries are most often defined by headlands, but they also can be embayments, rivers, or zones where alongshore drift is negligible. Waves breaking obliquely along the shoreline are the dominant marine-derived sediment transport process moving sediment within a drift cell. Alongshore sediment transport directions may shift on short time scales (i.e., over days, weeks, or months) as winds and wave directions change. Long-term net shore drift directions integrate over shifting wind and wave directions, and may be more relevant for management uses.

Drift cells often are used to create a sediment budget for a stretch of coast, accounting for the sediment sources, transport pathways, and sediment sinks. Beach sediment within the Sound comes primarily from erosion of adjacent bluffs (Figure 6), with rivers adding smaller amounts (Shipman, 1995). Coastal bluffs are the most common shore type around the Sound and are generally carved into sequences of glacial and inter-glacial sediment consisting of fluvial sands and gravels, coarse outwash deposits, and glacial till. Shipman (1995) summarized erosion rates of coastal bluffs in the Sound and found rates ranged from 3-150 cm/yr at the sites studied. The volume of material added to beaches from bluff erosion is closely related to wave energy or fetch and ranges from less than 1 m^3/m/yr to more than 10 m^3/m/yr. Bluff failure, occurring either slowly or catastrophically, is an important process for replenishing beach sediments and maintaining nearshore habitats.

Drift cell boundaries with net drift directions have been mapped for most of the Puget Sound shoreline (Department of Ecology, 1978; Schwartz et al., 1989; Schwartz et al., 1991). The irregular and complex coastline of Puget Sound results in hundreds of drift cells. Several different estimates of the amount of sediment movement within drift cells have been made, and although the magnitudes are small compared to outer coast drift rates, they still result in significant potential for movement of sediment alongshore within the Sound (Finlayson and Shipman, 2003). Sediment availability—due to shoreline or riverine sources affects the rates of sediment transported. Along Hale Passage, a heavily armored stretch of coast in south Puget Sound, the drift rates are very low, from 30-50 m^3/yr, whereas for Vaughn Bay Spit, a stretch of coast with similar fetch, but fewer shore defense structures, the rates are much higher, 2000 m^3/yr.

The extensive development of the coastal bluffs around the Sound has led to widespread use of engineering structures designed to protect the upland properties. Concrete bulkheads and rip-rap are the most common forms of shore protection used on Puget Sound shorelines (Canning and Shipman, 1995). The extent of shoreline armoring for Thurston County revealed that by 1993 56% of all shoreline parcels were armored. The extent of armoring in 1993 amounted to 29% of the total shoreline length in Thurston County, as compared to 14 % that was armored by 1977. With more people moving near the coast, the increasing trend has continued. More than half of the shoreline of the Main Basin and 79% of the eastern shoreline of the Central Basin has been modified by shoreline armoring (Puget Sound Action Team, 2000).

Although shoreline armoring is often used to add some protection to upland structures such as buildings, there may be a negative impact in terms of a decrease in the supply of sediment to the beaches. In general, shoreline armoring can lead to a variety of impacts, direct effects such as impoundment or loss of sediment behind structures, and burial or loss of upper portions of a beach due to placement of the structure (Figure 7). Indirect impacts can include beach starvation, modification of groundwater hydraulics, increased wave energy and scour in front of or adjacent to a structure, beach lowering, changes in beach sediment grain size, and loss of organic debris.

<u>Impacts of Processes on Biological Resources</u>

This section is fairly nearshore-centric: what more can reviewers suggest for marine basin processes and their impacts?

Loss and modification of beach habitat due to shoreline armoring is having a deleterious effect on the ecosystem health of the Sound (Thom et al. 1994). The various structures that affect drift cells and nearshore physical processes also impact nearshore habitats and biological resources.

There is substantial indirect evidence of serious harm to species and habitats due to shoreline armoring. Much of the concern centers around the critical importance of beaches for finfish spawning, foraging and rearing, and habitat for adult and juvenile invertebrates (Canning and Shipman, 1995). Negative impacts to finfish can arise from direct loss of spawning habitat, loss of shoreline vegetative cover, loss of organic debris, and modification of migratory corridors. Although not verified, the indirect impact that armoring can have on beach substrate could have significant effects on forage fish spawning. Similarly, changes in beach substrate could modify the habitat for shellfish. Armoring can also impair development of upland vegetation, groundwater flow, and the supply of sediment and nutrients to the upper beach.

What about other impacts of impaired processes? E.g., how might have changes to timing and quantity of freshwater input to Sound, either due to water flow alteration or climate change—changed species, habitats, or ecosystem services such as nutrient cycling? Also, what about the possible threat to upwelling along outer Pacific coast due to future changes in large-scale atmospheric circulation and local winds as a result of climate change?

Possibly include a section on another process--Recruitment of wood and shoreline riparian dynamics

Key Gaps in our Scientific Understanding of Processes

The issues below are those gaps in our scientific understanding of processes that, if filled, will enhance the ability of decision-makers to make wise decisions about managing the Puget Sound ecosystem. As more information becomes available on the topics below, actions can be better targeted at protecting or restoring processes that underlie the ecosystem's ability to provide species, habitat, and ecosystem service objectives for Puget Sound.

This following section is fairly nearshore-centric—need to make sure we are considering deeper marine water processes, too. We also need to shorten the list of 'key' science gaps below.

Comprehensive efforts to identify data and information gaps associated with nearshore processes, structures, and biological resources can be found in the State of the Nearshore Report (Williams et al. 2001) and in the research plan written for the Puget Sound Nearshore Ecosystem Restoration Program (PSNERP) (Gelfenbaum et al., in press). Both reports argue there is a paucity of scientific information with regard to nearshore ecosystem processes, structures, and biological resources. Without this understanding, we will not be able to develop action plans aimed at redressing underlying causes of habitat and species losses.
Some of the pressing science gaps identified thus far are listed below.

- Surface circulation in Puget Sound is not well described – important in transport of planktonic organisms, oil spills, etc.
- Need improved predictions of the consequences of climate change:
    - E.g.-induced prevailing wind fields and coupling of surface currents, as well as actual tides vs. average tides.
    - Effect/Influence/Importance of advection of Pacific Ocean water – How much is Puget Sound water quality driven by advection of upwelled Pacific water? How important is this in predictions of nutrient dynamics and dissolved oxygen in the Sound?

- Need trend analysis – our observations consist of snapshots of a dynamic system and do not provide enough data for comprehensive trend analysis.
- Integrating and temporal/spatial scale issues—how do the processes interact to produce changes in ecosystem services in Puget Sound? A key science need is to be able to predict how processes such as changes in nutrient composition, production, consumption, and movement of sediments and water affect how marine communities and ecosystems function. Habitats important to species and food web function cannot be maintained without protecting or restoring the mechanisms (i.e., processes) that support those habitats.
- What are the underlying causes of impaired ecosystem processes and how can we mitigate these? In particular, what land use, estuarine, and marine water activities impair ecosystem processes in the marine environment? For example, we understand relatively well how dams disrupt the delivery of gravels and finer sediments to river mouths, which can starve nearshore beaches of much-needed sands and cause significant erosion problems along coastlines (Box—Elwha).
- What actions will enable the marine ecosystem to generate and maintain natural processes, which will in turn generate desirable ecosystem structures (e.g., eelgrass meadows, baitfish spawning gravels) and important functions (e.g., salmon and bivalve production, clean beaches and water)?

Figure 6. Bluff failures contribute sediment to beaches (photo by Guy Gelfenbaum)

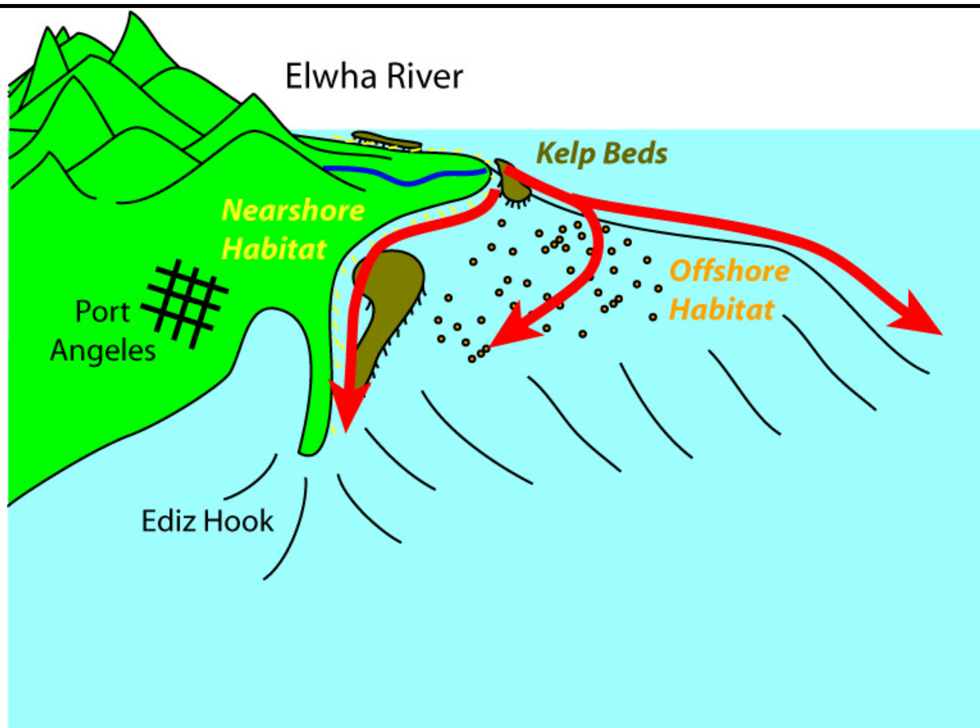
Figure 7. Railroad grade along shoreline from Seattle to Everett (photo by Guy Gelfenbaum)

Box 4. Ecosystem Response to the Elwha River Restoration Project

The Elwha River, one of ten major rivers on Washington State's Olympic Peninsula, has 83% of its watershed located within Olympic National Park. Over 90 years ago, 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 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. [also include small photos of dams in this panel]

The ecological effects of the Elwha River dams on the river, estuary and nearshore environments were large and cumulative. Aside from the obvious impacts of changing the fish community and starving the upper river of marine-derived nutrients (provided via salmon carcasses), there also were cascading effects in the riparian and upland areas. At least 22 species of birds and mammals that utilized salmon carcasses were deprived of an important source of nutrients. 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. Impacts to the plant and animal species dependent on the river, estuary and nearshore habitats are only partly understood, but major changes in food web composition, habitat structure, and processes delivering sediment to Puget Sound have occurred. For example, the amount and quality of spawning habitat for salmon in the lower river has been greatly diminished, since it is dependent upon sediments and large woody debris supplied from the upper river.



The release of sediment from behind the dams when they are breached is hypothesized to alter nearshore and marine habitats as well as add to beach protection.

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 2008/2009. 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.

Terrestrial and Marine Linkages

Ecosystem structure, such as species and habitats, is affected by linkages between the freshwater/terrestrial and marine environments (Fig. 2). Freshwater and saltwater environments commonly are viewed as separate ecosystems, yet physical, chemical, and biological linkages between them are so strong that management actions in one dramatically affect the other. Examples include damming of rivers and reducing the flow of sediments to nearshore environments, urbanization and increased delivery of pollutants, and fishing pressures that reduce the number of spawning salmon returning to rivers. These interactions occur along two distinct interfaces between freshwater and saltwater environments: (1) nodes of high material transfer (both upstream and downstream) at river deltas, and (2) zones of lower material transfer along intervening shorelines Figure 8 -- Illustration of some processes for each zone here. In Puget Sound we have fundamentally altered these interactions by land management and fishing practices, resulting in reduced capacity and quality of nearshore habitats and food webs. To improve our ability to protect and restore the Puget Sound ecosystem, we need to understand how fluxes of water, sediment, nutrients, and pollutants between watersheds and Puget Sound alter ecosystem health and the goods and services it provides.

Linkages and Human Impacts

Nearshore, delta, and marine habitats in Puget Sound are in part shaped by the delivery of water, sediment, and wood debris from watersheds and shorelines to the marine environment. At Puget Sound river mouths, gravels and sand transported from watersheds build deltas and beaches, while fine silt and clay remain suspended in the water column far into saltwater. Sediments are also delivered to beaches from eroding bluffs, and wood transported downriver is deposited in deltas and along beaches where it reduces shoreline erosion. These processes create a variety of habitat types including freshwater and salt water marshes in deltas, beaches, and estuaries, as well as a variety of shoreline and beach habitats. Beach habitats provide spawning and rearing areas for forage fish and other species. Delta habitats are important to salmon, providing a critical rearing habitat as young salmon leave rivers and enter Puget Sound.

Water and sediment quality in Puget Sound are substantially degraded by pollutants delivered from watershed and nearshore industrial activities. Pesticides are used widely across the landscape (including applications in forestry, urban, residential, agricultural, and industrial uses). More on industrial problems, kinds of pollutants.

Insert Box 5 – POLLUTION IN SOUND, toxics discussion.

High input of organic and inorganic nutrients to Hood Canal also contribute to low dissolved oxygen levels (Box 3).

Rivers and streams of Puget Sound transport organic matter and nutrients downstream where they support food webs in river deltas and nearshore environments. Along shorelines, riparian forests provide organic matter for food webs, and shade that helps stabilize environmental conditions in intertidal spawning areas used by forage fish. Trees that fall from eroding bluffs and are deposited in littoral areas are habitat for beach, intertidal, and marsh-inhabiting species. A number of fish species such as juvenile chinook and chum salmon consume insects that come from terrestrial and freshwater habitats. The upstream migration of salmon each year also delivers important marine-derived nutrients to freshwater ecosystems

Insert BOX 6 – SALMON NUTRIENTS

Each of these linkages between terrestrial and marine ecosystems has been altered by human activities (Shared Strategy 2005). The most dramatic changes have occurred in urban landscapes where fresh and salt water marshes have been paved and converted to industrial uses but agricultural land uses have also eliminated vast delta habitats important to salmon and other species (Bortleson et al 1980, Collins and Sheikh 2005). (Figure 9 – Duwamish River). Reductions in supply of sediments from rivers by dams degrade nearshore habitats. Consequently, Puget Sound has seen declines in eelgrass and algal habitats for migrating salmon, forage fish and shellfish (Box 4). Fishing pressure reduces upstream transfer of nutrients.

Insert discussion of key threats to the functioning of freshwater-terrestrial linkages—summarize information in sources such as the Shared Strategy recovery plan and Puget Sound Management Plan (PSAT) for land use, other human impacts. Use a table or Box to provide concrete examples.

<u>Key Gaps in our Scientific Understanding of Terrestrial-Marine Linkages</u>

The issues below are those gaps in our scientific understanding of terrestrial-marine linkages that, if filled, will enhance the ability of decision-makers to make wise decisions about managing the Puget Sound ecosystem. As more information becomes available on the topics below, actions can be better targeted at protecting or restoring processes that underlie the ecosystem's ability to provide species, habitat, and ecosystem service objectives for Puget Sound.

This list of 'key' science gaps is incomplete and yet needs to be kept fairly short.

- Many land and water uses affect the quantity and timing of fresh water delivered to Puget Sound, including urban development (impervious cover), dams, water withdrawals, loss of wetlands, and channelization of rivers. However, we do not know the degree to which each factor contributes to altered stream flows and ecosystem degradation, or what percentage of each land use exceeds thresholds of degradation.
- The effects of water quality degradation on freshwater, estuarine and nearshore functions are not understood. While we are able to measure many aspects of water quality (including water temperature and concentrations of sediment, bacteria, and contaminants), we do not yet have a good understanding of the root causes of impaired freshwater quality (both ground water and stream flows), or how

declining water quality affects freshwater, estuary, and nearshore ecosystem functions.

- How does climate change effect the quantity, quality, and timing of the streamflow delivered to the coast? And how does that translate to changes in the Puget Sound ecosystem?
- We do not have good mechanistic linkages between human management actions (such as critical areas ordinances, shoreline master plans, zoning, restoration projects) and the functioning of processes that link terrestrial and marine environments.
- How declines in shoreline habitat quality are translated into effects on species up the food chain is not known. For example, if we understand how water quality in runoff from land and freshwater systems affects estuarine and nearshore habitat quality, quantity, and function, we can begin to develop mechanistic linkages between actions affecting water quality and ecosystem responses
- We know that biomass is transferred between freshwater and marine systems through organisms traversing the full range of habitats throughout their life cycle (e.g., anadromous salmon) or through passive and active transport of live and dead biota (e.g., freshwater algae washing downstream into estuaries; and seabirds, bears and other mammals carrying marine prey into terrestrial systems). There is virtually no information on how these fluxes of nutrients and organic matter affect the functioning of the Puget Sound ecosystem. Further, we do not know how human activities have altered the rates and magnitudes of such transfers, so encouraging recovery of the Puget Sound ecosystem is challenging.

Puget Sound Food Web and Species Biology

Description of the Puget Sound Food Web

Although a complete accounting of the plant and animal species of Puget Sound has not been accomplished, we know that this productive landscape supports at least 100 species of sea birds, 200 species of fish, 26 marine mammals, and thousands of different species of invertebrates. Although most are native species (including both full-time residents and seasonal residents), an increasing number of species are non-natives that have been intentionally or unintentionally introduced into the Puget Sound ecosystem.

The species that occupy the Puget Sound contribute to some of its most obvious goods and services. This section describes the food web and interactions between species in the Puget Sound system (Figure 2). It is critical to consider the relationships between all species in the environment, including year-round resident, seasonally resident, and migratory species. At the core of this approach is the study and understanding of food web and predator-prey dynamics. By striving to understand these relationships, steps can be taken to manage and sustain the Puget Sound ecosystem.

In what follows, major groups of organisms in the Puget Sound food web and anthropogenic threats that impact the biology of species and the number of species in the

Puget Sound food web are described. Although the information presented here is not exhaustive, key organisms in major trophic levels are discussed to provide a better perspective on the organization of the Puget Sound food web and to identify population trends and anthropogenic threats for some representative species of concern in the Puget Sound Ecosystem.

Phytoplankton

Phytoplankton in Puget Sound are highly productive. Daily productivity rates are among the highest of west coast estuaries (Emmett et al., 2000). The seasonal pattern of phytoplankton biomass is quite varied, both spatially and temporally, linked to the degree of stratification, sunlight availability, and in persistently stratified areas, nutrient limitation (Winter et al. 1975; Newton et al., 2002).

The high level of productivity, combined with a wide range of aquatic habitats within the Sound, is what sustains the highly diverse population of marine organisms. Puget Sound has seasonally high phytoplankton standing stock; chlorophyll a bloom concentrations can range greater 60 mg m^{-3} (Bricker et al., 1999). The high primary production is important for food web dynamics of the commercially important fisheries. The timing of phytoplankton blooms is influenced by depth of the mixed water column layer relative to light availability. One study found that primary production in central Puget Sound is controlled by light availability during the winter (October to March), however, other factors, such as nutrient availability and stratification, controlled the amount of production during other months (Nakata and Newton, 2001). Studies throughout Puget Sound show variance in the control on primary production for Budd Inlet (Newton et al., 1998), the Main Basin, Possession Sound (Newton and Van Voorhis, 2002) and Hood Canal (Newton et al., 1995).

Phytoplankton populations in Puget Sound consist of mainly large-sized phytoplankton of two major groups: diatoms and dinoflagellates, with diatoms accounting for most of the biomass. The role of nano- and pico-phytoplankton has not been well addressed. Diatom species are dominant in the fall and winter months and typically dominate the composition of the spring bloom. Dinoflagellates become more abundant in the spring and summer. Subsequent blooms have been characterized as a series of intense blooms appearing during favorable physical conditions (Winter et al., 1975). Phytoplankton abundance is highly heterogeneous or “patchy” both spatially and temporally. Abundance can vary significantly on time scales of hours to days, possibly due to diatom life cycles and spatial heterogeneity (Dexter et al., 1981).

The spatial abundance of phytoplankton has also been linked to upwelling, river runoff, stratification, and wind stress. Mixing and upwelling of water are important factors affecting phytoplankton distribution as they provide nutrients for population growth, seed populations, and affect residence time within a basin. Upwelling at locations such as the Tacoma Narrows provides a source of nutrients to the upper layers of the water column, supporting the high productivity of the Main Basin. Tidally-driven mixing at the Narrows contributes to spatial heterogeneity as surface water parcels originating on ebb tides are advected northward. The reflux of upper water layer into deeper waters due to mixing in Admiralty Inlet causes an increase in chlorophyll and a decrease in nutrients at depth (Boss et al., 1998).

Zooplankton

The Puget Sound's entrance sill alters the pattern of estuarine circulation by causing mixing and by restricting the exchange of water with adjacent basins (Strickland 1983), with apparent consequences for zooplankton assemblages. The plankton fauna of Puget Sound appears to differ from that of adjacent waters in the Strait of Juan de Fuca and the Pacific Ocean in a having a high proportion of shallow-water, coastal, and estuarine taxa such as the cyclopoid copepod *Oithona similis*, the calanoid copepods *Acartia* (*Acartiura*) spp. and *Paracalanus*, and the cladocerans *Podon* and *Evadne* (Chester et al. 1964, Dumbauld 1985, Giles and Cordell 1999, B. Frost unpublished data). In this respect, it is similar to other coastal marine embayments such as San Francisco and Tomales Bays (Ambler et al. 1985, Kimmerer 1993) and estuaries (Miller 1983). However, Puget Sound also has relatively deep basins with populations of deeper distributed species such as the calanoid copepod *Calanus pacificus*, the euphausiid *Euphausia pacifica*, the amphipod *Themisto pacifica*, and the chaetognath *Sagitta elegans*. Unfortunately the differences and similarities between Puget Sound and other coastal environments are poorly known, because quantitative studies of the zooplankton assemblage in the Puget Sound region are rare and quite limited in scope, consisting of several unpublished student theses (Dempster 1938, Hebard 1956, Damkaer 1964, Dumbauld 1985) and a few other studies.

The habitats of zooplankton encompass all of Puget Sound and are best known from surveys and ecological studies of the food habits of regional biota. The zooplankton community is complex and diverse but represents one of the most critical components of the food web transforming matter derived from primary production into food for fish, birds, and mammals. Diatoms and phytoflagellates dominate spring blooms and are the major foods for suspension-feeding, dominant copepods such as *Arcartia* and *Calanus*. Secondary to the copepods are euphausiids, amphipods, and mysids (Strickland, 1983). The euphausiids are also suspension-feeders, feeding on the largest chains of diatoms and microzooplankton. Mysids are omnivorous and amphipods are carnivorous. There are may carnivorous zooplanktors at the third trophic level including predatory copepods, micronekton, an gelatinous species such as the chaetognaths, ctenophores, and medusae (Strickland, 1983).

On the west coast of the United States, a number of estuaries and embayments have been invaded by planktonic copepods (Cordell and Morrison 1996, J. Cordell, unpublished data), but none so profoundly as San Francisco Bay. Eight Asian copepods have invaded this system (Orsi and Ohtsuka 1999), with apparent wholesale occupation of a variety of salinity zones and of both grazer and predator trophic levels (Orsi 1995). Findings from several recent sampling surveys (J. Cordell, unpublished data, Cohen et al. 1998, Cordell and Morrison 1996) indicate that reproducing populations of introduced planktonic copepods may not yet exist in Puget Sound. However, one species, *Pseudodiaptomus* *inopinus*, has established itself in the Columbia River and many other estuaries along the coasts of Oregon and Washington (Cordell and Morrison 1996).

Benthic and Epibenthic Marine Invertebrates

There are more than 10 shrimp species, 30 crab species and 35 bivalve molluscs (e.g., oysters, clams, scallops, and mussels) in Puget Sound (Kozloff 1983). The benthic community, infauna, epifuana, and water column organisms, is incredibly diverse in terms of species and habitats, and thus our focus is limited to the status of listed priority species: Dungeness crab (*Cancer magister)*, pandalid shrimp (*Panadalus* spp.), geoduck clam (*Panopea abrupta*), butter clam (*Saxidomus giganteus*), littleneck clam (*Protothaca staminea*), Japanese littleneck clam, (*Tapes philippinarum*), Olympia oyster (*Ostrea lurida*) and the Pacific oyster (*Crassostrea* gigas). Priority species require protective measures and/or management guidelines to ensure their perpetuation and must meet at least one of three criteria including 1) State listed and candidate ESA species; 2) vulnerable aggregations (i.e. shellfish beds); and 3) vulnerable species of recreational, commercial, and/or tribal significance (http://wdfw.wa.gov/hab/phspage.htm --Priority habitats and species; © 1997-1999 Washington Department of Fish and Wildlife). Not all priority species are native to Puget Sound and some, like the Pacific oyster, have impacted native populations within the benthic community. Recently, two exotic tunicates have been reported in Puget Sound and their invasions are predicted to impact regional bivalve populations. The blue mussel (*Mytilus edulis*) is widespread throughout Puget Sound and the West Coast shoreline and as such is an important integrator of coastal processes, such as bioaccumulation of contaminants, and is a prominent indicator species in the Nation's benthic surveillance program.

The Dungeness crab supports a valuable commercial and sport fishery in Puget Sound. Annual landings for the state commercial fishery from 1993 through 2001 averaged 2.3 million pounds (http://wdfw.wa.gov/fish/shelfish/crabreg/comcrab/historiclandings.shtml). In 2001 the Dungeness sport fishery landings totaled 1,264,584 (http://wdfw.wa.gov/fish/harvest/index.htm). Crab stocks are currently considered to be healthy even though there has been a continual increase in fishing pressure in recent years (http://www.dfo-mpo.gc.ca/zone/underwater_sous-marin/crab-crabe/crab-crabe_e.htm). Dungeness crab habitats are found from the intertidal to depths exceeding 180 meters. The species is widespread and occurs in bays and inlets, in estuaries, and across shelf waters. Although found on mud and gravel substrates, this crab is most abundant on sandy bottoms, and in shallow waters around eelgrass. Its larval form is planktonic (Pauley *et al.* 1989). Major prey include clams, other crustaceans, and small fish. Other crabs, Pacific halibut, dogfish, sculpins, octopus and sea otter feed on Dungeness crabs. Salmon and other finfish are predators of Dungeness larvae during the planktonic phase (Pauley *et al.* 1989).

The geoduck is the largest bivalve found in Puget Sound. Populations are distributed subtidally, and regional stocks support important sport and commercial fisheries (Goodwin and Pease 1989). There are an estimated 109 million adult geoducks in Puget

Sound (http://www.ecy.wa.gov/programs/sea/pugetsound/species/geoduck.html). Geoduck densities in Puget Sound bays and estuaries are the highest in the United States and the species is especially abundant in the South Sound. Geoducks are most abundant in sandy muds of the lower intertidal and subtidal zones at depths extending from 3 to 30 meters below mean low tide. The species has planktonic larvae that are fed upon by fish, other plankton, and other suspension-feeding invertebrates. Post larvae stages are eaten by demersal and other finfish, worms, snails, starfish and crabs (Goodwin and Pease 1989).

Olympia oysters have an irregularly-shaped, fluted shell ranging in color from a chalky-white to purplish-black (Couch and Hassler 1989). Once an important resource for tribal, commercial and recreational interests, this species has declined to levels below sustainability. The oyster has been commercially exploited since the 1850’s, and, in the South Sound, while fishing is not permitted, the population is threatened by pollution from motorboats, pulp mills and wastewater discharge, and increased siltation of shallow water beds. Some increases in local oyster populations have been associated with improved water quality in Puget Sound. Despite management efforts, Olympia oyster stocks have not returned to pre-exploitation levels and it is presently listed as a Federal Species of Concern and a Washington State candidate endangered species (Couch and Hassler 1989). Olympia oysters are found in estuaries, tidal channels; on the undersides of floats and on pilings. They are filter feeders and their primary prey is phytoplankton. Major predators include seaducks, various crabs, and two introduced species, the Japanese oyster drill (*Ocenebra japonica*) and a parasitic flatworm (*Mytilicola orientalis*). The larger and faster-growing Japanese and Pacific oysters and the slipper shell (*Crepidula fornicate*) are major competitors in Puget Sound habitats (Couch and Hassler 1989).

There are hundreds of other benthic invertebrates in Puget Sound, yet their significance in food web structure and sustainability is poorly defined. Key species among them that are commercially fished are sea urchins and sea cucumbers. The 2001 commercial harvest was almost half a million pounds for each species (http://wdfw.wa.gov/fish/shelfish/divereg/). Pinto (Northern) abalone and the red sea urchin are listed as Washington State Priority species (http://wdfw.wa.gov/hab/phspage.htm). The red sea urchin (*Strongylocentrotus franciscanus*) is a "spiny-skinned" echinoderm with a spherical body encased in a hard shell completely covered by many sharp spines. Their color varies from a uniform red to a dark burgundy (http://seaurchin.org/Sea-Grant-Urchins.html#red). In Washington State, the commercial fishery grew rapidly from 1986 to 1988 and landings peaked at 8.1 million pounds in 1989 prompting a first-ever emergency closure. Today, harvest quotas are limited to 215,000 pounds for commercial and tribal landings (http://wdfw.wa.gov/fish/shelfish/divereg/). Urchin habitats are located in the rocky subtidal from just below mean low tide line to 90 m. Larvae are planktonic. The urchins feed on seaweeds and kelp and are preyed upon by sea stars and crabs (http://seaurchin.org/Sea-Grant-Urchins.html#red).

Pinto (Northern) abalone are marine gastropods that are closely-related to clams, oysters, mussels, and squids. The pinto abalone is one of the smallest species of abalone. It can grow to 6 inches in length, but its size is rarely larger than 5 1/2 inches (http://mehp.vetmed.ucdavis.edu/pdfs/browngaydos05.pdf). Very low population numbers have resulted in the Pinto abalone's listing as a 'Species of Concern' under federal, and state endangered species provisions (http://mehp.vetmed.ucdavis.edu/pdfs/browngaydos05.pdf). Pinto abalone are found in coastal kelp beds and over sandy bottoms from low-low mean water to 10-15 meter depths. Larvae are planktonic. Pinto abalone feed on marine algae from minute particles to giant bull kelp. Its main predators include crabs, octopi, starfish, finfish, and marine snails (Harbo 1997).

<u>Squid</u>

Several species of squid have been reported in Puget Sound; however, the most common is the market squid (*Loligo opalescens*). Stock structure among Pacific coast populations of *L. opalescens* is currently unknown (California Fish and Game 2005), but previous genetic research revealed little differentiation between stocks sampled from southern and central California (Reichow and Smith 2001; Gilly 2002).

Market squid are likely an important component of the food web in Puget Sound as in California. As predators, squid feed on a variety of food items, including copepods and euphasiids, polychaete worms, squid (cannibalism), crustaceans, and some fishes (California Fish and Game 2005). As prey, they are important at several trophic levels and predators include killer whales (NOAA 2002), pinnipeds (NMML 1996), seabirds (Croxall and Prince 1996), Pacific salmon (Groot and Margolis 1991, California Fish and Game 2005), and many other marine species. Data on standing stocks in Puget Sound are scarce, but anecdotal information suggests that abundance varies annually and seasonally. Adults in significant numbers are present in central and south Puget Sound from September through February (WDFW, date unknown) and preliminary trawl data produced estimates of 0-1 g/m2 (T. Essington, University of Washington, personal communication). In general, habitat requirements of market squid in Puget Sound are not well documented but it is likely that a variety of habitats are utilized at various life stages. They are occasionally found in the nearshore habitat (C. Rice, NOAA, Northwest Fisheries Science Center, personal communication) and were captured during October in trawls at 20-80m (but not at 160 m; T. Essington, University of Washington, personal communication). In California, non-spawning squid are believed to be pelagic, migrating to the upper water column at night (California Fish and Game 2005) and preliminary data from acoustic tagging in the sound suggests some individuals travel a minimum of 10-12 miles (John Payne, NOAA, Northwest Fisheries Science Center, personal communication). In Monterey Bay (California), offshore cohorts appear to move inshore for reproduction (Ish et al. 2004) and in Puget Sound spawning appears to occur on gently sloping bottoms, at depths of 15-60 feet with eggs found at almost all times of the year (WDFW, date unknown). Further research will be required to determine the status and importance of squid in Puget Sound.

Demersal Fish (other than rock fish)

Demersal fishes are defined as those that spend most or all of their life histories associated with bottom or benthic habitats. Some fish species which have demersal egg or larval stages (e.g., herring and surf smelt) and species which spend some time feeding in benthic habitats (e.g., salmon) are not included here. Rockfish are also not included here as demersal fish. Most the fish that live in Puget Sound are demersal species which includes flatfish, surf perches, sculpins, gunnels, and gadids. While many demersal species change habitats within Puget Sound (e.g., moving from deep to shallow water in the summer), none of the demersal species migrates to and from Puget Sound.

Other than several species which are commercially or recreationally harvested, such as some flatfish species and gadids, we have a poor understanding of the status and trends of this species group. This is primarily because we do not monitor abundance levels of most demersal species. One demersal species that has exhibited a dramatic decline in abundance is Pacific cod in central Puget Sound which was heavily overfished in the 1970s and 1980s.

Demersal species use the full range of shallow subtidal to deep benthic habitats. Major attributes of benthic habitat that affect composition of demersal species include depth, substrate type, and vegetation. For example, eelgrass beds have a diverse and abundant fauna comprised of perch, gunnels, and various sculpin species. In deeper benthic habitats, species that are commonly found include dogfish, ratfish, larger flatfish, larger sculpins, and gadids (e.g., tomcod). In general, there is a shift in fish size as a function of depth with smaller fish associated with shallower water and larger fish occupying deeper water. Several demersal species are tolerant of lower salinity and so can be found closely associated with major deltas. Many species undergo seasonal shifts in habitat use. Shiner perch are generally absent from inshore habitats in fall and winter but move from deeper water habitats. Postlarval flatfish settle on shallow intertidal mud and sand flats in late spring and summer (often in brackish areas) and then move progressively into deeper waters as fish size increases.

Not surprisingly, most prey items eaten by demersal species are associated with benthic food webs. While information on food web relationships in nearshore areas have been well studied, diets in deeper benthic areas are still poorly understood. Major factors affecting prey eaten are fish species, fish size, season, and habitat where fish are foraging. In general, major invertebrate prey of demersal species include polychaetes, amphipods, mysids, bivalves (mostly siphons), and copepods (e.g., harpacticoids). While many demersal fishes eat similar prey (have high overlap) we do not know if and under what conditions food is limiting. Major predators within this species group include large size classes of several species such as halibut, cabezon, lingcod, and staghorn sculpin. Marine mammal species, probably sharks, as well as larger salmon often prey on demersal species. Great blue herons and several raptor species (Peregrine falcons) also prey on demersal species in nearshore areas. As with all Puget Sound found webs, there are a number of species that feed on the same types of prey as demersal species but spend little time in these habitats (e.g., juvenile salmon).

Rockfish (section to be developed).

Salmonids

There are five species of Pacific salmon that occupy the waters of Puget Sound. Each of the five species of Pacific salmon found in Puget Sound has the same basic anadromous life cycle, although several species also have life history types that spend their entire life cycles in freshwater (e.g., sockeye salmon). Within Puget Sound, a statewide inventory of anadromous salmon populations conducted in the state in 1992 and repeated in 2002 identified 146 populations of all five species combined in Puget Sound. Abundance levels of a number of these stocks are low. As a group, Chinook salmon is in the worst condition and the federal government listed Puget Sound Chinook salmon as threatened in 1999. Chum salmon populations that spawn in Hood Canal and the eastern Strait of Juan de Fuca were also listed as Threatened.

All species of salmon do not use Puget Sound habitats in the same way. Habitat use is a function of species, size, population, time of year, location within Puget Sound, and environmental conditions. Because salmon are migratory, they never are truly residents of any habitat once they leave freshwater.

Salmon enter the waters of Puget Sound throughout most of the year. The first habitats these fish encounter are the deltas of natal spawning streams. The time spent in these systems and the habitats used are largely a function of fish size. For example, Chinook salmon fry that enter a delta in March can spend many months rearing in this system while coho salmon or Chinook salmon yearlings spend little time in the deltas. Channel networks in marshes provide high quality rearing habitat for salmon of all species. Once salmon enter Puget Sound, they first occupy shoreline or littoral areas. The time spent in these habitats depends primarily on fish size. Fish size and residence time in shoreline areas are inversely related. As fish grow, they progressively move from shoreline areas into more offshore areas. Eventually, by fall, most young salmon have moved into the deeper more offshore waters of Puget Sound as they are migrating towards the Pacific Ocean. Eventually, most salmon leave Puget Sound, although there is a component of each species that remains as residents in Puget Sound.

Salmon are part of all food webs in Puget Sound and can occupy multiple levels of these food webs at the same time. They also perform an important function in freshwater ecosystems by transferring nutrients in the form of their tissues from marine systems into freshwater. Salmon of any species eat a progression of food that changes as the fish grows, as seasonal food web processes change, as the fish change location (e.g., between south Puget Sound and the Strait of Juan de Fuca. In general, fish size and species has a dramatic influence on what is eaten. Prey size tends to increase as the salmon get larger. For example, juvenile Chinook salmon shift from a diet of insects and amphipods to larger invertebrates such as amphipods, crab zoea, and polychaetes to a diet that is mostly fish by the time they occupy the offshore waters of Puget Sound.

The organic matter and nutrients eventually utilized by juvenile salmon as food come from terrestrial (e.g., insects), benthic (e.g., amphipods and polychaetes), and pelagic food webs (e.g., copepods, crab larvae). The organic matter and nutrients that support each food web of course vary. One type of food web that is especially important to salmon is the detritus based food web. These nearshore food webs depend upon internally derived organic matter (e.g., from eelgrass). This organic material which is called detritus supports a grazing community of micro flora and fauna that in turn supports invertebrate prey such as copepods that are eaten by smaller size classes of juvenile Chinook salmon and chum salmon.

Because salmon are associated with all types of food webs and occupy many different trophic levels they are eaten by many species of fish, birds, and mammal. As the salmon increase in size, the number of species that are predators declines as the salmon simply outgrow their predators (e.g., become too large for the predators to handle and eat). By the time salmon have reached subadult size, only mammals (including humans) are large enough to eat them.

Within the marine waters of Puget Sound, there is no evidence that food is limiting, although such a possibility has not been rigorously tested. Many of the species salmon co-occur with have similar diets to salmon. And, often different species of salmon will have similar diets. There is evidence that food is limiting (i.e. resulting in density dependent processes) for Chinook salmon in natal deltas.

<u>Non-salmonid pelagic fishes</u>

Non-salmonid pelagic fishes of Puget Sound include representatives from several families. Herring (*Clupeidae*), smelt (*Osmeridae*), sand lance (*Ammodytidae*), surfperch (*Embiotocidae*), tube snout (*Aulorhynchidae*), and anchovy (*Engraulidae*) are common, with rare occurrences of silversides (*Atherinidae*), pelagic sharks (*Lamnidae*), and armorheads (*Pentacerotidae*). However, the majority of biomass is concentrated in three key species; Pacific Herring (*Clupea pallasii*), Pacific sand lance (*Ammodytes hexapterus*), and surf smelt (*Hypomesus pretiosus*). This collective group of forage fishes represents a critical trophic link between primary / secondary producers (i.e. phytoplankton / zooplankton) and larger vertebrates, including endangered and other salmonids, seabirds, and marine mammals. Additionally, these three species transfer energy and nutrients from pelagic to nearshore regions during spawning (all three species) and nocturnal refuge (sand lance). They utilize surface, mid-column, epibenthic, and nearshore waters of Puget Sound.

Pacific herring are a substantial component of several trophic levels of the Puget Sound food web. The estimated carbon contribution of herring spawning products to the Strait of Georgia during the spring spawning period is greater than maximum estimates of primary productivity during the same period (Hay and Fulton 1983). Herring eggs and larvae represent a primary food source for invertebrates including crabs, medusae, ctenophores, chaetognaths, and amphipods; fish including juvenile salmonids, sturgeon, smelt, and surfperches; and marine gulls and diving birds. Juvenile and adult herring serve as the primary prey for marine mammals including harbor seals, sea lions, and orcas (Schmitt et al 1995), and finfishes including endangered Chinook salmon, coho salmon, Pacific cod, Pacific hake, lingcod, and halibut (Lassuy 1989).

Herring stocks in Puget Sound are defined by their spawning location; however, the extent to which these stocks are isolated and the residency of stocks in Puget Sound is still in question. Fish tagged in the Puget Sound have been recovered in the Strait of Georgia (British Columbia) and in the Pacific Ocean (Buchanan 1984, Trumble 1983). Cumulative spawning biomass estimates for herring in Puget Sound were 15,016 and 12,007 tons for 2003 and 2004 respectively. These estimates are 85% and 68% of the 25 yr mean (17,754 tons). Stocks in South-Central Puget Sound are relatively stable, while those in North Puget Sound are depressed primarily due to reduction in the Sound's once largest stock at Cherry Point. The spawning biomass of herring at Cherry Point in 2004 was only 43% of the 25 year mean (Stick 2005).

Other forage species in Puget Sound, including sand lance and surf smelt, historically received less attention than herring, likely because of their perceived economic value. However, their ecological value as primary forage species should not be overlooked because they occupy similar niches with herring and represent important components of the diets of larger vertebrates. For example, sand lance often comprise a substantial part of the diet of Chinook and coho salmon (up to 70%; Groot and Margolis 1991) and sea birds (Abbokire and Piatt 2005). Surf smelt also can be important prey for salmon (Groot and Margolis 1991) and seabirds (e.g., Caspian terns in Commencement Bay; Thompson et al. 2002). Declines in abundance of forage fishes seemed to be an important contributor to declines in seabird populations in the Gulf of Alaska even though increased numbers of gadids and flatfish were available (Piatt and Anderson 1996).

Sand lance and surf smelt deposit eggs in the intertidal zone of sand-gravel beaches. In Puget Sound 400 km and 320 km of beach have been identified as spawning habitat for surf smelt and sandlance respectively (Pentilla 1997, Pentilla pers. comm.). Because these beaches are scattered throughout Puget Sound and no apparent aggregations of adults occur, there is currently no practical methodology for monitoring the biomass of these species. Additionally, no data exist to suggest whether these species are resident or transient in Puget Sound (Pentilla pers. comm.).

<u>Marine Birds</u>

The Puget Sound area supports several species of marine and terrestrial birds. Although many species of terrestrial birds, including eagles and other raptors, prey on fish and other marine organisms in the Sound, it is the group of more than 100 species of marine birds that almost exclusively rely on the marine food web for nutrition. Whether surface gleaners, plunge divers, or pursuit divers, the seabird diet consists of small coastal pelagic fish, young-of-the-year-predatory fish (e.g., salmonids and groundfish), macro-zooplankton (large copepods and euphausiid crustaceans), and squids (Mills *et al.* 2005). As top predators in marine ecosystems, seabirds function as important indicators of ecological change because they are visible, abundant and relatively easy to study. In fact, seabird distribution and productivity have been linked to prey (forage fish and plankton) availability, nearshore habitat quality and oceanographic conditions (Piatt 2002, Speckman *et al.* 2005).

Many species of marine birds come ashore only to breed, while the remainder of the year is spent on the ocean. Thus, nearly all species of marine birds are seasonal in their occurrence within the Puget Sound, a region that provides habitat for migrant, winter resident, and breeding marine birds (Manuwal *et al.* 1979). In the northern Puget Sound, the San Juan Islands and Protection Island are important areas for nesting marine birds (Manuwal *et al.* 1979, Mills *et al.* 2005). In fact, Protection Island (located at the southeast end of the Strait of Juan de Fuca) is one of the largest breeding colonies of seabirds in the Pacific Northwest (U.S. National Fish and Wildlife Service), including one of the largest Rhinoceros Auklet breeding colonies in the world and the largest Glaucous-winged Gull colony in Washington (Mills *et al.* 2005). For all seabirds, predation on eggs and chicks can be high at breeding colonies (Mills et al. 2005). Depending on the location of the colony, sources of predation on seabirds can include a large suite of predators; namely gulls, raptors, corvids, rodents, cats and other large introduced mammals (Mills et al. 2005).

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 in their diets (Nysewander *et al.* 2001, Bower 2004). For example, Marbled Murrelets have declined by 83% in northern Puget Sound (Bower 2004) and have been identified as "highly imperiled" by the U.S. Fish and Wildlife Service (Seabird Conservation Plan 2005). Marbled murrelets forage in nearshore marine waters, but nest far above-ground in complex, multi-storied forest stands in old growth forests (Bentivoglio *et al.* 2000, Meyer and Miller 2002). One source of mortality for these birds is entanglement by salmon gillnet fisheries in the Puget Sound region (Melvin 1997).

Marked declines have also been observed in summer breeding populations of fish-eating seabirds. For example, Common Murres declined by 83% in the early 1980s, and numbers have never recovered (Manuwal et al. 2001). In large part because of these population trends, the U.S. Fish and Wildlife Service identified the Common Murre as species of "moderate conservation concern" (Seabird Conservation Plan 2005). These birds typically immigrate to the Strait of Juan de Fuca, Strait of Georgia, and Puget Sound following the breeding season in the late summer and fall where they mainly feed on Pacific herring and Pacific sand lance as well as some salmonids (Lance and Thompson 2005). One source of mortality for these birds is entanglement by salmon gillnet fisheries in the Puget Sound region (Melvin 1997, Lance and Thompson 2005). Another summer breeding population that has suffered a decline is the burrow nesting Rhinoceros Auklet (Mills et al. 2005). In fact, the Protection Island summer and spring breeding colony in the Strait of Juan de Fuca has declined steadily from a high of about

17,000 pairs in 1975 to 12,000 pairs in 2000 , and as a consequence, the U.S. Fish and Wildlife Service identified the Rhinoceros Auklet as species of “high concern” (USFWS 2005). When these birds forage in the Puget Sound, they prey primarily on Pacific herring, Pacific sand lance, and salmonids, but also consume considerable amounts of threespine stickleback (Lance and Thompson 2005). Sources of mortality include predation by Peregrine Falcons, Bald Eagles, and other avian predators at breeding colonies (Mills *et al.* 2005) and entanglement by salmon gillnet fisheries in the Puget Sound region (Melvin 1997, Lance and Thompson 2005).

Moderate 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 sub-tidal or inter-tidal invertebrates (e.g., gulls and scoters). Specifically, the Pelagic Cormorant has been identified as species of “high concern” by the U.S. Fish and Wildlife Service (Seabird Conservation Plan 2005). These birds depend on steep, rocky cliffs above the ocean to nest during the spring and summer months (Mills *et al.* 2005), but also require year-round roosting habitat on dry land for drying their feathers because their plumage is not waterproof (Mills *et al.* 2005). Similarly, the Pigeon Guillemot forages on both dispersed demersal fishes and aggregated pelagic fishes (Litzow *et al.* 2004), and is currently listed as species of “moderate conservation concern” by the U.S. Fish and Wildlife Service (Seabird Conservation Plan 2005). Pigeon guillemots are nearshore-foraging seabirds that rely on the relatively inaccessible cliffs and headlands along the mainland coast and on larger islands for nesting sites (Mills *et al.* 2005). Like other seabirds in the Puget Sound region, salmon gillnet fisheries are a source of mortality for Pigeon guillemots (Melvin 1997).

Increasing our knowledge of the biology and ecology of some key marine bird species that were at one time very abundant but are now declining will provide us with a better understanding of how the Puget Sound ecosystem is changing. The causes of these dramatic declines are unknown in most instances, but possible explanations include natural variability in food supply or foraging habitats, and the negative effects of human development and fisheries on the marine environment and breeding habitat (John Piatt, pers. comm.; Manuwal *et al.* 1979; Mills *et al.* 2005). A better understanding of all of these factors will also help us to understand the Puget Sound ecosystem as a whole.

<u>Marine mammals</u>

Eleven species of marine mammals that include six cetaceans (killer whale, gray whale, humpback whale, minke whales, harbor porpoise, and Dall’s porpoise) and five pinnipeds (harbor seals, California sea lions, Steller sea lions, northern elephant seals, and northern fur seals) are known to occur in the waters of Puget Sound, the Strait of Juan de Fuca, and Georgia Straits (i.e., the Salish Sea). Of these species, four of the cetacean species and two of the pinniped species can be considered key components of these systems due to their relatively large numbers or biomass or their potential influence on the abundance of their prey species. Key cetacean species include killer whales (piscivorous and mammal eating), harbor and Dall's porpoises, and gray whales. Key pinniped species include harbor seals and California seal lions.

Piscivorous and mammal eating killer whales are top predators that are distinct small populations of sympatric ecotypes (approximately 90 and 325, respectively (Caretta *et al.* 2005, Angliss and Lodge 2002). The piscivorous population has been increasing since 2001 following a 20% decline in the mid-1990s, but no trend data are available for the mammal eating population. Although both ecotypes occur throughout the Salish Sea year-round they have unique temporal and spatial habitat use patterns. There are seasonal peaks, with piscivorous whales being present most days during the summer and fall (Osborne 1999) and mammal eating being present sporadically in the fall (Baird and Dill 1997). Piscivorous killer whales occur primarily in major channels surrounding the San Juan Islands in the summer and expand their movements into the Puget Sound in the fall (Osborne 1999). Habitat use includes the central parts of these main channels as well as particular nearshore areas with steep slopes. Mammal eating killer whales are found most frequently off southeastern Vancouver Island in narrow channels or close to shore (Baird and Dill 1997), and travel in relatively small groups (avg=3, Baird and Dill 1996). Mammal eating killer whales are also typically present for only a few days, although there have been two occurrences of extended residency periods in Hood Canal in recent years (London *et al.* 2003, 2005). The diet of piscivorous whales has been found to include a variety of fish species based on stomach contents (Ford et al., 1998) but more numerous samples from predation events have indicated that salmon, particularly chinook are important prey (Ford *et al.* 1998, 2005, Hanson *et al.* 2005). Mammal eating killer whales forge primarily on harbor seals although a few harbor porpoises and California seal ions are also taken (Baird and Dill 1997). There are no known predators of killer whales. Piscivorous killer whales may compete with humans for fish resources but mammal eating killer whales likely have no competitors.

Each year very small fraction of the approximately 26,000 (Angliss and Lodge 2002) gray whales which migrate to Alaska from Baja California enter Puget Sound. The population has been steadily increasing since the first systematic counts were made in the late 1960s. They are observed periodically throughout the year but peak abundance of a few dozen individuals occurs in the spring. They occur throughout Puget sound, including the strait of Juan de Fuca and Hood Canal. Although they travel in the main channels it is not uncommon to observe them feeding in shallow waters areas with a sandy bottom . In particular, they are commonly observed in Port Susan and near the south end of Whidbey Island (Calambokidis *et al.* 1994) were they are known to feed on ghost shrimp (Weitkamp *et al.* 1992). Lower occurrence and residency time in Port Susan in subsequent years may indicate that the standing stock of ghost ship was temporarily depleted. Killer whales are known to prey on gray whale calves but this has not been observed in Washington State.

Harbor porpoises are the most numerous cetacean in the Salish Sea, with an estimated population of 10,682 in 2002/2003 of the Washington inland water stock (NMML, unpublished data). The estimated population size has increased almost 3 fold since the since the first systematic surveys were done in the early 1990s (Calambokidis *et al.*

1997). Despite their relative large numbers they are found almost exclusively in the Straits of Juan de Fuca and Georgia, with few sightings in Puget Sound. This situation contrasts with anecdotal observations from the 1940's of harbor porpoise being extremely common in the lower Puget Sound (Scheffer and Slipp 1948). Seasonal survey data (PSAMP unpubl. data) indicated that these species are present year-round, and radio telemetry data suggests that seasonal movement patterns are limited to regions within the Salish Sea (Hanson 2005). Radio-telemetry data and genetic data also indicate that animals in the Juan de Fuca and Georgia Straits do not move between areas or inter-breed (Hanson 2005). Although harbor porpoise can be found in nearshore shallow water (Calambokidis et al. 1997, Hanson unpubl. data), most are found in the deeper central portion of the main channels (Hanson 2005). Their primary prey are small schooling fish, particularly herring. and squid (Walker et al. 1998, in prep.) but other species of importance include pollock, hake, smelt, midshipman, and sculpin. Their primary predator is mammal eating killer whales. They may compete with Dall's porpoise for prey, (although generally, they appear to be spatially and temporally segregated), and harbor seals.

Dall's porpoise are a common small cetacean in the Salish Sea with an estimated population of approximately of 98,617 in the California/Oregon/Washington stock (Caretta *et al.* 2005). However, estimates for the inland Washington waters indicate about 3,500 porpoises are present (Calambokidis *et al.* 1997). There are no trend data available for this population. This species is found throughout the strait of Juan de Fuca and Puget Sound with primary concentrations in the Haro Strait area. Dall's porpoise typically use the main channels and are associated with deep water locations where they are known to dive to near the bottom (Baird and Hanson unpubl data.). Based on telemetry studies, there is also some indication that seasonal habitat use patterns exist. Although sample size is limited, Haro Strait was used in the winter and spring followed by movement to areas just off the entrance of the strait of Juan de Fuca in the summer (Hanson 2005b). In the fall, the porpoises utilized the central Strait of Juan de Fuca. Like harbor porpoise, Dall's porpoise prey on small schooling fish, but the diets of the two porpoise are somewhat different. Nearly half of the Dall's porpoise diet is composed of pollock, but sculpin, herring, hake, squid and eulachon contribute to the other half of the diet (Walker *et al.* In prep.). Predators include killer whales, although no known predation event on this species has been documented in this region. Dall's porpoise may compete with harbor porpoise, but it appears that these two species may be spatially and temporally separated. There may be some competition with harbor seals and California sea lions.

Harbor seals are the most common pinniped in the Salish sea with a population in the late 1990's numbering close to 8,000 animals (Jeffries *et al.* 2003). This population had increased from only 3,000 seals in the late 1970's (Jeffries *et al.* 2003), but appears to have plateaued in the early to mid-1990's. These seals are year-round residents with high haul-out site fidelity and generally limited movements from these sites. Harbor seals are wide spread throughout all three basins and Hood Canal, but the majority of the population is in the San Juan Islands, the bays to the east of this area, and the Strait of Juan de Fuca. The seals are commonly found in the shallow waters near their numerous haul out sites but also venture into deeper portions of the main channels. Their diet is comprised primarily of fish, and although some seasonal and site specific variation does exist, hake and herring comprise 70% of their diet with 9 other fish and one squid species comprising the rest (Olesiuk 1993). (There may be some differences in prey in south sound – looking for this). Consequently, harbor seals may be in competition with harbor porpoises to a limited extent. Harbor seals are also a primary prey item of mammal eating killer whales.

California sea lions were first observed in the mid 1970s and occur in relative small numbers throughout the Salish sea and Hood Canal. The number of sea lions in the area increases to over a thousand animals during the peak each spring. Recent counts number in the low hundreds despite the likely continued increase of this population (Caretta *et al.* 2005). These animals are comprised primarily of adult and subadult males that migrate north from the offshore islands in California during the post-breeding season. Although these sea lions are wide spread, they are known to concentrate in Shilshole Bay and in Port Gardner (Gearin et al 1999) . It is likely that the Shilshole Bay aggregation of sea lions formed because of the ease of foraging on concentrations of steelhead returning to Lake Washington watershed that are subject to increased vulnerability associated with the unnatural environment adjacent to the Government Locks. A relatively small number of California sea lions were responsible for nearly decimating this fish population (Gearin *et al.* 1988?). In Port Gardner the sea lions have been found to primarily prey on hake (80%), although 10 other fish species and one squid species make up the remainder of the diet (Gearin *et al.* 1999). Although hake was overfished prior to the arrival of sea lions in Port Gardner, the continued presence sea lions has been attributed to preventing this fish stock from recovering (Schmitt *et al.* 1995).

Threats to the Puget Sound Food Web

The Puget Sound is an area that has been enormously altered by human activity. However, the specific anthropogenic threats that most impact the food web have not been identified. Similarly, the specific mechanisms that cause adverse effects are also unknown. Although several human activities impact the food web on many levels, this section will focus on anthropogenic threats that are either conducted through the food web or directly impact the food web structure. These activities result in removals or additions of species, impact predator and prey relationships, or affect the health of species in the food web. Examples of such anthropogenic activities, include vessel disturbance, fishing operations, introduction of toxic substances and pollution, and the introduction of non-native species. Catastrophic events such as oil spills and disease outbreaks are also concerns. Destruction of habitat also seriously impacts species in the food web, but those anthropogenic impacts are discussed elsewhere in the document (see habitat section). It is important to assess all anthropogenic threats in the Puget Sound ecosystem because these threats and other unidentified factors, such as climate change, may act either singly or in concert to affect reproductive success or survival of species in the ecosystem.

Vessel Disturbance

Shipping, fishing, and recreational boating activities are high in the Puget Sound, and as a consequence, the mere presence of these vessels and the noise produced by them can negatively impact several species within the Sound. For example, cetaceans (e.g., killer whales and harbor and Dall's porpoises) rely on their highly developed acoustic sensory system for navigating, locating prey, and communicating. Consequently the impacts of vessel disturbance and noise pollution on these species are of utmost concern. Specifically, the ESA-listed Southern Resident killer whale, a seasonal inhabitant of the Puget Sound region, is almost continuously surrounded by whale watching vessels during the summer months in the San Juan Islands. In fact, this group of whales have been exposed to a greater number of commercial and private vessels in recent years. The increase in the number of vessels in the vicinity of Southern Resident killer whales during the past decade is of concern because the Southern Resident killer whale population also suffered a 20% population decline from 1996 to 2001 (Krahn *et al.* 2002). As a result, vessel disturbance was identified as a potential risk factor to this group of killer whales. This is because the masking effects of noise produced by vessels and/or the behavioral changes in killer whales caused by vessel disturbance may inhibit these animals from foraging efficiently and/or increase daily energy expenditures.

Seabirds are also impacted by vessel disturbance and noise pollution, particularly at colonies or roost sites. Human disturbance to seabird colonies can result from recreational and commercial boating activities, aircraft overflights, ecotourism, and investigator disturbance. Boats or aircraft that approach too closely to breeding seabirds on their nests may cause birds to flush, thereby leaving the eggs and/or chicks open to predation or overexposure to harsh elements (Mills *et al.* 2005). Like marine mammals, extra energy expended during disturbances or missed feeding opportunities by seabirds could act to reduce both reproductive success and survival, potentially having negative population-level consequences.

Fishing Operations

The Puget Sound, as a highly productive marine ecosystem, has a high abundance of fishers. This has resulted in encounters and conflicts between certain fisheries and marine wildlife. Fishing operations can both directly and indirectly impact organisms in the Puget Sound. Direct disturbances by fisheries include boats disrupting feeding or injuring non-targeted animals, such as seabirds and mammals, either through direct collision or entanglement in fishing gear. In particular, seabirds; including Common Murres, Rhinoceros Auklets, Pigeon guillemots, Marbled Murrelets; have high incidences of mortality due to entanglement in the salmon gillnet fisheries in Puget Sound (Melvin 1997). Incidental harvest of non-targeted fish is another important impact on several species of fish, including salmon, in the Puget Sound food web (National Science and Technology Council, Committee on Environment and Natural Resources 2002). Fisheries can also compete for the same fish or invertebrate species that are consumed by higher level organisms in the food web. For example, Southern Resident killer whales consume salmonid species which are also targeted by fisheries (Krahn *et al.* 2002).

Finally, indirect human threats can involve reduction of prey as a result of competition with fisheries for shared prey resources and changes in the ecosystem structure produced by commercial fisheries activities due to biomass removal or habitat degradation (Mills *et al.* 2005). For instance, although the Pacific salmon stocks have declined I the Puget Sound, these stocks are still subject to substantial levels of harvest by commercial, sport, and subsistence fisheries (National Science and Technology Council, Committee on Environment and Natural Resources 2002).

Toxic Substances and Pollution

Due to human activities in the Puget Sound region, persistent toxic chemicals such as Organochlorines (OCs) and other pollutants contaminate the region. The effects of urbanization, such as pollution from waste water and sewage treatment plants, pesticides, excess nutrients and chemical waste are also cause for alarm (Puget Sound Action Team 2005). Organochlorines comprise a diverse group of chemicals manufactured for industrial and agricultural purposes (including, polychlorinated biphenyls (PCBs), DDT, dioxins (PCDDs), and furans (PCDFs) that are highly toxic and remarkably persistent once released into the environment. These chemicals are initially introduced into the marine system from agricultural runoff and industrial effluents. Subsequently, as a result of biomagnification (substances become increasingly concentrated in organisms at higher trophic levels) through the food web, higher trophic level organisms in the Puget Sound, particularly marine birds (Ohlendorf and Fleming 1988) and mammals (O'Shea 1999) carry high levels of OCs. High levels of OCs are lethal to adult birds at high concentrations (Ohlendorf and Fleming 1988, Mills *et al.* 2005) and can cause immuno-deficiency and inhibit reproduction in marine mammals (Ross *et al.* 1996a, Ross *et al.* 1996*b*). Because Southern Resident killer whales have high levels of PCBs, compared to other fish-eating killer whales, including the closely related Northern Resident killer whales (Ross *et al.* 2000) that also inhabit the Pacific Northwest, contaminants has been listed as a risk factor for the Southern Resident population (Krahn *et al.* 2002).

A range of metals are present in trace quantities in the earth's crust and thus throughout the marine environment, but at levels that are not toxic to marine organisms. However, at higher concentrations, all metals are toxic. Such elevated concentrations of metals can occur in the marine or onshore coastal environment from anthropogenic sources (Mills *et al.* 2005). Like OCs, metals are susceptible to bioamplification and accumulate at higher concentrations in higher trophic levels. In addition, concentrations of most metals tend to increase throughout an animal's life. The primary metals of concern to marine mammals are lead, mercury, and cadmium (O'Shea 1999). These three metals, with the addition of selenium, are of concern to seabirds (Mills *et al.* 2005). With the exception of mercury, many marine mammal species are able to tolerate high amounts of metals or detoxify them (Reijnders and Aguilar 2002). In contrast, high levels of metals in bird birds can cause many adverse impacts, including reproductive failure (Mills *et al.* 2005).

Because of the high level of shipping and ferry traffic, oil pollution is a great threat to the Puget Sound food web. Catastrophic oil spills can kill species from every trophic level of the food web. However, relatively minor oil spill can still impact several species. In particular, marine birds and mammals are particularly susceptible to oil spills. Interestingly, the Puget Sound area, with an extremely high density of seabirds, has been identified as one of the most susceptible areas to population-level impacts from oil spills (Mills *et al.* 2005). For marine birds, oil disrupts the waterproofing, and hence the insulation value, of birds' feathers, often leading to hypothermia (Mills *et al.* 2005). Seabird mortality can also result from direct ingestion of oil, which occurs when birds preen oiled feathers (Mills *et al.* 2005).

<u>Exotic Species</u>

Exotic species are organisms that are not native to the Puget Sound, but rather have arrived to the region as a result of human activities. In the Puget Sound there has been a fair amount of work done on exotic species (see Carlton 1979, Elston 1997, Cohen 2004). The report from the Washington Department of Natural Resources (WDNR) Rapid Assessment Survey of exotic species in Puget Sound provided an updated and corrected list of 52 exotic species that were judged to be established in the Sound (Cohen *et al.* 1998). Most exotic species are detrimental to the food web because they either out-compete native species for prey or habitat, prey directly on native species, or alter habitat which impacts the survival of native species (for review see Cohen 2004). For example, non-native species that have been introduced to reservoirs, such as bass and walleye, prey on salmon and add to the mortality rates inflicted on young salmonids by native predators (National Science and Technology Council, Committee on Environment and Natural Resources 2002). Similarly, predation by rodents, cats and other large introduced mammals can impact breeding colonies of seabirds (Mills *et al.* 2005).

Only a few of the many anthropogenic activities that impact the Puget Sound food web are described above. Once basic data on the impacts of human activity in Puget Sound are gathered, and the most important impacts are identified, further studies need to be conducted to assess how impacts on individual species have the potential to affect the status of their population and possibly the ecosystem. Multiple factors are undoubtedly responsible for changes in the populations of key species in the Puget Sound ecosystem. However, a thorough understanding of the anthropogenic threats in the Puget Sound will help us to reduce some of the uncertainty when modeling the viability of populations and assessing the relative risk of particular threats to the population.

<u>Eutrophication</u>

Historically, Puget Sound has not been viewed as susceptible to eutrophication because of the typically high concentrations of nutrients incoming from the Pacific Ocean, as well as strong mixing in the Main Basin of Puget Sound, which limits exposure of phytoplankton to light and therefore reduces growth. These characteristics of central Puget Sound were responsible for the success of the diversion of sewage from Lake Washington to West Point (Puget Sound) in the late 1950's (Edmondson, 1991). While nutrient loading to Lake Washington caused excessive algal growth, the same loading at West Point did not. Much of the current understanding of Puget Sound phytoplankton dynamics has been based on modeling and measurements of ambient productivity and nutrients at West Point (Winter et al. 1975). However, a much more complex picture is emerging, as a diversity of responses to nutrient addition is apparent both spatially and temporally within greater Puget Sound.

Harrison et al. (1994) and Mackas and Harrison (1997) evaluated the issue of eutrophication in the Strait of Juan de Fuca, Strait of Georgia, and Puget Sound. They judged potential impacts from eutrophication of the Main Basin of Puget Sound to be relatively low. However, they reported that the more poorly flushed bays and inlets of Puget Sound, particularly in the southern end, showed depleted surface nitrate concentrations and very low oxygen concentrations at depth. They assessed that the "early warning signs of eutrophication" were already evident in these poorly flushed bays and inlets of southern Puget Sound.

Bricker et al. (1999) reported the overall level of expression of eutrophic conditions to be moderate in (the Main Basin of) Puget Sound and Whidbey Basin and high in Hood Canal and South Puget Sound. The symptoms contributing to eutrophic conditions were chlorophyll *a*, macroalgae, toxic blooms, and, in Hood Canal, low dissolved oxygen. They predicted conditions to worsen, especially in Hood Canal and South Puget Sound, due to increasing population pressures.

Studies utilizing nutrient addition experiments on phytoplankton productivity support this conclusion, as data from Budd Inlet (Newton et al., 1998) and Hood Canal (Newton et al., 1995) show substantially increased rates of primary production upon nutrient addition. In a study on phytoplankton production in Puget Sound's Central Basin and Possession Sound (Newton and Van Voorhis, 2002), considerable interannual variation in production was observed, potentially linked to differences in external physical forcings, and increased primary production due to experimental addition of nutrients was seen at times at all stations during spring and, more often, summer months but was most evident in Possession Sound.

<u>Harmful algal blooms</u>

Harmful algal blooms (HAB) found in Puget Sound are those that can cause Paralytic Shellfish Poisoning (PSP) and Amnesic Shellfish Poisoning (ASP). PSP was first recorded in the region when in June 1793, four crewmen with Captain Vancouver's expedition became sick and one died shortly after eating shellfish along the central coast of British Columbia. In Puget Sound, the causative agent for PSP is saxitoxim produced by the dinoflagellate *Alexandrium catenella*.

There has been a documented spread in the occurrence of PSP throughout Puget Sound (Trainer *et al*., 2003). These authors present Washington Department of Health data documenting shellfish closures due to PSP beginning in the 1950's, however these were constrained to sites just to the north of Puget Sound, outside of Admiralty Inlet (in Sequim Bay, Discovery Bay, San Juan Islands). The first closures within Puget Sound were reported during the 1970's - specifically in 1978 where a large event followed a late-summer warm spell and heavy rains. PSP illness was reported from Saratoga Passage to Vashon Island. The "southward creep" of PSP closures continued, with increased incidents during the 1980's and 1990's. PSP went above the FDA action level in north Hood Canal for the first time during 1987 and similarly, in various inlets of South Sound during 1988, 1991, and 1997. In 2000, seven people were stricken with PSP from mussels collected in Carr Inlet, South Puget Sound; one man was severely stricken and spending several days in the hospital on a respirator.

Diatoms in the genus *Pseudo-nitzschia* can produce the toxin domoic acid that can accumulate in shellfish and other organisms to levels dangerous to human and aquatic health causing ASP. In the fall of 1991, the WA Department of Health found domoic acid in razor clams along the Washington coast. Shellfish closures due to domoic acid levels are presently not uncommon and can be fairly chronic on the outer Washington coast. Prior to 2003, domoic acid had not been detected at closure levels within Puget Sound, though *Pseudo-nitzschia* and domoic acid had been documented in Hood Canal (Horner *et al*., 1996). In 2003, the first shellfish closure due to domoic acid was declared near Port Townsend, in the very north of Puget Sound.

In 2005, elevated levels of domoic acid prompted closure of shellfish harvesting throughout Sequim Bay, Penn Cove, Saratoga Passage and Holmes Harbor. The factors prompting domoic acid production is a current topic of research, as the concentration of *Pseudo-nitzschia* is not correlated with the amount of domoic acid found in the shellfish (Trainer *et al*., 2000; 2002).

<u>Effects of Multiple Stressors</u>

While much research has been performed on the direct effects of certain specific threats to the health of aquatic species (e.g. pollutants, pathogens), the effects of multiple, sub-lethal stressors on the health and population structure of aquatic animals are largely unstudied. Stressors could include, but are not limited to: infectious agents (e.g. viral, bacterial, protozoan or fungal pathogens), physical factors (e.g. abnormal temperatures, salinity, low dissolved oxygen, and contaminants including toxicants, pollutants, endocrine disrupters, pharmaceuticals and flame retardants), habitat alterations (e.g. quantity and quality) as well as various biological factors that are outside the normal range (density, competition, food availability, forage base). It is very likely that various species and life stages will respond differently to these threats. It is also likely that synergistic effects will be seen when sub-lethal levels of such stressors are combined, resulting in losses in affected populations. For example, we know that fish in the Puget Sound region are infected with erythrocytic necrosis virus and that such infections result in a severe anemia. While fish in normal habitats can often survive such infections, the combined effects of infection and other stressors (low dissolved oxygen, low salinity, other pathogens) can resulted in large mortality of some species (MacMillan & Mulcahy 1979, Meyers et al 1986).

Food Web Science Needs

The prey base that supports a large number of marine birds, marine mammals and predatory fish species in Puget Sound, Washington is largely understudied in terms of marine habitat requirements, life history, distribution and abundance. In Puget Sound, forage fish species including Pacific herring, surf smelt and Pacific sandlance provide an important link between lower trophic levels and marine predators like seabirds, marine mammals and predatory fish such as salmon (Puget Sound Action Team 2005). In Puget Sound, concerted efforts to describe the distribution and dynamics of most species of forage fishes occurring in the Puget Sound region are lacking— but major declines during the past 15 years in a large number of fish-feeding marine birds and changes in distribution of marine mammals (e.g. harbor porpoise) indicate that that forage fish populations in Puget Sound may no longer be adequate to support a wide variety of marine predators.

Unfortunately, concerted efforts to describe the distribution and dynamics of most species of forage fishes occurring in the Puget Sound region have been limited, and there has been almost no effort to examine forage fish ecology and population trends with regard to oceanographic conditions or ocean climate change. Furthermore, seasonal and geographical variation in forage fish, salmon, marine bird and marine mammal abundance is undoubtedly linked to variability in plankton abundance (primary and secondary production), invertebrate abundance, oceanographic conditions (habitat parameters such as temperature, salinity, dissolved oxygen, and sediment load), bathymetry, and sediment type (or quality, including pollutants). While many studies have been conducted historically in Puget Sound that offer insight into some of these components individually, there has yet to be a study which attempts to examine co-variation in marine predators, prey and habitats, or integrate these across differing temporal and spatial scales.

Species Biology Science Needs

Many species in the Puget Sound have undergone a reduction in population number (e.g. salmon stocks and the Southern Resident killer whale population), a change in distribution patterns (e.g. harbor and Dall's porpoises), or both. Although the basic biology of some key species are well known, basic biological information for other species in the ecosystem are lacking. Additional information could contribute greatly to a better understanding of the organisms in the Puget Sound and the ecosystem as a whole. Knowledge of the basic biology of individual species are essential to assessing the factors that may be contributing to their decline and/or change in distribution and to understanding the effects of anthropogenic inputs or other perturbations in their habitat. The biological information that is needed can be classified broadly in the following categories: genetic relationships, life history patterns, birth and death rates, factors affecting survival, body condition indices, reproductive physiology, nutritional requirements, and physiological responses to anthropogenic inputs, disturbance, and environmental change. Data on the genetic relationships of key species in the ecosystem will help us to understand the degree to which populations and subpopulations are evolutionarily isolated and demographically closed as well as provide accurate estimates of the time of divergence and rate of gene flow among groups. Consequently, we will be able to provide more accurate population definitions, determine gene flow rates, and assess the potential for inbreeding depression. Accurate data on the life history patterns (e.g. age at sexual maturity, age at functional sexual maturity, birthing interval, etc.), birth and death rates, factors affecting reproduction, and factors affecting survival of key species will help us to better assess the status of populations; and by continually monitoring these factors, we can better assess changes in the status of populations and how they respond to environmental perturbations. Physiological data on body condition, reproduction, nutritional requirements, and responses to anthropogenic inputs, disturbance, and environmental change are necessary to determine potential risk factors to organisms in the Puget Sound. Once additional data on these basic components are gathered, further studies need to be conducted to better determine how the biological characteristics of each species have the potential to affect the status of their population and possibly the ecosystem. Multiple factors are undoubtedly responsible for changes in the populations of key species in the Puget Sound ecosystem. However, a thorough understanding of the biology of key species within the Puget Sound will help us to reduce some of the uncertainty when modeling the viability of populations and assessing the relative risk of the threats to the population, and provide key information for management actions.

Specifically Identified Science Needs for Species Groups

Some Key Science Needs for Invertebrates

1. Despite the regional importance geoducks, reliable information about the species population dynamics, recruitment and genetics does not exist.

2. It is important to point out that although some species are commercially or recreationally harvested, it is not clear what the impact of this is on lesser defined benthic organisms.

3. The impacts of global climate change are already being visualized by increased Puget Sound water temperatures. It is probable that our changing environment will alter the dynamic impacts of marine harvests on lesser defined organisms and hence food web structure and sustainability, but how these things might change is unknown.

Some Key Science Needs for Salmonids

1. Define the critical ecosystem features for the full life cycle of salmonid species and stocks.

2. Quantitatively assess the risks (natural and anthropogenic) to salmon during upstream, downstream, and estuary/ocean life stages.

Some Key Science Needs for Non-Salmonid Pelagic Fish

Aside from limited information regarding populations size and age structure of Pacific herring in Puget Sound, major information gaps exist in basic knowledge of forage fish stock abundances and roles in ecosystem function. Basic information necessary to effectively manage these stocks, including gross population sizes, relative abundances, bioenergetic values, and ecological selection pressures, is not available.

Effective protection and management of forage fish, and threatened / endangered species that directly depend upon forage fish availability cannot occur until the following basic knowledge gaps are addressed:

1. Total and relative size of forage fish populations in Puget Sound.

2. Relative bioenergetic values of the primary forage species in Puget Sound.

3. Seasonal residency and migration patterns of the primary forage species.

4. Ecological factors influencing forage fish abundance, availability, and assemblages in Puget Sound.

5. Significant species interactions among forage fishes and between them, their predators, and other competitors.

Some Key Science Needs for Marine Birds

1. Investigate the predator and prey associations for each marine birds species, and assess the effect of prey abundance and distribution on the status of marine bird populations.

2. Identify what factors cause disturbance or increase mortality of chicks at seabird colonies.

3. What are the physiological effects and population effects of high contaminant loads in marine bird species in the Puget Sound?

Some Key Science Needs for Marine Mammals

1. Assess how and if each of the key marine mammal species have the ability to switch prey versus moving geographically when prey resources change in abundance or distribution.

2. Investigate the predator and prey associations for each marine mammal species, and specifically determine how and when the predators move relative to changes in prey abundance and distribution.

3. Investigate the predator and prey associations for each marine mammal species, and assess the effect of prey abundance and distribution on the status of marine mammal populations.

4. How are harbor porpoises able to remain resident to Puget Sound year round? Are they able to feed on same species all year or are there seasonal changes in prey availability and selection?

5. Since harbor seals have now hit carrying capacity, what are the effects on prey and competitors?

6. What are the physiological effects and population effects of high contaminant loads in marine mammal species in the Puget Sound?

Humans and the Puget Sound Ecosystem

The Puget Sound region is home to more than 7 million people, with that number expected to grow to more than 9 million by 2020. The human population is a source of stress to the Puget Sound ecosystem but is also motivated to find ways to manage and relieve that stress. Our motivation partly lies in what are called ecosystem goods and services, which emanate from the structures and functions of the Puget Sound ecosystem (Figure 2). Sometimes these values are passively enjoyed, the proximity or even merely the existence of Puget Sound sufficient to generate them. In other cases, it is human actions like fishing or boating that generate these values.

The same activities that generate these values, however, can also be sources of ecological stress if they exceed certain thresholds. Similarly, the presence of a growing population increases the passively enjoyed values of Puget Sound but also places more demands on the region's resources and so increases the stress as well. Finding a balance arguably is a major goal of the effort to manage Puget Sound on an ecosystem scale. Identifying the goods and services generated by the Puget Sound ecosystem is therefore an important step in formulating management alternatives.

While there is a growing literature on the identification, categorization, and nature of various ecosystem goods and services, empirical research directly related to Puget Sound is scarce. Because so much of the empirical research is indirect or only marginally relevant, this section concentrates on a conceptual framework for assessing ecosystem goods and services in Puget Sound. The key science need identified is to conduct basic empirical research relevant to a Puget Sound ecosystem-scale management effort.

Ecosystem Goods and Services

Ecosystem goods and services are generated by the structure and function of natural systems, often in combination with other, "human-made" goods and services (Figure 2). The values of ecosystem goods and services come from direct consumption, through actions that enjoy but do not consume them, and through passive enjoyment or mere knowledge of their existence. The actions motivated by these values may produce effects that feedback and affect the ecosystem structure and functions. An evaluation of ecosystem goods and services, then, takes place in the context of this integrated, dynamic system (NRC 2004).

Ecosystem goods and services are the "outputs" of ecosystems that benefit humans. In building a conceptual framework from this foundation, we note at the outset that the majority of values we attach to these goods and services are what are known as economic values. These are not just values that flow through markets, but any value that is rooted in the satisfaction of human wants. This admittedly anthropocentric view does not capture intrinsic values that stem from moral premises. Nonetheless, economic values are broadly defined to include not only the value derived from direct use of an ecosystem service (use value), but also nonuse values such as existence and bequest values. It thus includes the value of protection "for protection's sake," which is viewed as desirable by many humans.

The Millennium Ecosystem Assessment, a recent global effort to catalog and assess ecosystem status and functions, offers a useful classification scheme (Box 7). 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 biophysical production, such as tons of salmon landings.
- *Regulating services* are the benefits obtained from the regulation of ecosystem processes, such as erosion control and pollination. 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 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.

Ecosystem goods and services are potentially useful concepts for policy analysis because they can be used as performance measures for different management strategies. In a policy context, the evaluation of a management strategy is not concerned with quantifying the value of an entire ecosystem (unless the strategy under consideration would effectively destroy the entire ecosystem); rather, it is concerned with connecting physical changes in the ecosystem to a set of changes in ecosystem goods and 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, but not a necessary one.

Forecasting changes in ecosystem goods and services across management scenarios is an exercise that involves a combination of modeling and expert judgment (MA, 2004, especially chapter 4). This approach is useful for revealing possible tradeoffs in particular goods and services (see next section of this report), but is less useful for addressing potential problems of ecological thresholds, extreme events, and irreversible changes. It is also an exercise that is inherently local in nature for the goods and services derived from ecological structures and functions that are less than global in scale.

Assessing Ecosystem Goods and Services for Puget Sound

Marine and estuarine ecosystems like Puget Sound provide many of these goods and services (Peterson and Lubchenco, 1999). Puget Sound is home to commercial, recreational, and tribal ceremonial 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. Puget Sound hosts myriad forms of recreation, including an active whale watching industry (Box 8). Underlying all of these are Puget Sound's basic supporting services such as primary production and the provision of habitat for salmon, killer whales, and other species. A similar set of goods and services are provided by the freshwater ecosystems that are linked to Puget Sound (Postel and Carpenter, 1999).

Quantifying this set of goods and services for Puget Sound is much more difficult. Assessing the quantities and values of ecosystem goods and services is a science in its infancy. This isn't to say that economists and other social sciences have ignored the natural world, or that they have failed to develop models and conduct analyses that incorporate specific types of ecological structures and functions. Numerous studies and entire social science fields have done so over the past fifty years, but only recently has social science explicitly adopted the ecosystem as a unit of study. As a result, the overwhelming majority of this work cannot be used to link specific changes in ecological structures and functions to the resulting changes in the quantities and values of ecosystem goods and services (NRC, 2004).

Among studies that are useful, relatively few cover marine or even aquatic ecosystems (NRC 2004), and only a handful have considered goods and services in the Puget Sound region. Leschine et al. (1997) estimates the economic value of wetland enhancement projects in two Puget Sound urban watersheds. They found annual values for these projects of between $2000 and $13,300 per hectare. In a study of Maury Island and its nearshore area, Herrera Environmental Consultants, Inc. et al. (2004) used existing empirical studies from other locations to estimate a comprehensive set of ecosystem goods and services. A second local study conducting a similar analysis was included in the development of the salmon recovery plan for the Green/Duwamish and Central Puget Sound watershed (WRIA 9) (Green/Duwamish and Central Puget Sound Watershed Water Resource Inventory Area 9 (WRIA 9) Steering Committee, 2005, Chapter 6, Ecological Economics Foundation).

All of these studies have methodological and other limitations, however. Leschine et al. (1997) used a method known as the "cost of treatment" method, which equates the cost of a project (or sometimes the cost of replacing ecosystem goods and services) with its value. While this approach can be used as a "last resort" if certain conditions are met, its general use should be avoided (NRC, 2004).

The other two studies used a method known as benefits transfer, which takes empirical results from studies undertaken in one location and "transfers" those values to another location. As NRC (2004) notes, studies that have investigated the validity of benefit transfers in valuing ecosystem services have found that this approach is not highly accurate. Natural systems exhibit considerable variability across space, scale, and even time in both their structure and functions. A small estuary in Puget Sound, for example, may have a far different structure and set of functions than a similarly sized one in the Gulf of Mexico, or than Puget Sound as a whole. As a result, transferring values from one ecosystem to another is an exercise fraught with peril.

This conclusion points to the major science needs in this area:

1. A better understanding of the links between the Puget Sound's ecological structure and functions and specific ecological goods and services;
2. Region-specific data on the magnitudes of these ecological goods and services; and
3. A better understanding of the incremental effects of policy choices on ecological goods and services

Meeting these science needs should proceed not by identifying abstract goods and services in a checklist, but by using actual ecological models such as those described in Section IV to link model components and relations to particular types of ecosystem goods and services. In this way, performance measures for ecosystem-scale management efforts could be identified and described in terms of ecosystem goods and services, while management strategies are devised that focus on the factors that stress the corresponding ecological components, structures, and functions. Alternative management strategies could then be evaluated using these measures grounded in an ecosystem goods and service framework.

Box 7: Ecological Goods and Services		
Provisioning Services • Food and fiber. • Fuel. • Fresh water. • Genetic resources. • Biochemicals, natural medicines, and pharmaceuticals. • Ornamental resources.	*Regulating Services* • Air quality maintenance. • Climate regulation. • Water regulation. • Erosion control. • Water purification and waste treatment. • Regulation of human diseases. • Biological control. • Pollination. • Storm protection.	*Cultural Services* • Recreation and ecotourism. • Cultural diversity. • Spiritual and religious values. • Knowledge systems (traditional and formal). • Educational values. • Inspiration. • Aesthetic values. • Social relations. • Sense of place. • Cultural heritage values.
Supporting Services: Necessary for the production of all other ecosystem services. Examples include soil formation, primary production, production of atmospheric oxygen, soil formation and retention, nutrient cycling, water cycling, and provisioning of habitat.		
Source: MA (2003)		

Box 8: Whale Watching in Puget Sound

Whale watching is an increasingly important tourism industry in the Puget Sound region, with an estimated 52,000 participants 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).

Whale watching would not be possible without the existence of the orca and other whales, and so it is tempting to ascribe the entire value of this activity to this ecological component. This ecosystem service, however, is the output of a combination of inputs, including human-made capital (boats) and fuel. Without any one of these components, this particular service would not be possible, making it problematic to ascribe the entire value of the service to any one input.

Managing Puget Sound on an ecosystem basis is likely to change the value captured by whale watching, but how this value changes over time may be complicated. If the orca population increases through management efforts, whale watching opportunities may also increase, increasing the value of the service. At the same time, management may focus on the industry itself. Any restrictions deemed necessary to protect the population would effectively decrease the value of the service in the near term.

Decision Frameworks for Ecosystem Approaches to Management in Puget Sound

Effective management of a complex ecosystem like Puget Sound requires not only information about the individual components – the species and processes that constitute that ecosystem -- but also scientific and policy frameworks with which to evaluate efforts to restore and protect the ecosystem (Pew 2003, USCOP 2004). In previous sections, we have discussed individual components of the Puget Sound ecosystem; this section addresses the task of combining these components in a framework that supports management capable of achieving the dual goals of a robust natural system and thriving coastal communities in the Puget Sound region.

A number of past and present efforts have addressed a variety of Puget Sound management issues. For that reason, this section discusses the development of an ecosystem-scale management framework for Puget Sound in general terms; the task of describing and developing the actual framework is one that this document is intended to support. We begin with a discussion of the potential use of a decision-support system – a framework for incorporating science into decision-making – to evaluate alternative sets of management strategies for the Puget Sound ecosystem. We then focus on an important component of such a system: conceptual and quantitative ecological and socioeconomic models.

Decision-Support Systems for Ecosystem-scale Management

The focus of ecosystem-scale management typically encompasses a wide variety of objectives, covering such issues as sustainable fisheries, endangered species, habitat structure, biodiversity, ecosystem integrity and resilience, as well as broader, regional economic and social objectives. Multiple ecosystem objectives such as these often arise from policies that describe a set of guidelines by which humans should exploit biological resources. The Puget Sound Partnership established by the Governor will set goals for Puget Sound "...to ensure that the Puget Sound forever will be a thriving natural system, with clean marine and fresh waters, healthy and abundant native species, natural shorelines and places for public enjoyment, and a vibrant economy that prospers in productive harmony with a healthy Sound." As noted above, the choice of these objectives lies outside the purview of science; yet science can help policy makers illuminate the consequences of setting and pursuing multiple objectives such as these, and evaluate potential tradeoffs between strategies designed to pursue those objectives.

For example, there is a clear potential for conflicts when policy embraces diverse objectives (Box 9). As a consequence, a useful support for ecosystem-scale management is a set of scientific tools that help policy makers identify potential conflicts and minimize their occurrence (Mangel 2000). We refer to this set of tools as a decision-support system.

The complexity of managing an ecosystem requires a decision-support system that can relate the ecological and socioeconomic consequences of potential specific management actions to the broader policy goals (Sainsbury et al., 2000). They coined the phrase Management Strategy Evaluation (MSE) to describe a decision-support system that uses the following elements:

1. Evaluate the status of the system being managed as a whole (not just isolated parts);
2. Specify policy objectives and performance measures that are connected to those objectives;
3. Relate alternative management strategies to predicted changes in the performance measures;
4. Monitor the system; and
5. Provide for iterative decision making that is based on data from the monitoring program.

This approach recognizes and illustrates but does not resolve the conflicts among competing objectives. Instead, it relies on a number of candidate models that are put forward to evaluate multiple hypotheses. The choice of a "best" solution is then left to the policy makers (Box 9). The use of a formal framework, however, contributes to the transparency of the decision-making process.

The approach outlined above is an example of a decision-support system that supports the evaluation of the managed system as a whole (Box 10). The ecological, socioeconomic, and management systems as well as the connections between them are modeled. The evaluation of alternative management strategies proceeds with a clear statement of management objectives and a choice of measures to gauge performance. Performance measures are best viewed as signals or surrogates, providing information on the status of the underlying systems, but should not be treated as policy ends in and of themselves (Van Cleve et al., 2004). Using performance measures implicitly embodies hypotheses about the relations between the measures chosen and higher level policy objectives such as ecological health, economic vitality, and social welfare.

The framework described by Sainsbury et al. (2000) is intended for management that is adaptive (Walters 1986). If that approach is embraced by policy makers, each strategy to be evaluated should include a monitoring program; what measurements will be taken; how these data will be analyzed; and how they will be used in subsequent scientific assessments. A management strategy should also specify how the results of scientific analyses will be used in management decesions, and which instruments will be used to implement decisions.

This formal adaptive-management approach can be used to investigate the consequences of a variety of scenarios evaluated across a range of models. Importantly, it can be transparent and collaborative if resource managers and stakeholders have input into candidate models and management scenarios. This approach encourages all participants to be clear about their goals, and the ground rules by which decisions are reached to be transparent.

The decision-making process represented in a MSE approach is simplest if a single governance body controls the human activities that influence the ecological components of the system under consideration. For example, applying this approach to fisheries is often straightforward in cases where a single regulatory body is responsible for making harvest and gear decisions. Such a body has control over the full set of policy instruments and a limited set of objectives, which simplifies the analysis.

This simple case does not apply to Puget Sound, however. The policy instruments needed to implement management at an ecosystem-level are distributed among dozens of government bodies. Local governments are responsible for traditional regulations zoning and the Washington State Growth Management Act; the Washington State Department of Ecology implements the Shoreline Management Act; the Department of Natural Resources manages the state's aquatic lands; the Department of Fish and Wildlife sets fishing regulations in conjunction with tribal governments; NOAA Fisheries is responsible for the conservation of Puget Sound species listed under the Endangered Species Act and the Marine Mammal Protection Act; the Environmental Protection Agency sets water quality standards under the Clean Water Act; and so forth. Each of these government agencies effectively has jurisdiction over a part of the Puget Sound ecosystem, limited to a particular geographic subregion or to a subset of the ecosystem's functions, or both.

Given the diversity of governance bodies in Puget Sound, a major challenge for any decision-support system is accounting for interactions among the governance bodies themselves (Rosenberg and McLeod 2005). This problem can be partly addressed by identifying the particular set of management instruments each government agency effectively controls. In this way, management strategy evaluations can reveal important interactions among the individual agency objectives, as well as the advantages of pursuing a coordinated ecosystem-scale management effort.

Additionally, a decentralized, uncoordinated management strategy can be established as a baseline against which to gauge the performance of other strategies, including ones that increase the coordination of the government agents or increasingly centralize their authority. By comparing performance measures across a range of possible strategies of these sorts, the incremental value of various degrees and forms of ecosystem-scale management can be estimated, at least in terms of the performance measures identified by the policy makers.

Integrated Assessment Modeling

Within Puget Sound, problems or causes of degradation are multiple and cumulative, and so management will also likely involve multiple and cumulative actions (Fresh et al., 2004). For that reason, management must recognize the connectivity of marine, estuarine, nearshore, terrestrial, freshwater, and shoreline ecosystems with one another. It must also recognize the connectivity of these natural systems with the economic and social systems that use or simply enjoy them.

Addressing these myriad connections within a decision-support system is often accomplished by using what is known as integrated assessment modeling (Millennium Ecosystem Assessment, 2005). Integrated assessment models usually include some description of the socioeconomic system and its interaction with the environmental system (regional water pollution, the climate system, land cover/land use, and so on). They can be qualitative (conceptual models) or quantitative (formal computer models), or include elements of both.

A conceptual model for Puget Sound could illustrate how individual ecological and socioeconomic components are connected, as well as detail their inner workings (PSNP, 2004b). It could also identify the directions and strengths of the connections and how stresses work their way through the system. It could thus help identify the types and locations of changes (i.e., resulting from restoration actions) needed to achieve a particular outcome (e.g., improved growth and survival of juvenile salmon); therefore, it can provide some insight into what actions might be most effective.

These models can also illuminate possible unanticipated or unintended consequences. A narrow, single species management focus often overlooks effects that act through prey or predator species, some of which may have undesirable effects on yet other species. And the failure to consider human reactions to policy prescriptions often leaves management blind to possible effects that could counter the intended outcome.

Generally, conceptual models are distinguished from quantitative models, which take the relations identified in a conceptual model and give them a dynamic, quantitative form. Obviously, the latter type of model is far more data intense, yet it is also capable of providing deeper insights into the workings of the ecosystem and therefore into the implications of particular policy choices. In some cases, for example, a conceptual model will identify multiple connections that act as opposing forces on a performance measure. A quantitative model is better able to address the relative strengths of these forces.

Both conceptual and quantitative models of the Puget Sound ecosystem can play an important role in supporting ecosystem-based management. The models embody hypotheses about how each system is likely to respond to a given set of changes. If management decisions are focused on implementing such changes, the models can be integrated and incorporated as part of a decision-support system for ecosystem-scale management.

<u>Ecological models</u>

Ecosystem-scale management for marine and related ecosystems is in part an outgrowth of the limitations of single species fishery models. These models have been criticized by some as inadequate for fisheries decision analysis because they consider only one possible effect of fisheries policy (Mangel and Levin, 2004). In contrast, management that focuses on an ecosystem needs to recognize and analyze a broader suite of system responses. For example, fishery management in an ecosystem context should explicitly recognize that fish stocks respond to underlying yet unpredictable ecosystem dynamics and that fishing itself can induce ecosystem changes.

We presently have many (but not all) of the tools to identify potential ecosystem responses and behaviors. We have expanding knowledge, for example, of food web processes in marine ecosystems, building a strong conceptual framework of the types of food web relationships that are common, rare, and most importantly, potentially sensitivity to perturbation in the context of management focused on fisheries. In many systems, detailed site-specific information is available describing meso- and whole-basin scale oceanographic drivers of primary and secondary productivity.

Existing analytical tools for ecosystem-scale management range from simple modifications of single species models to complex full ecosystem models. Single species models can be augmented with predator or prey abundance or environmental correlates. In these models, only the dynamics of single species are examined as a function of some aspects of the ecosystem. The utility of these models is limited because environmental feedback is unidirectional (from environment to target species), and indirect ecological interactions are ignored. A number of dynamic age- or size-structured multi-species models have been used in fisheries management. Such approaches often link fish survival to the abundance of predators and prey, and growth can be modeled as a function of food supply. These models are thus useful for examining trade-offs among different fishery sectors in the face of a variable environment.

Models of entire ecosystems are even more complex than multi-species models. Ecosystem models are largely based on food web and bioenergetics. Typically, these models aggregate species at lower trophic levels into functional groups while target species may be examined individually. Among these models, Ecopath with Ecosim (EwE) is especially notable: More than 150 publications have used this approach (Christensen and Pauly 2004). EwE is essentially a biomass-dynamic model analogous to those commonly used in single species stock assessments. Unlike single species models in which ecological processes are implicitly represented through static functions (density-dependence, natural mortality rates, and so forth), EwE explicitly considers the ecological interactions that give rise to population dynamics.

ATLANTIS, a modeling approach developed by CSIRO scientists in Australia, achieves the crucial goal of integrating physical, chemical, ecological, and fisheries dynamics in a three-dimensional, spatially explicit domain (Box 3). The ATLANTIS model has been used with great success in Australia, and versions of this model are currently being developed for the California Current and George's Bank ecosystems (Fulton et al., 2003).

Management for an ecosystem such as Puget Sound must encompass more than an individual species focus, however, as the objectives usually run the gamut of ecosystem goods and services. Developing conceptual and quantitative models for the Puget Sound ecosystem will be a major challenge.

Socioeconomic models

Like ecological modeling, socioeconomic modeling of marine and related ecosystems began with single species models applied to the problem of overfishing (Bjorndahl and Munro, 1999). These models typically utilize a simple stock-recruitment relationship and derive the optimal economic level of harvest for a fishery. Increasingly sophisticated models have refined numerous dimensions of the economic analysis of a fishery. For example, models have incorporated the effects of environmental stochasticity on optimal harvesting strategies and fisheries management; examined the use of transferable quotas and other rights-based management strategies; and addressed the problem of unintended bycatch for fisheries management.

An important innovation in economic modeling that makes it more relevant to ecosystem management is the incorporation of spatial dimensions in fishery models (Wilen et al., 2002). These models have been applied to the problem of creating marine reserves. As Wilen et al. (2002) show, a model that includes spatial location decisions as well as the choice to participate or not in the fishery can produce significantly different management recommendations than one that does not include these features. As they note, how fishery participants disperse spatially is just as important to the health and character of the ecosystem as is the biological dispersal process.

Outside of the economics of fisheries, the social sciences have tended to model the human components of ecological systems at a highly aggregated level (Millennium Ecosystem Assessment, 2004). An exception is the growing field of multi-agent simulation (MAS) models (Bousquet and Page 2004). In this type of model, individual agents such as households, businesses, and land developers behave as if they are solving simple optimization problems given constraints imposed by market opportunities (*e.g.* prices and budgets) and government policies (*e.g.*, zoning and pollution regulation). Changing a government policy then changes the set of constraints, which in turn changes their predicted behavior.

An example of a socioeconomic model being developed for Puget Sound is UrbanSim (Waddell, 2002; Box 4). The UrbanSim model operates at the level of individual land ownership parcels, which have GIS-based attributes such as land cover, land use, regulatory constraints, and so forth. Individual agents' decisions cover location, travel, consumption, production, and so forth. The advantage of a model like UrbanSim is its ability to predict behavioral responses to policy changes rather than simple presume those responses are in lockstep with the policy.

Integrating ecological and socioeconomic models

As Perrings (2001) notes, most environmental problem involve the interaction between social and ecological processes, and there are effects that provide feedback running in both directions. Integrating both ecological and economic models will therefore produce a more complete and possibly more accurate set of policy recommendations.

Many ecological models have some economic components, and vice versa, but the components from the complementary system invariably have their levels set by the modeler rather than determined endogenously. Modeling a few components of the complementary system in this way vastly reduces the complexity and computational requirements of the model but may also provide inaccurate policy advice. A socioeconomic model with a limited set of ecological components is unable to capture the full range of potential ecosystem interactions, crippling its ability to consider issues such as resilience and stability. Conversely, an ecological model with a limited set of socioeconomic components is unable to discern whether restrictions on one set of socioeconomic components may induce human behavior that mitigates or even overwhelms the intended outcome (Wilen et al. 2002). Acknowledging these real world concerns can take forms ranging from simple methods of incorporating uncertainty into the effects of a management strategy to more complicated multiple-agent simulations in which individuals react to management instruments such as regulation and market incentives.

In the context of Puget Sound ecosystem-scale management, an integrated model could combine an ecological model such as ATLANTIS with an economic model such as UrbanSim. Integrating the two types of models involves identifying links between human activity and the ecosystem's natural components. For example, Section III above notes that activities such as shoreline development, habitat loss, water contaminants, and invasive species are among the sources of stress for Puget Sound species. By linking activity in the socioeconomic model to these sources, the two models can then be integrated and incorporated into a decision-support system for ecosystem-scale management.

Conclusions

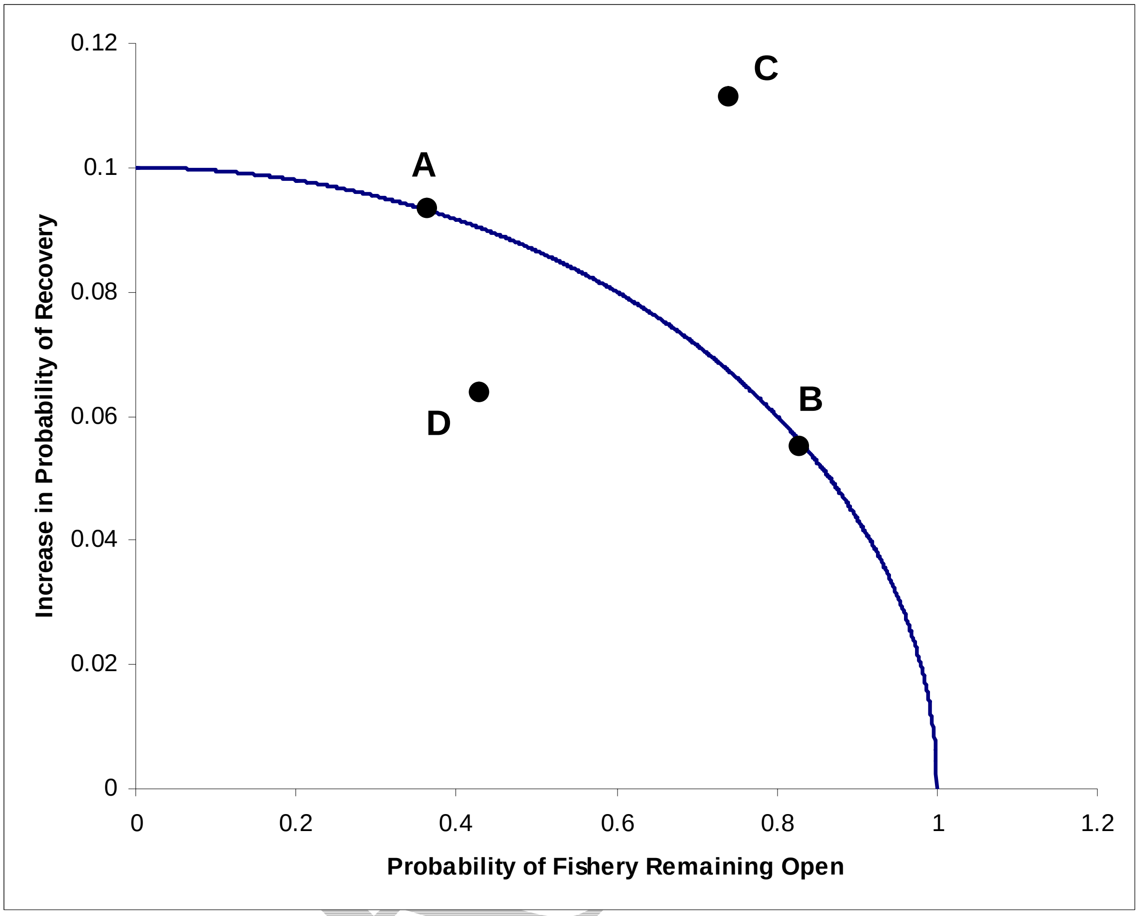
Putting the pieces of Puget Sound ecosystem science together is not an easy task, of course, nor is it one that involves science alone. Developing a management framework in an ecosystem context involves more than just building models of the Puget Sound ecological and socioeconomic systems. The choice of policy objectives and goals is a primary task, of course, for it clarifies the areas where scientific information and analysis can best be used to illuminate the consequences of alternative policy choices. But incorporating science into the policy process is an iterative process, requiring ongoing scientific participation from the outset.

This section has covered some of the key points involved in developing scientific support for the management of Puget Sound in an ecosystem context, including the following:

- Building a decision-support system requires both scientific and policy inputs, with the two spheres interacting as the framework is developed and implemented;
- A formal decision-support system can contribute to the transparency of making management decisions, encouraging a collaborative process that will strengthen the foundation of the process.

- Formal modeling, conceptual and quantitative, of both the ecological and socioeconomic components of the Puget Sound ecosystem is an important element of a decision-support system.

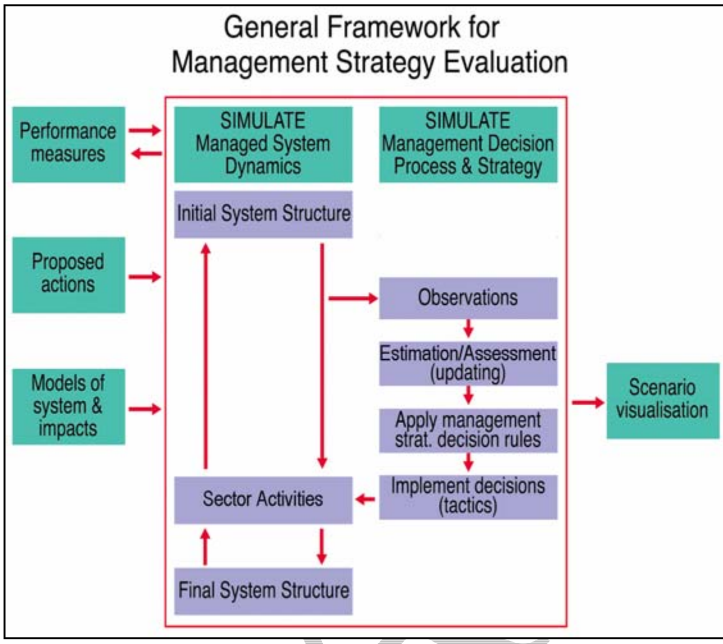
Box 9 – Tradeoff between Conservation and Economic Objective for the New Zealand Arrow Squid Fishery.



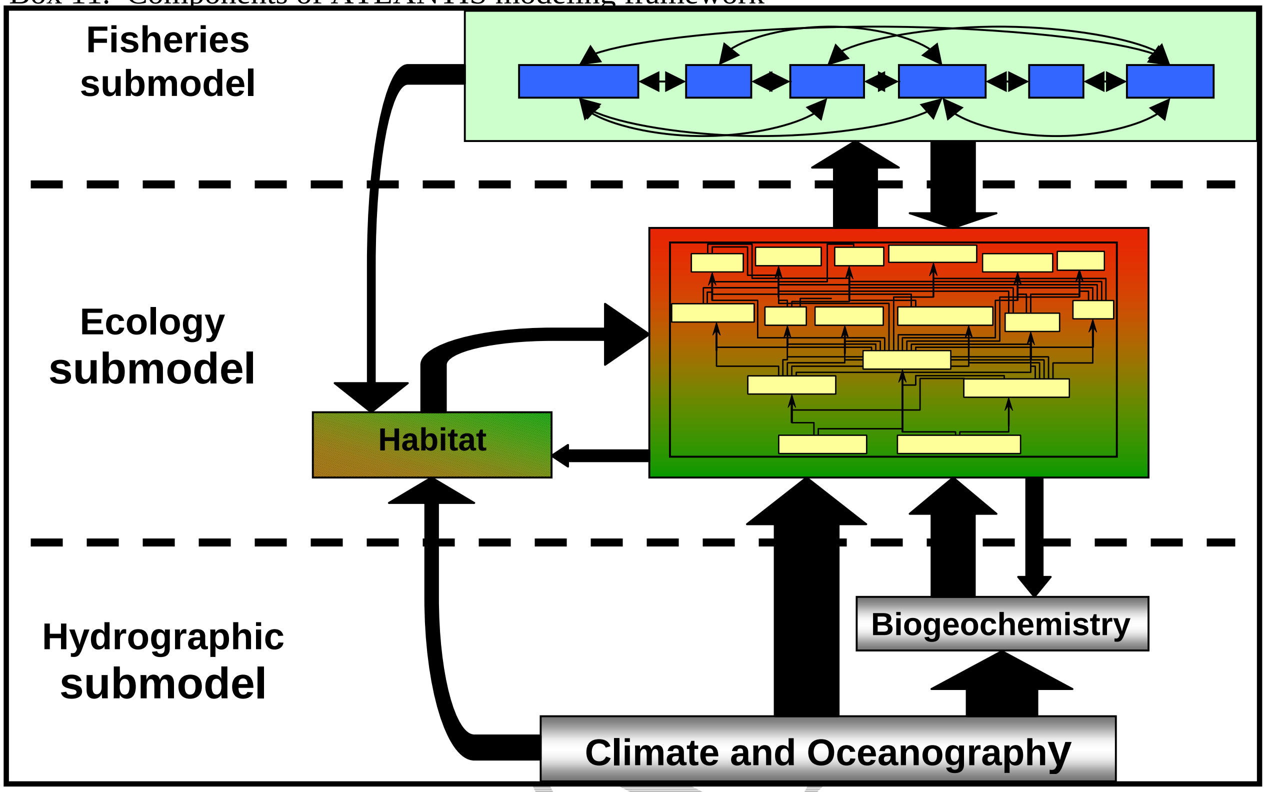
Maunder et al. (2000) considered the tradeoff between conservation and economic objectives for a New Zealand fishery (arrow squid) that impacted a sea lion population. They examined a policy of closing the fishery if the estimated fishery-related kill of sea lion exceeded a given threshold. Maunder et al. modeled the effects of this strategy on both the recovery of the sea lion population and the potential loss of yield for the fishery. They then derived feasible levels of each.

This example illustrates the two roles of science and policy, as well as the iterative process of one informing the other. The identification of objectives such as the conservation of sea lions and the vitality of the arrow squid fishery are set by policy makers. Analyzing the tradeoffs between the two objectives, along with the sensitivity to other factors, the effects of uncertainty, and so forth, are scientific tasks. In the figure, science can identify points like A and B that produce the maximum possible level of one objective given a level for the other; it can also identify levels that are infeasible (C) or that do not take full advantage of the possible ways of increasing either objective without the diminishing the other (D). The choice between any point, however, is in the policy realm

Box 10. Management Strategy Evaluation, from Sainsbury et al. 2000

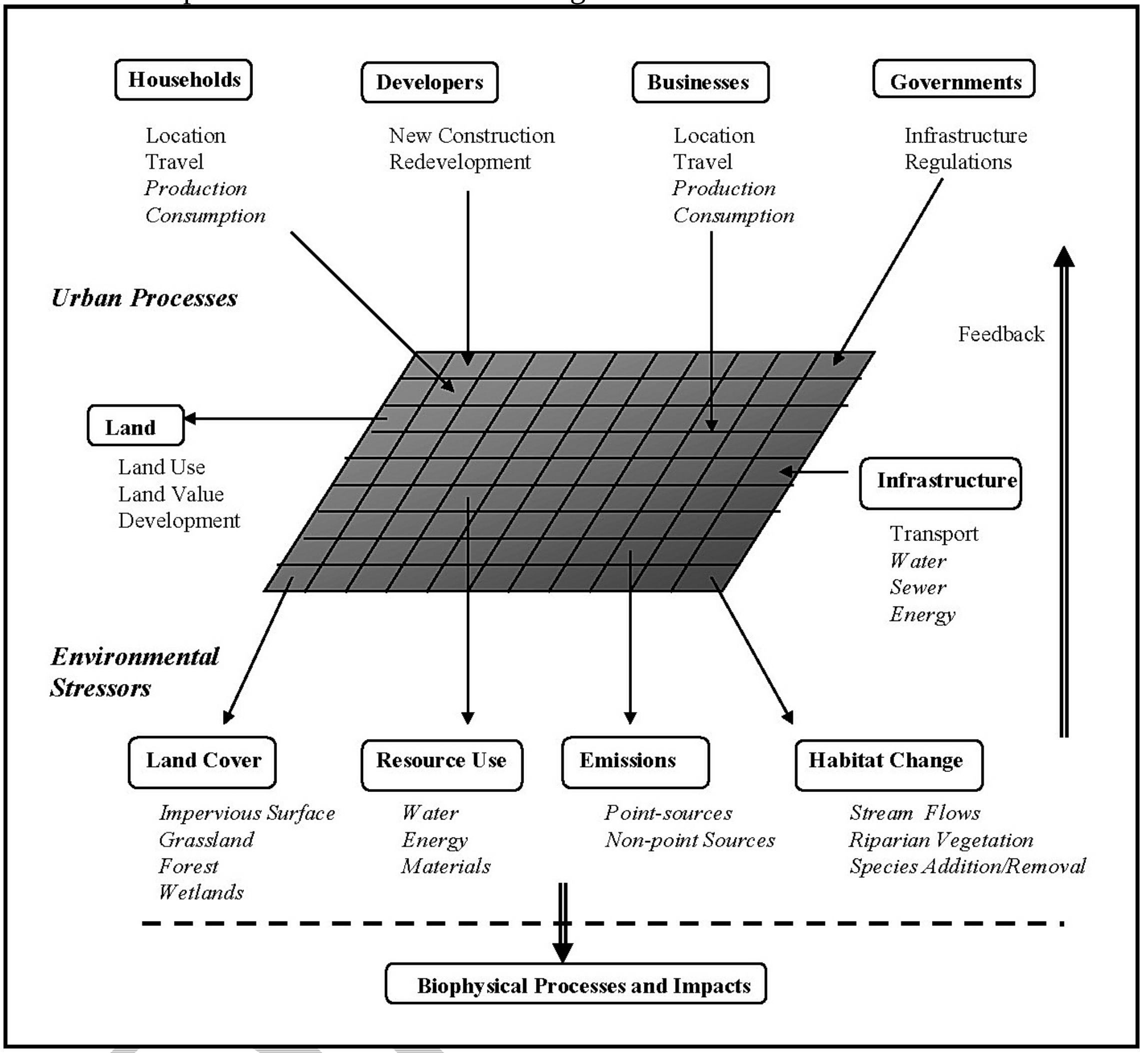


Box 11. Components of ATLANTIS modeling framework



ATLANTIS achieves the crucial goal of integrating physical, chemical, ecological, and fisheries dynamics in a three-dimensional, spatially explicit domain (Fulton et al. 2003). In ATLANTIS, marine ecosystem dynamics are represented by spatially-explicit sub-models that simulate hydrographic processes (light- and temperature-driven fluxes of water and nutrients), biogeochemical factors driving primary production, food web relations among functional groups, and the model represents key exploited species at the level of detail necessary to evaluate direct effects of fishing.

Box 12. Components of UrbanSim modeling framework



The UrbanSim model (Waddell, 2002) operates at the level of individual land ownership parcels, which have GIS-based attributes such as land cover, land use, regulatory constraints, and so forth. Individual agents' decisions cover location, travel, consumption, production, and so forth. Land use, land cover, and spatial location interact to produce flows that are linked to the ecosystem in which the urban system is embedded. The agents then make dynamic decisions about the use of their land. Changes in land use change the biophysical processes, habitat area, environmental emissions, and resource use. The urban behavior model is linked to four types of human-induced environmental change: land conversion, resource use, emissions, and habitat change. Each of these types of environmental change can be developed as a model that spans and therefore links the natural ecosystem models and the human system models. Currently, UrbanSim is a land-based effort but adapting and linking it to a marine ecosystem would be straightforward (if quite complex).

Key Science Findings to Inform Near-Term Actions and Longer-Term Strategies for the Puget Sound Ecosystem

In this section, we highlight briefly key findings from this document and summarize how they could inform development of goals, near-term actions, or longer-term strategies for achieving the 2020 vision for Puget Sound.

The content of this section will be determined during the review process—if you have suggestions for which findings are critical and should be highlighted here, please provide those in your comments.

Examples of the level of detail we could provide here (topics are meant to be illustrative only):

- Key finding: future climate impacts in the region will result in reduced summer freshwater flows and increased winter peak flows.

  Implications for Puget Sound action plan:
  - Actions aimed at improving storage, reducing use, or allowing re-use of fresh water could mitigate the potentially negative impacts of future climate on Puget Sound species, habitats and ecosystem services.
  - Strategies to reduce the magnitude of stormwater runoff events or the toxics and excess nutrients they deliver during winter high flows will help improve survival of commercially, recreationally and ecologically important species.

- Key finding: projected increases in human population growth in the Puget Sound region will place increasing pressure on goods and services in the region such as undeveloped shorelines, recreational and commercial fishing, and whale-watching.

  Implications for Puget Sound action plan:
  - Actions designed to allow shoreline development, fishing, or whale watching only in strategically chosen areas will allow ecosystem services such as beach nourishment, bank stabilization, maintenance of eelgrass and kelp habitats, or tourism to function in a way consistent with ecosystem goals.
  - Strategies that include incentives for fishers or whale watchers to manage the resources they consume in a sustainable way will increase the chances that an increasing human population can continue to benefit from the ecosystem.

- Key finding: the nature and strength of interactions among species in Puget Sound food webs is not well understood.

  Implications for Puget Sound action plan:

- Management strategies designed to recover or re-build salmon, marine fish and Orcas should explicitly consider what happens as predators such as Orcas or salmon increase in number and potentially cause reductions in imperiled prey species such as salmon or herring.

References

Abookire, A.A., and J.F. Piatt. 2005. Oceanographic conditions structure forage fishes into lipid-rich and lipid-poor communities in lower Cook Inlet, Alaska, USA. Marine ecology progress series, 287:229-240.

Ambler, J.W., J.E. Cloern, and A. Hutchinson. 1985. Seasonal cycles of zooplankton from San Francisco Bay. Hydrobiologia 129:177-197.

Angliss and Lodge. 2002. Alaska Marine Mammal Stock Assessments, 2002. NOAA-TM-NMFS-AFSC-133. 224pp.

Baird and Dill 1995. Occurrence and behavior of transient killer whales: seasonal and pod-specific variability, foraging behaviour and prey handling. Canadian Journal of Zoology 73:1300-1311.

Baird and Dill 1996. Ecological and social determinants of group size in transient killer whales. Behavioral Ecology 7:408-416.

Calambokidis et al. 1994. Gray whales of Washington State: natural history and photographic catalog. Cascadia Research Collective, Olympia, Washington.

Calambokidis et al.1997. Aerial surveys for marine mammals in Washington and British Columbia inside waters. Final report to the National Marine Mammal Laboratory, Seattle, Washington.

Carretta, J.V., K.A. Forney, M. M. Muto, J. Barlow, J. Baker, B. Hanson, and M. S. Lowry. 2005. U.S. Pacific Marine Mammal Stock Assessments: 2005. NOAA-TM-NMFS-SWFSC-375. 316pp.

Ford et al, 1998. Dietary specialization in two sympatric populations of killer whales (Orcinus orca) in coastal British Columbia and adjacent waters. Canadian Journal of Zoology 76: 1456-1471.

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. Syesis 9:277-290.

Beechie, T. J., P. Roni, E. A. Steel, E. Quimby. (Eds.) 2003. Ecosystem recovery planning for listed salmon: An integrated assessment approach for salmon habitat. U.S. Dept. of Commerce, NOAA Tech. Memo., NMFS-NWFSC-58, 183 p.

Bentivoglio, N., J. Baldwin, P.G.R. Jodice, D.E. Mack, T. Max, S. Miller, S.K. Nelson, K. Ostrom, C.J. Ralph, M. Raphael, C. Strong, C. Thompson, R. Wilk. 2000. Northwest Forest Plan Marbled Murrelet Effectiveness Monitoring 2000 Annual Report. U.S. Fish and Wildlife Service.

Bjorndal, T., and G. Munro. 1999. The economics of fisheries management: A survey. In T. Tietenberg and H. Folmer (eds.), The International Yearbook of Environmental and Resource Economics 1998/1999.

Bortleson, G. C., M. J. Chrzastowski, and A. K. Helgerson. 1980. Historical changes of shoreline and wetland at eleven major deltas in the Puget Sound region, Washington. Prepared in cooperation with the U.S. Department of Justice and the Bureau of Indian Affairs, Renton, Washington. U.S. Geological Survey, Hydrologic Investigations Atlas HA-617, Washington, D.C.

Boss, E., M.J. Perry, and M.C. Talbot, 1998. Observation of an Intense Deep-Water Intrusion in Puget Sound. In: Puget Sound Research '98 Proceedings. Puget Sound Action Team, Olympia, WA.

Bousquet, F. et Le Page, C. 2004. Multi-agent simulations and ecosystem management: a review. Ecological Modeling 176 (3-4): 313-332

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].

Bricker, S.B., C.G. Clement, D.E. Pirhalla, S.P. Orlando, and D.R.G. Farrow. 1999. National Estuarine Eutrophication Assessment: Effects of Nutrient Enrichment in the Nation's Estuaries. NOAA, National Ocean Service, Special Projects Office and the National Centers for Coastal Ocean Science. Silver Spring, MD: 71 pp.

Buchanan, K.D. 1984. Tagging of Washington Herring, 1936-1984. Unpublished Data. Washington Department of Fish and Wildlife. P.O. Box 1100, La Conner, WA 98257.

Burns, R., 1985. The Shape and Form of Puget Sound. Puget Sound Books. Washington Sea Grant Publication. University of Washington Press.

Canning, D., and Shipman, H., 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.

Cannon, G.A., J.R. Holbrook, and D.J. Pashinski. 1990. Variations in the onset of bottom-water intrusions over the entrance sill of a fjord. Estuaries 13(1):31-42.

Carlton, J.T. 1979. History, Biogeography, and Ecology of the Introduced Marine and Estuarine Invertebrates of the Pacific Coast of North America. Ph.D. thesis, University of California, Davis.

Calambokidis et al.1997. Aerial surveys for marine mammals in Washington and British Columbia inside waters. Final report to the National Marine Mammal Laboratory, Seattle, Washington.

Calambokidis et al. 1994. Gray whales of Washington State: natural history and photographic catalog. Cascadia Research Collective, Olympia, Washington.

Carretta, J.V., K.A. Forney, M. M. Muto, J. Barlow, J. Baker, B. Hanson, and M. S. Lowry. 2005. U.S. Pacific Marine Mammal Stock Assessments: 2005. NOAA-TM-NMFS-SWFSC-375. 316pp.

California Fish and Game. 2005. Final Market Squid Fishery Management Plan (MSFMP)

Chester, A.J., D.M. Damkaer, D.B. Day, G.A. Heron, and J.D. Larrance. 1980. Plankton of the Strait of Juan de Fuca, 1976-1977. Interagency Energy/Environment R&D Program Report, United States Environmental Protection Agency, Office of Environmental Engineering and Technology, Washington, D.C. EPA-600/7-80-032.

Christensen V., D. Pauly. 2004. Placing fisheries in their ecosystem context, an introduction. Ecological Modelling 172:103-107.

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.

Cohen, A.N. 2004. An Exotic Species Detection Program for Puget Sound, Report prepared for the Puget Sound Action Team, Publication # OTH04-02.

Collias, E.E., N. McGary, and C.A. Barnes. 1974. *Atlas of Physical and Chemical Properties of Puget Sound and Approaches*. Washington Sea Grant 74-1, Seattle, 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.

Cordell, J.R. and S.M. Morrison. 1996. The invasive Asian copepod Pseudodiaptomus inopinus in Oregon, Washington, and British Columbia estuaries. Estuaries 19 (3):629-638.

Couch, D., and T. J. Hassler. 1989. Species profiles: life histories and environmental requirements of coastal fishes and invertebrates (Pacific Northwest)--Olympia oyster. U.S. Fish Wildl. Serv. Biol. Rep. 82(11.124) U.S. Army Corps of Engineers, TR EL-82 4. 8 pp.

Croxall, J.P. and P.A. Prince. 1996. Cephalopods as prey .1. Seabirds. Philosophical Transactions of the Royal Society of London Series B-Biological Sciences 351 (1343): 1023-1043.

Curl, H.C., Jr. and A.J. Paulson. 1991. "The biochemistry of oxygen and nutrients in Hood Canal." *In: Puget Sound Research '91 Proceedings*, Volume 1, T.W. Ransom (Ed.). Puget Sound Water Quality Authority, Olympia, WA, pp, 109-115.

Damkaer, D.M. 1964. Vertical distribution of Copepoda in Dabob Bay, December 1960. M.S. Thesis, University of Washington, Seattle, WA. 84 pp.

Dempster, R.P. 1938. The seasonal distribution of plankton at the entrance to Hood Canal. M.S. Thesis, University of Washington, Seattle, WA.

Department of Ecology, 1978, Coastal zone atlas of Washington, Jefferson County: WA Department of Ecology Shorelands Division, DOE Pub. No. 77-21-11.

Dexter, R.N., D.E. Anderson, E.A. Quinlan, L.S. Goldstein, R.M. Strickland, S.P. Pavlou, J.R. Clayton, Jr., R.M. Kocan, and M. Landolt, 1981. A Summary of Knowledge of Puget Sound related to Chemical Contaminants. NOAA Technical Memorandum OMPA-13. National Oceanic and Atmospheric Administration, Boulder, CO. 435 pp.

Downing, J., 1983, The coast of Puget Sound: Its processes and development: University of Washington Press, Seattle, 126 p.

Duffy, E.J. 2003. Early marine distribution and trophic interactions of juvenile salmon in Puget Sound. MS Thesis, University of Washington, Seattle, WA.

Dumbauld, B.R. 1985. The distributional ecology of zooplankton in East Passage and the Main Basin of Puget Sound, Washington. M.S. Thesis, University of Washington, Seattle, WA. 211 pp.

Edmondson, W.T. 1991. The Uses of Ecology: Lake Washington and Beyond. University of Washington Press. 329 p.

Elston, R. 1997. Pathways and Management of Marine Non-indigenous Species in the

Shared Waters of British Columbia and Washington. Puget Sound/Georgia Basin Environmental Report Series No. 5, Puget Sound Water Quality Action Team, Olympia, WA.

Emmett R., R. Llansó, J. Newton, R. Thom, C. Morgan, C. Levings, A. Copping, and P. Fishman. 2000. Geographical Signatures of North American West Coast Estuaries. Estuaries 23(6): 765-792.

Finlayson, D. and Shipman, H., 2003, Puget Sound littoral cells: the importance of waves and wave climate. Puget Sound Notes. Puget Sound Action Team: Olympia, WA, p. 1-4.

Ford et al, 1998. Dietary specialization in two sympatric populations of killer whales (Orcinus orca) in coastal British Columbia and adjacent waters. Canadian Journal of Zoology 76: 1456-1471.

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.

Fulton E. A., A. D. M. Smith, C. R. Johnson. 2003. Effect of Complexity on Marine Ecosystem Models. Marine Ecology-Progress Series 253:1-16.

Gearin et al. 1999. Washington State Pinniped Diet Studies 1983-1998. Pp. 249-258, In: A.L.Lopez and D.P. DeMaster (eds.) Marine Mammal Protection Act and Endangered Species Act Implementation Program 1998. AFSC Processed Rept. 99-08. 305 pp.

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.

Giles, S.L. and J.R. Cordell. 1999. Zooplankton composition and abundance in Budd Inlet, Washington. Pp. 634-642 in: Puget Sound Research '98: From Basic Science to Resource Management, Puget Sound Water Quality Action Team, Olympia, Washington.

Gilly, W.M. 2003. Population analysis of the California Market Squid, Loligo opalescens using DNA microsatellite analysis. Final report to the California Department of Fish and Game. Contract Number FG7334MR.

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.

Groot, G. and L. Margolis (editors). 1991. Pacific salmon life histories. University of British Columbia Press, Vancouver, British Columbia, Canada, 564 pp.

Gross, M.R. 1987. Evolution of diadromy in fishes. American Fisheries Society Symposium 1: 14-25.

Hanson, M.B., R.W. Baird, and G.S. Schorr. 2005. Focal behavioral observations and fish-eating killer whales: Improving our understanding of foraging behavior and prey selection. Abstract. Sixteenth, Biennial Conference on the Biology of Marine Mammals, December 12-16, 2005, San Diego, CA,

Hanson, M.B. and R.L. DeLong. 2005. A tale of two porpoise species: Seasonal movements and habitat use of Dall's and harbor porpoise in the Salish Sea as determined by radio-telemetry. Abstract, 2005 Puget Sound Georgia Basin Research Conference 29-31 March 2005, Seattle, WA.

Harbo, R.M. 1997. Shells & Shellfish of the Pacific Northwest, Harbour Publishing.

Harrison, P.J, D.L. Mackas, B.W. Frost, R.W. Macdonald and E.A. Crecelius. 1994. An assessment of nutrients, plankton and some pollutants in the water column of Juan de Fuca Strait, Strait of Georgia and Puget Sound, and their transboundary transport. Canadian Technical Report of Fisheries and Aquatic Sciences, No. 1948: 138-174.

Hay, D.E. and J. Fulton. 1983. Potential secondary production from herring spawning in the Strait of Georgia. Canadian Journal of Fisheries and Aquatic Sciences, 40(2):109-113.

Hebard, J.F. 1956. The seasonal variation of zooplankton in Puget Sound. M.S. Thesis, University of Washington, Seattle, WA. 64 pp.

Herrera Environmental Consultants, Inc. 2004. Ecological Economic Evaluation, Maury Island, King County, Washington, report prepared for King County, Department of Natural Resources and Parks, Water and Land Resources Division, Seattle, Washington.

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.

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.

Ish, T., E.J. Dick, P.V. Switzer, and M. Mangel. 2004. Environment, krill and squid in the Monterey Bay: from fisheries to life histories and back again. Deep-sea research part II: topical studies in oceanography. 51(6-9):849-862.

Jeffries et al. 2003. Trends and Status of Harbor Seals in Washington State: 1978-1999. Journal of Wildlife Management 67(1):207-218.

Kaczynski, V.W., R.J. Feller, and J. Clayton. 1973. Trophic analysis of juvenile pink and chum salmon (Oncorhynchus gobusha and O. keta) in Puget Sound. J. Fish. Res. Board Can. 30:1003-1008.

Keeley, E.R., and J.W.A. Grant. 2001. Prey size of salmonid fishes in streams, lakes, and oceans. Can. J. Fish. Aquatic. Sci. 58:1122-1132.

Kimmerer, W.J. 1993. Distribution patterns of zooplankton in Tomales Bay, California. Estuaries 16:264-272.

Kozloff, E. N., 1983. Seashore life of the northern Pacific coast, 2nd. Edition. University of Washington Press

Komar, P.D., 1998, Beach processes and sedimentation, Englewood Cliffs NJ, Prentice-Hall.

Krahn, M.M., et al. 2002. Status Review of Southern Resident killer whales (*Orcinus orca*) under the Endangered Species Act U.S. Dept. Commer., NOAA Tech. Memo. NMFS-NWFSC-54, 133p.

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.
Lassuy. D.R. 1989. Pacific Herring. Species Profiles: Life Histories and Environmental Requirements of Coastal Fishes and Invertebrates (Pacific Northwest). U.S. Department of the Interior and U.S. Army corps of engineers. Biological report 82 (11.126), 18 p.
Leschine, T., Wellman, K. and Green, T. 1997. The Economic Value of Wetlands. Ecology Publication No. 97-100. Washington State Department of Ecology, Bellevue , Washington.
Levings, C.D., and R.M. Thom. 1994. "Habitat Changes in Georgia Basin: Implications for Resource Management and Restoration." In: Review of the Marine Environment and Biota of Strait of Georgia, Puget Sound and Juan de Fuca Strait - Proceedings of the BC/Washington Symposium on the Marine Environment, January 13-14, 1994, Vancouver, British Columbia, Canada.
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.
Mackas, DL, Harrison, PJ. "Nitrogenous nutrient sources and sinks in the Juan de Fuca Strait of Georgia Puget Sound estuarine system: Assessing the potential for eutrophication." Estuar. Coast. Shelf Sci. 44: 1, 1997.
MacMillian JR, Mulcahy D (1979) Artificial transmission to and susceptibility of Puget Sound fish to viral erythrocytic necrosis (VEN). J Fish Res Board Can 36:1097-1101
Mangel M. 2000. Trade-offs between fish habitat and fishing mortality and the role of reserves. Bulletin of Marine Science 66:663-674.
Mangel M., and P. S. Levin. 2005. Regime shifts, phase shifts and paradigm shifts: Making community ecology the basic science for fisheries. Philosophic Transactions Royal Society of London 360:95-105.
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, D.C. 132 pp.
Maunder, M. N., Starr, P. J., and Hilborn, P. 2000. A Bayesian analysis to estimate loss in squid catch due to the implementation of a sea lion population management plan. Marine Mammal Science, 16: 413–426.
Melvin, E.F., et. al., 1997. Seabird bycatch reduction: new tools for Puget Sound drift gillnet salmon fisheries: 1996 sockeye and 1995 chum non-treaty salmon test fisheries. Final report to the Washington Sea Grant Program, Seattle, WA.

Meyer, C.B. and S.L. Miller. 2002. Use of fragmented landscapes by marbled murrelets for nesting in southern Oregon. Conservation Biology 16:755-766.
Meyers TR, Hauck AK, Blackenbeckler WD, Minicucci T (1986) First report of viral erythrocytic necrosis in Alaska, USA, associated with epizootic mortality in Pacific herring, Clupea harengus pallasi (Valenciennes). J Fish Dis 9:479-491
Millenium Ecosystem Assessment (MA). 2003. Ecosystems and Human Well-being: A Framework for Assessment. Island Press, Washington, D.C.
Millenium Ecosystem Assessment (MA). 2004. Ecosystems and Human Well-being: Scenarios, Volume 2. Island Press, Washington, D.C.
Miller, C.B. 1983. The zooplankton of estuaries. In : Ketchum, B.H. (ed.) Estuaries and enclosed seas. Elsevier Science, Amsterdam, pp. 293-310.
Mills, K. L., W.J. Sydeman, and P.J. Hodum (Eds.). 2005. The California Current Marine Bird Conservation Plan, v. 1, PRBO Conservation Science, Stinson Beach, CA.
Mofjeld, H.O. and Larsen, L.H., 1984. Tides and tidal currents in the inland waters of Western Washington, *NOAA Tech Memo ERL PMEL-56*, Seattle, 52 pp.
Morejohn, G. V., J. T. Harvey, and L. T. Krasnow. 1978. The importance of Loligo opalescens in the food web of marine vertebrates in Monterey Bay, California. In: C.W. Recksiek and H.W. Frey (Editors), Biological, oceanographic, and acoustic aspects of the market squid, Loligo opalescens Berry. California Department of Fish and Game, Fish Bulletin No. 169:67-98.
Mote, P. W., A. F. Hamlet, M. P. Clark, and D. P. Lettenmaier. 2005. Declining mountain snowpack in western north America. Bulletin of the American Meteorological Society **86**:39-+.
Mundy, P. R., editor. 2005. The Gulf of Alaska; biology and oceanography. Alaska Sea Grant, University of Alaska, Fairbanks.
Nakata, K. and J. Newton, 2001. Seasonal Patterns and Controlling Factors of Primary Production in Puget Sound's Central Basin and Possession Sound. In Puget Sound Research 2001 Proceedings. Puget Sound Action Team, Olympia, WA
National Oceanic and Atmospheric Administration (NOAA). 2002. Status review of southern resident killer whales (Orcinus orca) under the endangered species act. NOAA Technical Memorandum NMFS-NWFSC-54.
National Marine Mammal Laboratory (NMML). 1996. Working paper: Biomass consumption estimates of California sea lions and harbor seals in Puget Sound, 13 p. (Available from Alaska Fisheries Science Center, Natl. Mar. Fish. Serv., NOAA, 7600 Sand Point Way NE, Seattle, WA 98115.)
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, D.C.
National Science and Technology Council, Committee on Environment and Natural Resources. 2002. From the Edge: Science to Support Restoration of Pacific Salmon, Washington, DC.
Newton, J. and Van Voorhis, K. 2002. Seasonal Patterns and Controlling Factors of Primary Production in Puget Sound's Central Basin and Possession Sound. Washington State Department of Ecology, Environmental Assessment Program, Publication #02-03-059. Olympia, WA.

Newton, J.A., S.L. Albertson, K. Van Voorhis, C. Maloy, and E. Siegel. 2002. *Washington State Marine Water Quality, 1998 through 2000*. Washington State Department of Ecology, Environmental Assessment Program, Publication #02-03-056, Olympia, WA.

Newton, J.A., Siegel, E., and Albertson, S.L., 2003. Oceanographic Changes in Puget Sound and the Strait of Juan de Fuca during the 2000-01 Drought. Canadian Water Resources Journal., 28(4), 715-728.

Newton, J.A., M. Edie, and J. Summers. 1998. Primary productivity in Budd Inlet: Seasonal patterns of variation and controlling factors. In Puget Sound Research '98 Proceedings. Puget Sound Action Team, Olympia, WA, pp. 132-151.

Newton, J.A., A.L. Thomson, L.B. Eisner, G.A. Hannach, and S.L. Albertson. 1995. "Dissolved oxygen concentrations in Hood Canal: Are conditions different than forty years ago?" In: Puget Sound Research '95 Proceedings. Puget Sound Water Quality Authority, Olympia, WA, pp. 1002-1008.

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

PSAT, 1988. State of the Sound Report.

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).

Ohlendorf, H.M. and W.J. Fleming. 1988. Birds and environmental contaminants in San Francisco and Chesapeake Bays. Marine Pollution Bulletin. 19: 487-495.

Olesiuk 1993. Annual Prey Consumption by Harbor Seals (Phoca vitulina) in the Strait Of Georgia, British Columbia. Fishery Bulletin 91:491-515.

Orsi, J. J. 1995. Radical changes in the estuary's zooplankton caused by introductions from ballast water. Interagency Ecological Studies Program for the Sacramento-San Joaquin Estuary, Newsletter, Summer 1995: 16-17.

Orsi, J.J., and S. Ohtsuka. 1999. Introduction of the Asian copepods Acartiella sinensis, Tortanus dextrilobatus (Copepoda: Calanoida), and Limnoithona tetraspina (Copepoda: Cyclopoida) to the San Francisco estuary, California, USA. Plankton Biol. Ecol. 46(2):128-131.

Osborne 1999. A historical ecology of Salish Sea "resident" killer whales (Orcinus orca): with implications for management. University of Victoria, Victoria, BC.

O'Shea, T.J. 1999. Environmental contaminants and marine mammals. Pages 485-563 in J.E. Reynolds III and S.A. Rommel, eds. Biology of Marine Mammals. Smithsonian Institution Press, Washington, D.C.

Pauley, G.B., DA Armstrong, R. Van Citter, and G.L. Thomas. 1989. Species profiles: life histories and environmental requirements of coastal fishes and invertebrates (Pacific Southwest)—Dungeness crab. U.S. Fish Wildl. Serv. Biol. Rep. 82(11.121). U.S. Army Corps of Engineers, TR EL-82-4.20 PP-

Pentilla, D.E. 1997. Investigations of intertidal spawning habitats of surf smelt and Pacific sand lance in Puget Sound, Washington. p. 395-407. *In*: Proceedings of the international symposium on the role of forage fishes in marine ecosystems, Lowell Wakefield Fisheries Symposium Univ. of Alaska Sea Grant College Program, Report No. 97-01.

Pentilla, D.E. pers. comm. Washington Department of Fish and Wildlife. P.O. Box 1100, La Conner, WA 98257.

Perrings C. 2001. Modelling sustainable ecological-economic development, in H. Folmer and T. Tietenberg (eds) The International Yearbook of Environmental and Resource Economics 2001/2, Edward Elgar, Cheltenham.

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, D.C.

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

Piatt, J.F., and P.J. Anderson. 1996. Response of common murres to the Exxon Valdez oil spill and long-term changes in the Gulf of Alaska marine ecosystem. American Fisheries Society Symposium 18:720-737.

Piatt, J.F., editor. 2002. Response of seabirds to fluctuations in forage fish density, *Exxon Valdez* Oil Spill Restoration Project Final Report (Restoration Project 01163M), and Minerals Management Service (Alaska OCS Study MMS 2002-068), Alaska Science Center, U.S. Geological Survey, Anchorage, Alaska.

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, D.C.

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

Puget Sound Water Quality Action Team, 2000, Puget Sound update: Seventh Report of the Puget Sound Ambient Monitoring Program. Olympia, Washington. 127 pp.

Reichow, D. and M.J. Smith. 2001. Microsatellites reveal high levels of gene flow among populations of California squid, Loligo opalescens. Molecular Ecology. 10(5) 1101-1109.

Reijnders, P.J.H. and A. Aguilar. 2002. Pollution and marine mammals. Pages 948-957 *in* W.F. Perrin, B. Würsig, and J.G.M. Thewissen, eds. Encyclopedia of marine mammals. Academic Press, San Diego, CA.

Rosenberg, A.A., and K.L. McLeod. 2005. Implementing ecosystem-based approaches to management for the conservation of ecosystem services. Marine Ecology Progress Series 300: 241–296.

Ross, P.S., R.L. de Swart, R.F. Addison, H. van Loveren, J.G. vos, and A.D.M.E. Osterhaus. 1996*a*. Contaminant-induced immunotoxicity in harbor seals: wildlife at risk? Toxicology 112:157-169.

Ross, P.S., R.L. de Swart, H. van Loveren, A.D.M.E. Osterhaus, and J.G. vos, 1996*b*. The immunotoxicity of environmental contaminants to marine wildlife: a review. Annual Review of Fish Diseases 6:151-165.

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

Sainsbury, K.J., A. E. Punt, and A. D. M. Smith. (2000) Design of operational management strategies for achieving fishery ecosystem objectives. ICES J. Mar. Sci. 57: 731-741.

Scheffer and Slipp 1948.The whales and dolphins of Washington State with a key to the cetaceans of the west coast of North America. American Naturalist 39(2):257-337.

Schmitt, C.C., S.J. Jeffries, and P.J. Gearin. 1995. Pinniped predation on marine fish in Puget Sound. p. 630-637. In E. Robichaud (Ed.) Puget Sound Research '95 Proceedings, Bellevue, WA. Puget Sound Water Quality Authority. 2 Vols. 1038 p.

Shared Strategy 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.

Simenstad, C.A., K.L. Fresh, and E.O. Salo. 1982. The role of Puget Sound and Washington coastal estuaries in the life history of Pacific Salmon: an unappreciated function. Pages 343-364 in V.S. Kennedy (Ed.), Estuarine Comparisons., Academic Press

Smith, A. D. M., K. J. Sainsbury, and R. A. Stevens. 1999. Implementing effective fisheries-management systems–management strategy evaluation and the Australian partnership approach. ICES Journal of Marine Science, 56: 967–979.

Snover, A.K., Mote, P.W., Whitely Binder, L., Hamlet, A.F., and Mantua, N.J., 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).

Speckman, S., J.F. Piatt, C. Minte-Vera and J. Parrish. 2005. Parallel structure among environmental gradients and three trophic levels in a subarctic estuary. Progress in Oceanography 66: 25-65.

Stick, K.C. 2005. 2004 Washington State Herring Stock Status Report. Washington Department of Fish and Wildlife Fish Program, Fish Management Division. P.O. Box 1100, La Conner, WA 98257.

Strickland, R.M. 1983. The Fertile Fjord. University of Washington Press, Seattle, 145 pp.

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

Thom, R.M., Shreffler, D.K, and Macdonald, K., 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

Thompson, C.W., E.R. Donelan, M.M. Lance, and A.E. Edwards. 2002. Diet of Caspian Terns in Commencement Bay, Washington. Waterbirds: Vol. 25(1):78–85.

Trainer, V.L., N.G. Adams, B.D. Bill, C.M. Stehr, J.C. Wekell, P. Moeller, M. Busman, and D. Woodruff. 2000. Domoic acid production near California upwelling zones, June 1998. Limnol. Oceanogr., 45(8), 401-440.

Trainer, V. L., B. M. Hickey, and R. A. Homer. 2002. Biological and physical dynamics of domoic acid production off the Washington coast. Limnology and Oceanography **47**:1438-1446.

Trainer, V. L., B. T. L. Eberhart, J. C. Wekell, N. G. Adams, L. Hanson, F. Cox, and J. Dowell. 2003. Paralytic shellfish toxins in Puget Sound, Washington State. Journal of Shellfish Research **22**:213-223.

Triangle Associates, Inc. 2004. Technical workshop on nearshore restoration in the central Strait of Juan de Fuca. Available from Olympic National Park, Port Angeles, Washington.

Trumble, R.J. 1983. Management Plan for baitfish species in Washington State. State of Washington Department of Fisheries Progress Report No. 195. 106p.

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

U.S. Fish and Wildlife Service (USFWS). 2005. Regional Seabird Conservation Plan, Pacific Region. U.S. Fish and Wildlife Service. Migratory Birds and Habitat Programs, Pacific Region, Portland, Oregon.

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.

Waddell, P. 2002. UrbanSim: Modeling Urban Development for Land Use, Transportation and Environmental Planning. Journal of the American Planning Association 68: 297-314.

Walters, C.J, V. Christensen, S.J. Martell, and J.F. Kitchell. 2005. Possible ecosystem impacts of applying MSY policies from single-species assessment. ICES Journal of Marine Science 62: 558-568.

Walters C. 1986. Adaptive management of renewable resources. New York: Macmillan Publishing.

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.

WDFW. Date unknown. The Tantalizing squid. Washington Department of Fisheries.

Weitkamp, L.A., R.C. Wissman, C.A. Simenstad, K.L. Fresh, and J.G. Odell. 1992. Gray whale foraging on ghost shrimp (Callianassa californiensis) in littoral sand flats of Puget Sound, U.S.A. Canadian Journal of Zoology 70:2275-2280.

Wilen, J.E., M.D. Smith, D. Lockwood, and L.W. Botsford. 2002. Avoiding Surprises: Incorporating Fisherman Behavior into Management Models. Bulletin of Marine Science70: 553-575.

Williams, G.D., R. M. Thom, D. Woodruff, A. Borde, A. Skillman, M. Miller, R. Kropp, S. Blanton), Pentec Environmental (Jim Starkes, Jon Houghton), Striplin

Environmental Associates, Shapiro Associates, King County DNR (Laura Blackmore, Jim Brennan). (2001).State of the Nearshore Ecosystem: Central Puget Sound including Vashon and Maury Islands (WRIAs 8and 9). Prepared for King County Department of Natural Resources, Seattle, Washington. 266 pp.
Williams, G.D., R.M. Thom. M.C. Miller, D.L. Woodruff, N.R. Evans, and P. N. Best. 2003. Bainbridge Island nearshore assessment: summary of best available science. PNWD-3233. Prepared for the City of Bainbridge Island, Bainbridge Island, WA, by Battelle Marine Sciences Laboratory, Sequim, WA.
Winter, D.F., K. Banse, and G.C. Anderson. 1975. The dynamics of phytoplankton blooms in Puget Sound, a fjord in northwestern U.S. Marine Biology, 29: 139-175.
Wunderlich, R.C., B.D. Winter, and J.H. Meyer. 1994. Restoration of the Elwha River ecosystem. Fisheries 19(8):11-19.

Figures, Tables and Boxes

Overview and Introduction

Figure 1. Map of Puget Sound, with five subbasins indicated.

Table a. List of previously identified impacts to Puget Sound

Box 1. Kelp-urchin-sea otter interaction story (with photos of urchin barrens/kelp forest)
Box 2. List and description of ecosystem goods and services

The Puget Sound Ecosystem

Figure 2. Conceptual model of elements/components of Puget Sound ecosystem and their interactions
Figure 3. Panel of photos showing variety of Puget Sound habitat types.
Figure 4. Map of Puget Sound, showing drift cell locations and subbasins
Figure 5. Fresh and salt water flow in Puget sound, pycnocline.
Figure 6. Bluff failure
Figure 7. Shoreline armoring
Figure 8. Illustration of landscape processes in river deltas and shorelines
Figure 9. Duwamish river

Box 3. Dissolved oxygen in Hood Canal
Box 4. Ecosystem response to Elwha Dam
Box 5. Contaminants and toxics in Puget Sound (in development)
Box 6. Nutrients and salmon carcasses (in development)
Box 7. Ecosystem goods and services
Box 8. Whale watching in Puget Sound

Decision Frameworks for Ecosystem Approaches

Box 9. Tradeoff between conservation and economic objective for a New Zealand fishery
Box 10. General framework for Management Strategy Evaluation
Box 11. Components of the ATLANTIS model
Box 12. UrbanSim model.