Science synthesis in support of ecosystem-based management: The Puget Sound Science Update

The Puget Sound Science Update

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One of the oft-cited impediments to conducting ecosystem-based management is a lack of broadly available, peer-reviewed and synthesized scientific information about the system of interest (Rosenberg and Sandifer 2009, Ruckelshaus et al. 2009). A well-governed ecosystem recovery effort involves a demanding process--agreeing on a common set of objectives, selecting and assessing indicators for tracking progress, implementing priority actions, and iterating and adapting the process through time in response to monitoring—each stage of which relies on scientifically sound information. Providing credible and relevant scientific information that is widely available to participants in an ecosystem-based management (EBM) process can help crystallize policy deliberations by avoiding distracting debates about the facts. In the absence of a common synthesis of relevant scientific information, policy leaders and managers can be reduced to arguing over anecdotal stories from the white-to-grey literature or ad-hoc syntheses of unpublished data. Managing an ecosystem based on file-drawer scientific anecdotes sets up an inherent mistrust and skepticism of science on the part of policy leaders.

The science and policy bodies governing a legislatively-mandated ecosystem-based management effort for Puget Sound, Washington were determined not to let disputes over the science hamstring their opportunity to recover their ecosystem. The premise of the Puget Sound effort we summarize in this paper is that if peer-reviewed science syntheses are available, leaders governing EBM processes will use credible scientific information as a source of legitimacy for tough decisions, rather than using scientific uncertainty as an excuse for inaction.

The Process to Produce a Puget Sound Science Synthesis

The Puget Sound Science Update (hereafter, *Update*) is a state-of-the-science document supporting the work of the Puget Sound Partnership (PSP)—a legislatively mandated public-private entity charged with restoring and protecting the Puget Sound ecosystem (Puget Sound

Partnership 2008). As its content develops over time, it will be a comprehensive reporting and analysis of science related to the ecosystem-scale protection and restoration of lands, waters, and human social systems in Puget Sound. The policy and science leadership of the PSP called for a rigorous synthesis of science to provide focused input to decisions about indicators of ecosystem condition and priority strategies for action. In committing to use the *Update* as the definitive source of scientific information for their decisions, the PSP leadership has provided a critical incentive for scientists to contribute information and analyses.

The initial outline for the *Update* report was co-developed by the policy and science governance groups overseeing the PSP. Four key Chapters were identified, generally following the logical progression of policy questions in the integrated ecosystem assessment (IEA) decision framework used by the PSP (Puget Sound Partnership 2008, Levin et al. 2009). The four Chapters of the *Update* are: (1) Understanding Future and Desired System States, (2) The (a) Biophysical and (b) Socio-economic condition of Puget Sound; (3) Impacts of Natural Events and Human Activities on the System, and (4) Effectiveness of Strategies to Protect and Restore the System.

The approach used to create the *Update* represents an advancement in the development and use of science to support ecosystem recovery in two important ways. First, the content of the *Update* was developed through a process modeled after the rigorous peer-review approach used by the Intergovernmental Panel on Climate Change (IPCC), in which small author groups produce draft assessment reports synthesizing existing, peer-reviewed scientific information on specific topics identified by policy leaders. Author teams for different Chapters of the report were selected through a competitive process and were comprised of a mix of university, agency, and consulting scientists. Initial drafts were peer-reviewed before final reports were released to the public. Second, the *Update* is published on-line following a wiki model, so that further refinements and expansion of content to support ecosystem recovery occur via a moderated, web-based dialog using peer-reviewed information. Every few months, existing versions of the document are time-stamped and archived for reference points. New content, revisions to existing material and subsequent review of content occur on line through a wiki-enabled dialog. Anyone can offer new content for the report, provided that new information or analysis has been previously peer-reviewed.

The wiki-type design of the *Update* is based on the premise that scientists will voluntarily add new information to relevant chapters, motivated by assurances that the information will be used to guide policy and management decisions in a place they care about. It is too early to tell how quickly scientific information will develop in the report under the voluntary model. Filling significant information or assessment gaps in some topical areas (e.g., effects of changes in natural system on human system metrics) may require more active commissioning of first drafts, as was done for the first 4 Chapters of the report.

Table 1. Alignment between policy questions guiding the ecosystem recovery plan (PSP Action Agenda 2008) and the scientific assessment steps in an Integrated Ecosystem Assessment (IEA) being conducted in Puget Sound.

Policy questions	IEA step
What does a healthy ecosystem look like? How can we measure progress?	Identify ecosystem goals, indicators, and targets
What is the current health of PS? How much improvement in ecosystem elements is needed to meet targets? What are the biggest impediments to indicator health?	Conduct risk analysis: current status and key threats for indicators
What actions should be considered (e.g. priority toxic sources to limit/abate, nearshore protection sites and approaches, stormwater approaches)?	Generate alternative management strategies
Where should we start? What actions, at what level of effort, and where?	Evaluate strategies and resulting ecosystem status

The *Update*

The Puget Sound Science Update is designed to support the EBM approach adopted by the Puget Sound Partnership. The initial results of the EBM process are documented in the first iteration of an ecosystem recovery plan, the *Puget Sound Action Agenda* (Puget Sound Partnership 2008). The indicators, identified threats, and priority near-term strategies outlined in the Action Agenda fit into the integrated ecosystem assessment (IEA) framework proposed by Levin et al. (2009) whereby a synthesis is conducted that incorporates relevant biological, ecological and socioeconomic factors to facilitate the implementation of EBM. The four chapters of the *Update* each address a different component of the five-step IEA process such that Chapter 1 informs the development of ecosystem targets and indicators, Chapter 2 is a synthesis of the status of ecosystem components, largely informed by monitoring efforts throughout the Puget Sound ecosystem, Chapter 3 informs the risk analysis portion of the IEA by identifying threats to the Puget Sound and Chapter 4 evaluates different management strategies, focusing in its first iteration on protection and restoration. Because Chapters 1 and 2 of the *Update* were written simultaneously rather than sequentially, ecosystem components reported upon in Chapter 2 do not reflect the outcome of a formal indicator selection process and thus cannot yet be thought of as an assessment of ecosystem status as envisioned by Levin et al. (2009). As the *Update* is expanded upon, future iterations of Chapter 2 will likely more closely reflect indicators that have been selected by the framework developed in Chapter 1. Although Chapter 1 provides a method for ranking indicators based on the existing scientific evidence, it recognizes that values and management goals must first be established before they are selected, a process that will benefit from the participation of a variety of stakeholders (Levin et al. 2009). When appropriate, we further subdivided chapters to reflect both the natural and social system perspectives. We discuss the structure and findings from each of these chapters below.

Chapter 1A. Desired futures and measuring progress

In this portion of the *Update,* we first reviewed published reports that describe desired future states of the Puget Sound ecosystem, suggesting ways to incorporate new information generated by such future visions into the logic models developed in the *Action Agenda* and further articulated in ongoing work of the PSP (Neuman et al. 2009b). We next introduced a flexible framework for selecting ecosystem indicators of the biophysical components of the ecosystem and establishing transparent criteria for judging an indicator's ability to reliably track changes in ecosystem status. Using these criteria, we then provided an evaluation of 270 candidate ecosystem indicators. Finally, we reviewed targets and benchmarks for ecosystem indicators in Puget Sound; where they were found to be inconsistent with criteria or lacking, we described a number of approaches that could be applied to scientifically inform the development of management targets and benchmarks.

Understanding the myriad of potential futures for Puget Sound is a key component of setting ecosystem targets toward which specific strategies can be directed. Although there have been multiple efforts to describe potential future scenarios for Puget Sound--including the Puget Sound Regional Council 2040 plan (Puget Sound Regional Council 2009), the Puget Sound Nearshore Partnership and Urban Ecology Research Lab (Urban Ecology Research Lab 2009), the Future Risk Assessment Project (FRAP) and the Ecosystem Portfolio Model (EPM) (Bolte 2009, Labiosa et al. 2009), and the Puget Sound Recovery Plan (Shared Strategy for the Puget Sound 2007), a calculation of the tradeoffs among the ecological and socio-economic components of future scenarios for Puget Sound has not been conducted. Tradeoffs among a diverse set of natural and social system targets are particularly important to enumerate; and can be calculated using a management strategy evaluation approach outlined in an IEA process such as that adopted by PSP. Management strategy evaluation is an effective way to quantitatively understand tradeoffs among targets and how they are likely to change under different management strategies.

Although there is clear agreement that the future state of Puget Sound should be different than it is now, the region lacks a lucid vision of the desired state of the coupled human-ecological system. We stress the importance of incorporating both socioeconomic drivers and climate change into both model-based future scenarios and assessments of potential management actions so that a comprehensive vision of the desired state of Puget Sound can be developed based on available information. However, the foundation to generate scenarios of a future Puget Sound is in place. As the efforts described here continue and expand, we expect more comprehensive visions of Puget Sound's possible future to emerge.

We developed a transparent framework for ranking and ultimately selecting ecologically and socially relevant indicators that will allow ecosystem metrics to be linked with societal goals. The first set of indicators we classified are those describing the status of the natural system in Puget Sound; thus social system indicators will need to be evaluated with these criteria as an important next step. We based our 270 candidate indicators largely on those selected by O'Neill et al. (2008) as representative of the Puget Sound ecosystem and for which existing monitoring programs have produced some status information. We derived 19 criteria from the literature to evaluate the candidate indicators, and then ranked each potential indicator against these criteria. The primary criteria are that the indicator: (1) is theoretically sound, (2) is relevant to management concerns, (3) responds predictably and is sufficiently sensitive to changes in a specific ecosystem attribute(s), and (4) specific management action(s) or pressure(s), (5) is linkable to scientifically defined reference points and progress targets, and (6) complements existing indicators. The remaining criteria relate to data quality (e.g., spatial coverage and historical information available), and non-science considerations such as the likelihood that the indicator will resonate with the public. For each candidate indicator, we tallied the number of evaluation criteria for which published (peer-reviewed) evidence existed. The results are in the form of summary tables, showing for each indicator the number of criteria supported by peer-reviewed information (examples of results for a few indicators are shown in Appendix A). However, we did not attempt to distinguish between weak and strong evidence, and suggest that future versions of the *Update* would benefit from such an exercise

To help select a diverse portfolio of indicators using information in the criteria rankings, we introduced a framework for classifying indicators according to both their *specificity*, which is determined by the number of ecosystem attributes tracked by the indicator (Rapport et al. 1985) and their *sensitivity*, which reflects the time lag between an ecosystem change and the indicator response. These designations allow the adoption of indicators that complement one another with respect to both specificity and sensitivity. We also recognized the difference between indicators that are more likely to resonate with the general public and policy makers ('Vital Sign' indicators) vs. those that speak to a more technical understanding of ecosystem structure and function ('Ecosystem Assessment' indicators).

Management goals and operation objectives must be precisely defined prior to indicator selection. This can be done by ranking the relative importance of the evaluation criteria. Failure to assign different weights to different criteria results in equal weighting for all of them. Different weighting schemes can emphasize different management goals and priorities. For example, weighting schemes that emphasize communication to a broad audience will favor the selection of 'Vital Sign' indicators whereas weightings that emphasize more technical data aspects will favor the selection of 'Ecosystem Assessment' indicators. To be useful in practice, there must be known reference levels for selected indicators. Both conceptual and quantitative ecosystem models can aid in the development of target reference levels since they can simultaneously assess the inherent tradeoffs between various indicators.

Next steps for this process include broadening the spatial scope of the indicators from a largely marine focus to include candidate indicators from freshwater, terrestrial and interface habitats, a fuller set of water quality indicators, and an expansion to include more indicators which reflect energy and material flow and population condition (e.g., age and population structure). An additional and vital next step for this process is the incorporation of ecosystem models to test the performance of indicators that measure food web health.

Chapter 1B. Incorporating human well-being into ecosystem-based management

The next part of Chapter 1 of the *Update* notes that human well-being is both a goal for the Puget Sound Partnership and a potential metric for assessing the effects of conservation and restoration actions that further all Partnership goals. Although difficult to measure objectively, human well-being can be organized into material, emotional, work/productivity and personal safety domains (Land 1983, Sharpe 1999). These domains include objective measures such as education, employment, health and public safety and subjective measures such personal satisfaction, happiness and life fulfillment. The approaches we take are modeled after Welsh and Kuhling (2009) which combine individual (both objective and subjective), community and environmental factors into a single measure of human well-being. There are many ways to effectively measure the various components of human well-being. To link human well-being with environmental factors, hedonic analyses can be employed since they are inherently place-based and correlate environmental characteristics of given locations with factors such as property value (e.g., Bin and Polasky 2005, Cho et al. 2009). For cases where market values cannot be used, willingness to pay and state preference approaches are useful for linking changes in environmental conditions to human well-being (e.g., Murray et al. 2001, Egan et al. 2009). These approaches quantify the value placed on improving or declining environmental conditions by assessing the dollar amount that visitors or residents of area would be willing to pay for improved conditions (e.g., a reduction in pollution) based on either indirect (e.g., travel expenses) or direct (e.g., surveys) methods of data collection. Each of these measures has both strengths and drawbacks and much work remains to be done linking human well being with economic, social and environmental factors for the Puget Sound system. Some ecological factors that are indicators of the biophysical condition of the Puget Sound system (e.g., salmon abundance) may also be good indicators of human well-being (Bell et al. 2003).

Standard methods exist to assess the determinants of human well-being; and we review methods used to investigate the strength of connections between economic, social, and environmental factors and human well being. There is still much work to be done, however, in documenting these connections, particularly those between changes in environmental factors in general and for Puget Sound in particular.

We conclude that the Puget Sound Partnership can identify indicators associated with relatively strong connections between biophysical changes and shifts in human well being. Such information that exists can at least give some insights into the overall effect on human well being in cases where proposed management actions have multiple effects and potential tradeoffs among goals. In general, our review made clear that evidence is sparse, particularly for the connections among biophysical conditions, human behavior and values, and overall human well-being in the Puget Sound region. This can help set priorities for future social science research to support the Puget Sound Partnership's mission.

Chapter 2A. The biophysical condition of Puget Sound

The objective of this section was to review the status and trends of biophysical components of Puget Sound that speak to the Puget Sound Partnerships key biophysical goals: species and food webs, habitats, water quality and water quantity. We used the term 'component' to denote specific biophysical constituents of the Puget Sound ecosystem. In our usage, a component can be a species (e.g., pinto abalone), a group of species (e.g., bentho-pelagic fish), habitat (e.g., tidal wetlands) or biophysical attribute (e.g., dissolved oxygen). We avoided the term 'indicator" because the components we describe were selected prior to the completion of the indicator evaluation criteria presented in Chapter 1A.

Lacking an evaluative framework, we adopted two overarching considerations in selecting components to include here: 1) components should reflect ecologically or policy relevant attributes of Puget Sound, and 2) each component must have been the focus of sufficient study to permit status evaluation. Consequently, some species that are recognized as important in the Puget Sound ecosystem, but for which sufficient data do not exist, were not included. In selecting components, we adopted additional guiding principles and considerations: 1) culturally important species for which there are clear policy goals (e.g., harvested species, iconic species such as killer whales) were included whenever possible, along with critical species and habitats upon which they rely; 2) species of particular conservation concern were incorporated; 3) water quality and water quality components were chosen to reflect the topical emphasis of scientific study in each of those disciplines; 4) species that have been specifically identified as ecosystem indicators (via peer reviewed publications) were considered whenever possible (e.g., jellyfish).

This set of principles provided criteria that allowed a systematic approach to selection of components to include in this analysis. However, it did result in some noteworthy exclusions. For example, the status and trends of invasive species (e.g., *Spartina, Ciona*) were not reported. Analysis of zooplankton community composition and trends is limited by the paucity of data, and therefore is not included. Ocean acidification, a growing concern with potentially substantial impacts on shellfish aquaculture and natural communities, was also not treated here. These and other omissions are not intended to imply that these are not important components or attributes of the Puget Sound ecosystem, and we anticipate that the next iteration of the Puget Sound Science Update will consider a broader range of components.

An ecosystem approach to Puget Sound requires a basin-wide perspective, extending from the crest of the Cascade and Olympic mountains to the marine waters of the Strait of Juan de Fuca and Hood Canal. Although we recognize the need for such a broad perspective, the biophysical components treated in this Section clearly emphasize marine and freshwater elements of the Puget Sound watershed. This emphasis reflected the historical focus of the Puget Sound Science Update and the specific expertise of the lead authors. Even so, we described terrestrial components that have some linkage to aquatic portions of the watershed. We anticipate that future iterations of the *Puget Sound Science Update* will take a broader view and include many more terrestrial topics than we could incorporate here.

Within each summary, we provided background and rationale for inclusion in the Section, a brief treatment of threats and drivers to give the needed context. We included in each section a synthesis of key data gaps and uncertainties. In some cases the uncertainties were scientific: uncertainties that can be resolved through additional scientific study. In other cases the uncertainties reflected emerging concepts, hypotheses and explanations that have not yet been vetted through a formal review process.

We found a wide range of available published information. For many of the components, we reported the findings of long-term monitoring programs in Puget Sound such as eelgrass, forage fish and killer whales. We noted known ecological importance or life history characteristics (e.g., life span, trophic position, habitat requirements) that were relevant to management concerns. For cases where there were no published accounts of abundance (e.g., geoducks, bentho-pelagic fish, Dungeness crabs), this descriptive information formed the bulk of our reporting. We also highlighted uncertainties pertaining to potentially important aspects of species biology and ecology as well as uncertainties surrounding drivers for species population dynamics. See Appendix B for a complete list of the components covered as well as key findings for each component.

Chapter 2B. Social and economic state of Puget Sound

It is well recognized that for ecosystem-based management to work effectively, humans must be recognized as both drivers and as components of the ecosystem itself (Shackeroff et al. 2009). As such, both the degradation and protection of natural resources will be reflected in lives of the people occupying coastal environments. While not yet complete, the objectives of this section are to organize existing and emerging information on the status and trends of the so-called "human dimensions" of Puget Sound. The approach will focus on human health and well-being, incorporating a suite of descriptive "state" and "governance" indicators that describe the condition of the social attributes contributing to a thriving human system in Puget Sound.

Chapter 3. Impacts of human activities on the ecosystem

Understanding the scope and relative importance of the various threats facing Puget Sound is a key component of implementing ecosystem-based management in Puget Sound. In this section we drew upon existing literature identifying the terrestrial, freshwater and marine derived threats to the Puget Sound ecosystem as well as reviewed existing approaches to ranking them (Hayes and Landis 2004, WBC 2007, Neuman et al. 2009a, (USEPA) 2010, CBP 2010, DoE 2010). We used the Driver-Pressure-State-Impact-Response (DPSIR) framework (Elliott 2002) to organize our discussion of these threats, highlighting what is known about the geographic scope, severity, irreversibility, imminence and uncertainty surrounding them. This framework is helpful in organizing our understanding of the underlying causes of changes in indicators we care about, and thus can be a useful tool in designing strategies to address threats (e.g., Appendix C).

We reviewed eight assessments of threats relevant to the Salish Sea ecosystem. Although each presented a unique list, there was considerable overlap and consistent high ranking of development, climate change, invasive species, pollution, and shoreline modification. Species harvesting was also highly ranked but not addressed in this *Update* and should be a priority topic for future synthesis. We did not find a peer-reviewed analysis of the relative magnitude of threats for Puget Sound proper and we identify this as an information need and recommend the development of a more comprehensive, quantitative and systematic assessment of the relative magnitude of threats and the uncertainty surrounding their estimation. We called attention to ecosystem models as a promising tool to identify and rank ecosystem threats in Puget Sound. Importantly, this chapter focused solely on the impacts of threats on the Puget Sound ecosystem and not on its human inhabitants; future iterations of the *Update* can be expanded to include assessments of the impacts of anthropogenic threats on the states of human health and well-being.

Of the important anthropogenic threats previously identified by the Puget Sound Partnership, we addressed climate change, development, shoreline modification, pollution and non-native species. For each threat, we enumerated the potential drivers, pressures, states and impacts. We also discussed different ecosystem models that provide quantitative approaches to ranking threats, identifying indicators and assessing uncertainty.

For climate change, the pressures for which states and impacts are best understood in Puget Sound are water cycle changes and weather/temperature shifts. Water cycle changes that result in reduced snowmelt are predicted to dramatically alter the timing of water availability to many Puget Sound streams (Mote et al. 2008), which could in turn affect stream biota (Beechie et al. 2006). Increased air temperature and temporal shifts in precipitation also are predicted (Climate Impacts Group 2009), further altering water availability to streams and increasing water temperature, resulting in shifts in species range and seasonality of their activities (Winder and Schindler 2004, Climate Impacts Group 2009). Salmon and trout are particularly vulnerable to shifts in stream temperatures (Richter and Kolmes 2005). Climate-related pressures resulting in sea level rise, increase in sea surface temperature in Puget Sound, increased ocean acidity and UV radiation also are discussed. Uncertainty in future levels of atmospheric greenhouse gases drives much of the uncertainty in the predictions of ecosystem response to climate change (Climate Impacts Group 2009, Zickfeld et al. 2010).

Population growth in Puget Sound and the resulting residential, commercial and industrial development has resulted in the pressures of vegetation loss and decreases in the absorptive capacity of landscapes (i.e., increased imperviousness) in the Puget Sound ecosystem. Loss of vegetation is particularly problematic since it results in both habitat loss and fragmentation for some species (e.g., Dunn and Ewing 1997, Stinson 2005) and altered nutrient and water fluxes in watersheds (Wickham et al. 2002, Brett et al. 2005, Walsh et al. 2005). In general, increased urbanization in Puget Sound also has been correlated with decreased biodiversity (e.g., Donnelly and Marzluff 2004) and decreased stream condition (Booth et al. 2004, Alberti et al. 2007). More specifically, two major impacts of increased imperviousness are increased runoff (e.g., Booth et al. 2002) and increases in deposition of nutrients, pathogens and contaminants into marine and fresh water bodies (e.g., Kaye et al. 2006). Together these impacts have been correlated with decreases in coho salmon abundance (Bilby and Mollot 2008) and indices of stream health (e.g., Morley and Karr 2002). Less is known about the effects of development on biogeochemical cycles and shifts in terrestrial plant and invertebrate communities.

Modification of shoreline regions such as increased armoring, tidal barriers, native vegetation removal, construction of overwater and transportation structures, breakwaters and jetties, and loss of wetlands is correlated with a wide range of state changes in nearshore ecosystems. For example, both shoreline armoring and construction of tidal barriers alter sediment and debris movement, which can result in increased turbidity and alteration of river delta habitat (Miles et al. 2001, Johannessen and MacLennan 2007). These changes in turn can lead to the loss of key habitats for many spices of fish, shorebirds and benthic invertebrates (Buchanan 2006, Dethier 2006, Fresh 2006, Mumford 2007). Shading from the construction of overwater structures has negative effects on nearshore vegetation and alters light regimes, affecting migratory and/or schooling behavior of fish and invertebrates (Nightengale and Simenstad 2001, Scheuerell and Schindler 2003). High quality, high resolution and comprehensive datasets on the extent of development and ecological impact in Puget Sound will help reduce uncertainty surrounding the individual and cumulative effects of shoreline modification in the region.

Pollution occurs when human activities (a) generate toxic chemicals, (b) concentrate or make available naturally occurring substances to levels that can be harmful, (c) change conventional water quality characteristics (e.g., temperature) or (d) introduce disease pathogens or conditions that exacerbate diseases. Puget Sound's fjord-like physiography, oceanographic isolation of some of its major basins, and relatively long water residence time may increase the susceptibility of its biota to contamination (Thomson 1994). Because the Sound possesses a wide range of oceanographic conditions and habitats, species that range from fully marine to diadromous may complete their entire life cycle within its waters, potentially exposing sensitive life stages to contamination. Hart Crowser (2007) catalogued nine important pathways or sources of pollutants to Puget Sound including aerial transport, surface runoff, groundwater discharge, discharges from industrial and municipal wastewater treatment plants, discharges from combined sewer overflows, direct spills, transport of pollutants through exchange of oceanic water and reintroduction of pollutants from contaminated sediments. The effects of pollutant exposure has had negative effects on English sole in Puget Sound (Johnson and Landahl 1993, Myers et al. 2003, Johnson et al. 2008) and has been shown to be accumulating in the body tissues of predator species (Cullon et al. 2005, West et al. 2008, O'Neill and West 2009). Uncertainties surrounding the threat of pollutants pertain to understanding the source, fate and transport of toxic contaminants in the environment as well as the toxicity and subsequent harm to organisms.

Approximately 700 invasive, non-native species have been introduced to the Puget Sound/Georgia Basin, many of which have become established in our native ecosystems (Washington Invasive Species Council 2009). An increase in invasive non-native species is associated with land cover change (human development and seral stage) and habitat fragmentation, human activities that transport the plants and animals or their eggs/seeds, and to changes in disturbance regimes (Hobbs 2000). The interactive effects of non-native species and other anthropogenic disturbances such as habitat loss can be particularly damaging to terrestrial systems (Murcia 1995, With 2002). Major pathways of marine non-native species include shipping (hull fouling, sold and water ballast) and shellfish (particularly oysters) and finfish imports (Wonham and Carlton 2005, Simkanin et al. 2009). Some species, such as cord-grass (*Spartina*), are extremely invasive and modify ecosystems (Hacker et al. 2001, Phillips et al. 2008). With so many non-native species, the state has begun to prioritize control efforts based upon ecological and economic impact. The ranking system used by the Washington Invasive Species Council allows invasive non-native species to be ranked according to their ecological impact and the likelihood of Washington state agencies being able to effectively implement prevention measures or conduct early action on a species.

Ecosystem models are a useful tool for identifying and ranking threats and impacts. Relative risk models (e.g., Hayes and Landis 2004) permit the analysis of cumulative impacts of stressors in different sub-regions and help identify most vulnerable subregions, the sources that contribute most to risk and the habitats and species most imperiled. Mass-balance models can help link food web responses to different management activities (Samhouri et al. 2009, Harvey et al. 2010). Spatial models that map cumulative impacts (Halpern et al. 2008, Leu et al. 2008, Halpern et al. 2009) are also useful for identifying habitats, taxa and locations that are under the most anthropogenic pressure and can be used to track changes in impacts using remote sensing methods. Other system-scale models available for the region include a suite of climate-related models, summarized by ((IPCC) 2007, Climate Impacts Group 2009), and water circulation models for Puget Sound (Edwards et al. 2007, PRISM 2010).

Chapter 4. A science-based review of ecosystem protection and restoration strategies for Puget Sound and its watersheds

The goal of Chapter 4 of the *Update* was to review the potential ecosystem protection and restoration strategies investigated in existing scientific research and their effectiveness at addressing threats. We summarized strategies for both protecting resources that remain intact and recovering or improving natural resources that have lost function. We described the state of our understanding of the level of effectiveness of different strategies, as well as the relative certainty associated with their reported effectiveness. Socioeconomic strategies for Puget Sound ecosystem protection and restoration were not included here (e.g., incentives vs. regulation), but we recognize that this should be part of future iterations of the *Update*.

Subsections of the Chapter are organized according to how the strategies might be implemented. First, we addressed overarching principles for protection and restoration strategies and reviewed broad strategies that apply generally across the landscape. Second, we reviewed protection and restoration strategies that apply specifically to streams, tributaries, and watershed habitat quality. Third, we discussed strategies that directly influence the ecology and habitats of Puget Sound proper, its estuaries, and shorelines. Fourth, we reviewed strategies that directly apply to fish and wildlife population recovery and restoration. In each section, we provided background regarding the strategy, its application in Puget Sound, and what is known scientifically about its effectiveness, listing placeholders for topics that were not covered in this first iteration of the *Update.*

In our treatment of overarching strategies, we identified three broad principles that addressed the combined ultimate drivers of human footprint and climate change. First, we stressed that many of the most valuable actions to mitigate the impacts of the growing human footprint in Puget Sound are also among the most valuable actions to reduce negative impacts of climate change. The rationale for action therefore does not depend on predictions of climate change, but is strengthened by the potential to provide multiple benefits (Whitely Binder et al. 2009). Second, increasing resilience of the ecosystem will allow ecological functions to continue in the face of climate change, increased weather extremes and other stressors (Whitely Binder et al 2009). Finally, principles of adaptive management should guide all protection and restoration actions identified in the PSP Action Agenda and recovery and restoration plans upon which the Action Agenda is based (Puget Sound Partnership 2008).

We reviewed specific strategies for streams, wetlands, lakes, stormwater management, Aquatic Resource Conservation Design (ARCD), wastewater treatment, agricultural pollution control and forestry water pollution. For stream management, taking a watershed approach such as is employed in Puget Sound was noted as being important (NRC 2009). For stream restoration, we identified the guiding principles of both protecting well functioning streams and habitats, and considering necessary restoration actions to achieve recovery goals (PSSRP 2007). For wetland management, we called attention to the general key strategy of protecting, restoring and creating wetlands in accordance with known preferences and tolerances of target biological communities, particularly their geomorphic, hydrological and hydroperiod requirements (Johnson et al. 2000, Cooke and Azous 2001, Horner et al. 2001, Reinelt and Taylor 2001, Reinelt et al. 2001). For lakes, we focused on protection and restoration strategies centered around controlling algal biomass and macrophytes (Cooke et al. 2005).

The strategy of employing ARCD practices was highlighted as a way to reduce urban stormwater runoff and pollutants entering watersheds (NRC 2009) although we noted that there may be cases when conventional stormwater management also is appropriate. ARCD techniques increase soil and vegetation cover and enhance natural drainage features of the landscape (NRC 2009). We promoted source control as a general ARCD strategy for stormwater problems by assessing ubiquitous, bioaccumulative, and/or persistent pollutants. We also suggested improving construction site stormwater control by prioritizing construction management practices that prevent erosion and other construction pollutant problem and practices that minimize erosion; and, finally, sediment collection after erosion has occurred.

For on-site (septic) wastewater treatment systems, and for cases where there are increased nutrients and pathogen loads to nearby water bodies, possible solutions included constructing sewers with municipal treatment plants, or applying advanced on-site treatment (USEPA 2002). However, more testing is required to assess the effectiveness of on-site nitrogen removal and disinfection strategies (WDOH 2005). For agricultural sources of runoff, we identified the strategies of upgrading the implementation of established agricultural best management practices (Mostaghimi et al. 2001). This was particularly important for cases where agricultural runoff is linked to a eutrophication threat as a result of nitrogen (N) and/or phosphorus (P), where it is a threat to shellfish production or recreation as a result of pathogens. To counteract dispersed sources of pathogens that compromise shellfish production and other beneficial uses, the literature findings supported implementing strong source controls and treatment of remaining sources with subsurface-flow constructed wetlands, assuming additional research and development verifies the promise of that technique. Nitrogen and phosphorous can be managed in concert by employing a phosphorus index to target management of critical P source areas, generally near receiving waters and applying N-based management to all other areas (Pionke et al. 2000, Horner et al. 2001). For water pollution from working forests, we identified the key strategy of implementing established forestry best management practices to protect stream water quality and hydrology in the vicinity of forestry activities and minimize the delivery of pollutants from those activities to downstream receiving waters, including Puget Sound (Rashin and Graber 1992, Rashin et al. 1999, USEPA 2005).

While many of the strategies to restore and protect Puget Sound watersheds also affect the marine portion of the Sound, we also addressed more specifically those strategies that are particularly relevant to the marine waters of Puget Sound, including estuarine and nearshore habitat and spatial management strategies such as the implementation of marine reserves and marine spatial planning.

Our initial review of strategies to protect and restore wildlife in the Puget Sound ecosystem was limited to salmonid harvest management, suggesting improved methods for estimating salmon and steelhead carrying capacity (e.g., Mobrand et al. 1997, Ruggerone et al. 2003, Ruggerone et al. 2005, Scheuerell et al. 2006), better run-size forecasting (e.g., Beamish et al. 2009, Holt et al. 2009, Noakes and Beamish 2009), improved accuracy and precision of in-season harvest management (e.g., Clark et al. 2006, Knudsen and Doyle. 2006, Dann et al. 2009, Smith et al.

2005), better ways to avoid genetic alteration of stock structure and diversity (Hard et al. 2007, Allendorf. et al. 2008), increased monitoring of escapement, harvests, and smolts (Starr and Hilborn 1988, Johnson et al. 1997), and advanced tools for harvest management decisions (Mobrand et al. 1997, Scheuerell et al. 2006, Hilborn 2009). We expect that available information for all other wildlife management approaches (including shellfish, marine mammals, birds and invasive species) will be added in subsequent versions of the *Update*.

Discussion

A key component of EBM such as that underway in Puget Sound is that it be grounded in science. *The Puget Sound Science Update* is a key resource from which those responsible for the legislatively mandated ecosystem recovery of Puget Sound can draw credible, reviewed and publicly available scientific information on Puget Sound. Although the 4 Chapters of the *Update* respectively address different components of the IEA process, several concepts are highlighted throughout. These include the treatment of uncertainty, the importance of external forcing factors such as climate change, the importance of models for synthesis, and the critical need for data to populate and validate them. Largely missing from the first iteration of the *Update* is information on the human dimensions of the Puget Sound region—especially in terms of the status of human well-being metrics that are part of the PSP's recovery objectives. One of the exciting opportunities arising from the PSP's inclusion of both human and natural system objectives in their goals is that decisions about what actions should be implemented in which places can explicitly consider the trade-offs in terms of benefits or costs to different human use groups (e.g., shoreline property owners, commercial or recreational fish and shellfishers). Information currently summarized in the *Update* represents human activities on the 'threats' or 'pressure' side of conceptual models, and not on the 'state', or 'response' end. Until more information on how human well-being responds to changes in our ecosystem is available and synthesized, it will be difficult to harmonize competing objectives among the diverse set of communities counting on benefits from Puget Sound.

The *Update* highlights the many values of Puget Sound and the threats to its functions that are well understood. A key point that emerges consistently in all 4 Chapters of the *Update* is the importance of highlighting our degree of scientific certainty surrounding conclusions, data or concepts. Scientific uncertainty can be due to a simple lack of information (e.g., for cumulative impacts of threats), highly variable information, or to situations where reports are either conflicting or are not conclusive. Chapter 1 incorporates this formally into the framework for developing and evaluating indicators, and also in its discussion of future scenarios. In Chapter 2A, the certainties surrounding our understanding of status and trends of ecosystem components are systematically documented. Similarly, key uncertainties in the effects of ecosystem threats are reported in Chapter 3, and Chapter 4 treats uncertainties in the effectiveness restoration strategies. In this way, a clear distinction is made between cases for which evidence is well documented and cases where more information is needed.

A second common thread that can be seen throughout the *Update* is the recognition that mathematical models can help to evaluate tradeoffs among threats, indicators, and strategies as well as help to predict ecosystem response to external forcing factors such as climate change. With this recognition is the need for data to populate the models and track progress of indicators, stressors, and strategy effectiveness over time.   The models are only as good as the information available.

The level of detail provided in these initial Chapters of the *Update* may not yet match perfectly with the needs of PSP staff and constituents in making their day-to-day decisions about indicators for monitoring, key threats that need to be abated, and the most promising strategies to apply in which places to achieve recovery goals. Some of this mismatch may be due to lack of available scientific information—as discussed in each Chapter, the data or analyses are not yet available to address some of the overarching questions posed by PSP leadership to authors of these Chapters. Monitoring plans underway should be pointing to areas where key data are not available, and modeling and syntheses using existing information can be commissioned to fill in critical needs right now.

Even as improved information and syntheses add to the richness of the scientific information in the *Update* over time, there always will be a gap between where scientific judgment ends and where policy decisions by PSP staff begin. The *Update* is designed to be a 'one-stop' reference that can inform science-policy dialogs around specific issues. The science-policy processes to bridge this gap are beginning to take shape in the PSP structure, where technical experts around a specific issue are working with policy leads taking decisions to translate the scientific information and draw out key lessons for action.

A real testament to the current need for the *Update* is that the findings therein have already been used for two different management purposes: the formation of the dashboard indicators by a science-policy team convened by the PSP, and as part of the Chinook salmon recovery monitoring and management plan carried out by the Federal Recovery Implementation Technical Team (the RITT, formerly the TRT). These two very different processes reflect the versatility of the evaluation process put forth by Chapter 1A of the *Update*. The dashboard indicators were developed by a team of scientists and PSP staff, which worked together and used the PSP goals to weight the criteria for evaluating indicators. The team then used the indicator evaluation framework from Chapter 1A to select a portfolio of 20 dashboard indicators for Puget Sound. These indicators were approved by the PSP Leadership Council , and will now be used by the PSP to gauge the health of Puget Sound ecosystem (both natural and human components) and the effectiveness of management actions. In a more species-specific example, the Puget Sound Chinook Recovery Implementation Technical Team (RITT) currently is in the process of using those indicators evaluated by Chapter 1A that pertain to Chinook salmon to inform recovery strategies for Chinook salmon in Puget Sound. These examples are clearly only the first of a myriad of ways the *Update* can be used to provide scientific information relevant to managing the Puget Sound ecosystem in an ecologically plausible manner.

Conclusions

The *Puget Sound Science Update* reflects the undertaking of agency, university and consulting scientists commissioned by the Puget Sound Partnership to put forth a body of peer-reviewed scientific information needed to effectively restore and manage the Puget Sound ecosystem. As a moderated wiki online document, the *Update* can be easily expanded to include components which are currently not included, and also to reflect new findings as they are reported. This effort represents a starting point for the Integrated Ecosystem Assessment being conducted in Puget Sound as the framework for the implementation of ecosystem-based management. It bridges the gap between the available science on ecosystem indicators, trends, threats and recovery strategies in Puget Sound and the policy makers who are becoming increasingly aware of the need to incorporate sound scientific information into management decisions.

Literature Cited

(USEPA), U. S. E. P. A. 2010. Puget Sound Georgia Basin Ecosystem, http://www.epa.gov/Region10/psgb/. Region 10, U.S. Environmental Protection Agency, Seattle, WA.

Alberti, M., D. Booth, K. Hill, B. Coburn, C. Avolio, S. Coe, and D. Spirandelli. 2007. The impact of urban patterns on aquatic ecosystems: An empirical analysis in Puget lowland sub-basins. Landscape and Urban Planning **80**:345-361.

Albertson, S. L., K. Erickson, J. A. Newton, G. Pelletier, R. A. Reynolds, and M. Roberts. 2002. South Puget Sound Water Quality Study Phase 1. Washington State Department of Ecology, Olympia, WA.

Allendorf., F. W., P. R. England, G. Luikart, P.A. Ritchie, and N. Ryman. 2008. Genetic effects of harvest on wild animal populations. Trends in Ecology & Evolution **23**:327-337.

Barnett, T. P., D. W. Pierce, H. G. Hidalgo, C. Bonfils, B. D. Santer, T. Das, G. Bala, A. W. Wood, T. Nozawa, A. A. Mirin, D. R. Cayan, and M. D. Dettinger. 2008. Human-induced changes in the hydrology of the western United States. Science **319**:1080-1083.

Beamish, R., R. Sweeting, and C. E. Neville. 2009. We Are on the Right Path, But It is Uphill Both Ways.*in* Pacific salmon environmental and life history models: advancing science for sustainable salmon in the future. American Fisheries Society,, Bethesda, MD.

Beechie, T., E. Buhle, M. Ruckelshaus, A. Fullerton, and L. Holsinger. 2006. Hydrologic regime and the conservation of salmon life history diversity. Biological Conservation **130**:560-572.

Bell, K. P., D. Huppert, and R. L. Johnson. 2003. Willingness to Pay for Local Coho Salmon Enhancement in Coastal Communities. Marine Resource Economics **18**:15-31.

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

Berry, H. D., A. T. Sewell, S. Wyllie-Echeverria, B. R. Reeves, T. F. Mumford, J. R. Skalski, R. C. Zimmerman, and J. Archer. 2003. Puget Sound Submerged Vegetation Monitoring Project: 2000-2002 Monitoring Report, Nearshore Habitat Program. Washington State Department of Resources, Olympia, WA.

Bilby, R. E., and L. A. Mollot. 2008. Effect of changing land use patterns on the distribution of coho salmon (Oncorhynchus kisutch) in the Puget Sound region. Canadian Journal of Fisheries and Aquatic Sciences **65**:2138-2148.

Bin, O., and S. Polasky. 2005. Evidence on the Amenity Value of Wetlands in a Rural Setting. Journal of Agricultural and Applied Economics **37**:589-602.

Bolte, J. 2009. Envision: A spatially explicity, distributed, multiagent-based framework for policy assessment and alternative futuring. Corvallis, OR.

Booth, D. B., D. Hartley, and R. Jackson. 2002. Forest cover, impervious-surface area, and the mitigation of stormwater impacts. Journal of the American Water Resources Association **38**:835-845.

Booth, D. B., J. R. Karr, S. Schauman, C. P. Konrad, S. A. Morley, M. G. Larson, and S. J. Burges. 2004. Reviving urban streams: Land use, hydrology, biology, and human behavior. Journal of the American Water Resources Association **40**:1351-1364.

Bower, J. L. 2009. Changes in marine bird abundance in the Salish Sea: 1975 to 2007. Marine Ornithology **37**:9-17.

Bradbury, A., B. Sizemore, D. Rothaus, and M. Ulrich. 2000. Stock assessment of subtidal geoduck clams (*Panopea abrupta*) in Washington. Washington Department of Fish and Wildlife, Olympia, WA.

Brett, M. T., G. B. Arhonditsis, S. E. Mueller, D. M. Hartley, J. D. Frodge, and D. E. Funke. 2005. Non-point-source impacts on stream nutrient concentrations along a forest to urban gradient. Environmental Management **35**:330-342.

Bricker, S., B. Longstaff, W. Dennison, A. Jones, K. Boicourt, C. Wicks, and J. Woerner. 2007. Effects of nutrient enrichment in the nation's estuaries : a decade of change. National Centers for Coastal Ocean Science, Silver Spring MD.

Buchanan, J. B. 2006. Nearshore Birds in Puget Sound. Report No. 2006-05, Puget Sound Nearshore Partnership, Seattle, WA.

Carretta, J. V., K. A. Forney, M. M. Muto, J. Barlow, J. Baker, B. Hanson, and M. Lowry. 2007. United States marine mammal stock assessments: 2006. National Marine Fisheries Service, La Jolla, CA.

CBP. 2010. Bay Pressures, http://www.chesapeakebay.net/baypressures.aspx?menuitem=13959. Chesapeake Bay Program, Annapolis, MD.

Cho, S.-H., S. G. Kim, R. K. Roberts, and S. Jung. 2009. Amenity values of spatial configurations of forest landscapes over space and time in the Southern Appalachian Highlands. Ecological Economics **68**:2646-2657.

Clark, J. H., R. D. Mecum, A. McGregor, P. Krasnowski, and A. M. Carroll. 2006. The commercial salmon fishery in Alaska. Alaska Fishery Research Bulletin **12**:1-146.

Climate Impacts Group. 2009. The Washington climate change impacts assessment evaluating Washington's future in a changing climate. Climate Impacts Group, [Seattle, Wash.].

Collins, B. D., and A. J. Sheikh. 2005. Historical reconstruction, classification, and change analysis of Puget Sound tidal marshes. Washington State Dept. of Natural Resources, Olympia, WA.

Cooke, G. D., E. B. Welch, S. A. Peterson, and S. A. Nichols. 2005. Restoration and Management of Lakes and Resevoirs, 3rd Ed. Taylor and Francis, Boca Raton, FL.

Cooke, S. S., and A. L. Azous. 2001. Characterization of Central Puget Sound Basin Palustrine Wetland Vegetation. Pages 69-95 *in* A. L. Azous and R. R. Horner, editors. Wetlands and Urbanization: Implications for the Future. Lewis Publishers, Boca Raton, FL.

Cullon, D. L., S. J. Jeffries, and P. S. Ross. 2005. Persistent organic pollutants in the diet of harbor seals (*Phoca vitulina*) inhabiting Puget Sound, Washington (USA), and the Strait of Georgia, British Columbia (Canada): a food basket approach. Environmental Toxicology and Chemistry **24**:2562-2572.

Dann, T. H., C. Habicht, J.R. Jasper, H.A. Hoyt, A.W. Barclay, W.D. Templin, T.T. Baker, F.W. West, and L. F. Fair. 2009. Genetic Stock Composition of the Commercial Harvest of Sockeye Salmon in Bristol Bay, Alaska , 2006-2008. . Alaska Department of Fish and Game, , Anchorage, AK.

Determan, T. 2009. Atlas of Fecal Coliform Pollution in Commercial Shellfish Areas of Puget Sound: Year 2007. Washington State Department of Health, Olympia, WA.

Dethier, M. 2006. Native Shellfish in Nearshore Ecosystems of Puget Sound. Puget Sound Nearshore Partnership Report No. 2006-04, Seattle, WA.

Donnelly, R., and J. M. Marzluff. 2004. Importance of reserve size and landscape context to urban bird conservation. Conservation Biology **18**:733-745.

Dunn, P., and K. Ewing. 1997. Ecology and Conservation of the South Puget Sound Prairie Landscape. The Nature Conservancy of Washington, Seattle, WA.

Edwards, K. A., M. Kawase, and C. P. Sarason. 2007. Circulation in Carr Inlet, Puget Sound, during spring 2003. Estuaries and Coasts **30**:945-958.

Egan, K. J., J. A. Herriges, C. L. Kling, and J. A. Downing. 2009. Valuing Water Quality as a Function of Water Quality Measures. American Journal of Agricultural Economics **91**:106-123.

Eissinger, A. M. 2007. Great blue herons in Puget Sound. Puget Sound Nearshore Partnership, Olympia, WA.

Elliott, M. 2002. The role of the DPSIR approach and conceptual models in marine environmental management: an example for offshore wind power. Marine Pollution Bulletin **44**:III-VII.

Fisher, W., and D. Velasquez. 2008. Management recommendations for Washington's priority habitats and species: Dungeness crab (*Cancer magister*). Olympia, WA.

Fresh, K. L. 2006. Juvenile Pacific salmon and the nearshore ecosystem of Puget Sound., Published by Seattle Districut, U.S Army Corps. of Engineeers, Seattle, WA.

Gaeckle, J. L., P.Dowty, H. Berry, and L. Ferrier. 2009. Puget Sound Submerged Vegetation Monitoring Project: 2008 Monitoring Report, Nearshore Habitat Program. Washington State Department of Natural Resources, Olympia, WA.

Good, T. P., R. S. Waples, and P. A. A. (editors). 2005. Updated status of federally listed ESUs of West coast salmon and steelhead. U.S Department of Commerce NOAA Technical Memo, Seattle, WA.

Gustafson, R. G., W. H. Lenarz, B. B. McCain, C. C. Schmitt, W. S. Grant, T. L. Builder, and R. D. Methot. 2000. Status review of the Pacific Hake, Pacific Cod, and Walleye Polluck from Puget Sound, WA. NOAA, Department of Commerce.

Hacker, S. D., D. Heimer, C. E. Hellquist, T. G. Reeder, B. Reeves, T. J. Riordan, and M. N. Dethier. 2001. A Marine Plant (Spartina Anglica) Invades Widely Varying Habitats: Potential Mechanisms of Invasion and Control. Biological Invasions **3**:211-217.

Halpern, B. S., V. K. Carrie, A. S. Kimberly, M. Fiorenza, M. E. Colin, K. Caitlin, M. C. Caitlin, G. M. Rebecca, S. Christine, and J. T. Sarah. 2009. Mapping cumulative human impacts to California Current marine ecosystems. Conservation Letters **2**:138-148.

Halpern, B. S., S. Walbridge, K. A. Selkoe, C. V. Kappel, F. Micheli, C. D'Agrosa, J. F. Bruno, K. S. Casey, C. Ebert, H. E. Fox, R. Fujita, D. Heinemann, H. S. Lenihan, E. M. P. Madin, M. T. Perry, E. R. Selig, M. Spalding, R. Steneck, and R. Watson. 2008. A global map of human impact on marine ecosystems. Science **319**:948-952.

Hard, J. J., J. M. Myers, M. J. Ford, R. G. Cope, G. R. Pess, R. S. Waples, G. A. Winans, B. A. Berejikian, F. W. Waknitz, P. B. Adams, P. A. Bisson, D. E. Campton, and R. R. Reisenbichler. 2007. Status review of Puget Sound steelhead (*Oncorhynchus mykiss*). U.S. Department of Commerce, NOAA Tech Memo, Seattle, WA.

Hart Crowser. 2007. Control of Toxic Chemicals in Puget Sound. Phase 1: Initial estimate of loadings. Washington Department of Ecology.

Harvey, C. J., K. K. Bartz, J. Davies, T. B. Francis, T. P. Good, A. D. Guerry, B. Hanson, K. K. Holsman, J. Miller, M. L. Plummer, J. C. P. Reum, L. D. Rhodes, C. A. Rice, J. F. Samhouri, G. D. Williams, N. Yoder, P. S. Levin, and M. H. Ruckelshaus. 2010. A Mass-balance Model for Evaluating Food Web Structure and Community-scale Indicators in the Central Basin of Puget Sound. NOAA Technical Memorandum NMFS-NWFSC-in press, U.S. Department of Commerce, National Oceanic and Atmospheric Administration, National Marine Fisheries Service, Seattle, WA.

Hayes, E. H., and W. G. Landis. 2004. Regional ecological risk assessment of a near shore marine environment: Cherry Point, WA. Human and Ecological Risk Assessment **10**:299-325.

Hilborn, R. 2009. Life history models for salmon management: the challenges.*in* Pacific salmon environmental and life history models: advancing science for sustainable salmon in the future. American Fisheries Society, Symposium 71, Bethesda, MD.

Hobbs, R. J. 2000. Land-Use Changes and Invasions.*in* H. A. Mooney and R. J. Hobbs, editors. Invasive species in a changing world. Island Press, Washington, D.C.

Holt, K. R., S.P. Cox, and J. Sawada. 2009. In-Season Forecasting of Coho Salmon Marine Survival via Coded Wire Tag Recoveries. North American Journal of Fisheries Management **29**:1165-1182.

Horner, R. R., A. L. Azous, K.O.Richter, S. S. Cooke, L. E. Reinelt, and K. Ewsing. 2001. Wetlands and Stormwater Management Guidelines. Pages 69-95 *in* A. L. Azous and R. R. Horner, editors. Wetlands and Urbanization: Implications for the Future. Lewis Publishers, Boca Raton, FL.

IPCC, 2007. Climate change 2007 : the physical science basis : contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change.*in* S. Solomon, D. Qin, M. Manning, Z. Chen, M. Marquis, K. B. Averyt, M. Tignor, and H. L. Miller, editors. Cambridge University Press, Cambridge; New York.

Jeffries, S., H. Huber, J. Calambokidis, and J. Laake. 2003. Trends and status of harbor seals in Washington state: 1978-1999. Journal of Wildlife Management **67**:207-218.

Johannessen, J., and A. MacLennan. 2007. Beaches and Bluffs of Puget Sound. Report No. 2007-04, Puget Sound Nearshore Partnership, Seattle, WA.

Johnson, L. L., and J. T. Landahl. 1993. Contaminant, liver disease, and mortality rates in English sole (*Pleuronectes vetulus*). Ecology Applications.

Johnson, L. L., D. P. Lomax, M. S. Myers, O. P. Olson, S. Y. Sol, S. M. O'Neill, J. West, and T. K. Collier. 2008. Xenoestrogen exposure and effects in English sole (*Parophrys vetulus*) from Puget Sound, WA. Aquatic Toxicology **88**:29-38.

Johnson, O. W., W. S. Grant, R. G. Kope, K. Neely, F. W. Waknitz, and R. S. Waples. 1997. Status Review of Chum Salmon from Washington, Oregon, and California. National Marine Fisheries Service, Northwest Fisheries Science Center, , Seattle, WA.

Johnson, P. A., D. L. Mock, E. J. Teachout, and A. McMillan. 2000. Washington State Wetland Mitigation Evaluation Study, Phase 1: Compliance. Washington Department of Ecology, Olympia, WA.

Kaye, J. P., P. M. Groffman, N. B. Grimm, L. A. Baker, and R. V. Pouyat. 2006. A distinct urban biogeochemistry? Trends in Ecology and Evolution **21**:192-199.

Knudsen, E. E., and E. G. Doyle. 2006. Science and technology are essential for sustaining salmon populations and their ecosystems.*in* Salmon 2100: The future of wild Pacific salmon. American Fisheries Society, Bethesda, MD.

Krahn, M. M., M. J. Ford, W. F. Perrin, P. R. Wade, R. P. Angliss, M. B. Hanson, B. L. Taylor, G. M. Ylitalo, M. E. Dahlheim, J. E. Stein, and R. S. Waples. 2004. 2004 Status review

of Southern Resident killer whales (*Orcinus orca*) under the Endangered Species Act. Page 73 *in* N. T. Memorandum, editor.
Kriete, B. 2007. Orcas in Puget Sound. Puget Sound Nearshore Partnership, Seattle.
Labiosa, W. B., R. Bernknopf, P. Hearn, D. Hogan, D. Strong, L. Pearlstine, A. M. Mathie, A. M. Wein, K. Gillen, and S. Wachter. 2009. The South Florida Ecosystem Portfolio Model - A Map-Based Multicriteria Ecological, Economic, and Community Land-use Planning Tool. Page 41 *in* U. S. G. Survey, editor., Menlo Park, CA.
Land, K. C. 1983. Social Indicators. Annual Review of Sociology **9**:1-26.
Leu, M., S. E. Hanser, and S. T. Knick. 2008. The human footprint in the west: A large-scale analysis of anthropogenic impacts. Ecological Applications **18**:1119-1139.
Levin, P. S., M. J. Fogarty, S. A. Murawski, and D. Fluharty. 2009. Integrated ecosystem assessments: Developing the scientific basis for Ecosystem-Based Management of the ocean. PLoS Biol **7**:e1000014.
Miles, J. R., P. E. Russell, and D. A. Huntley. 2001. Field measurements of sediment dynamics in front of a seawall. Journal of Coastal Research **17**:195-206.
Mobrand, L. E., J. A. Lichatowich, L. C. Lestelle, and T. S. Vogel. 1997. An approach to describing ecosystem performance "through the eyes of salmon". Canadian Journal of Fisheries and Aquatic Sciences **54**:2964-2973.
Morley, S. A., and J. R. Karr. 2002. Assessing and restoring the health of urban streams in the Puget Sound basin. Conservation Biology **16**:1498-1509.
Mostaghimi, S., K. M. Brannan, T. A. Dillaha, and A. C. Bruggeman. 2001. Best Management Practices for Nonpoint Source Pollution Control: Selection and Assessment.*in* W. F. Ritter and A. Shirmohammadi, editors. Agricultural Nonpoint Source Pollution: Watershed Management and Hyrology, Boca Raton, FL.
Mote, P., A. Hamlet, and E. Salathe. 2008. Has spring snowpack declined in the Washington Cascades? HYDROLOGY AND EARTH SYSTEM SCIENCES **12**:193-206.
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-+.
Mumford, T. F. 2007. Kelp and eelgrass in Puget Sound. Seattle District, U.S. Army Corps of Engineers, Puget Sound Nearshore Partnership, Seattle, WA.
Murcia, C. 1995. Edge effects in fragmented forests: implications for conservation. Trends in ecology & evolution. **10**:58.
Murray, C., B. Sohngen, and L. Pendleton. 2001. Valuing water quality advisories and beach amenities in the Great Lakes. Water Resources Research **37**:2583-2590.
Myers, M. S., B. F. Anulacion, B. L. French, W. L. Reichert, C. A. Laetz, J. Buzitis, O. P. Olson, S. Sol, and T. K. Collier. 2008. Improved flatfish health following remediation of a PAH-contaminated site in Eagle Harbor, Washington. Aquatic Toxicology **88**:277-288.
Myers, M. S., L. L. Johnson, and T. K. Collier. 2003. Establishing the Causal Relationship between Polycyclic Aromatic Hydrocarbon (PAH) Exposure and Hepatic Neoplasms and Neoplasia-Related Liver Lesions in English Sole (<i>Pleuronectes vetulus</i>). Human and Ecological Risk Assessment: An International Journal **9**:67 - 94.
Neuman, M., D. St. John, and J. Knauer. 2009a. Identification, Definition and Rating of Threats to the Recovery of Puget Sound. Puget Sound Partnership, Olympia, WA.

Neuman, M., D. St. John, J. Knauer, and N. Salafsky. 2009b. Using results chains to develop objectives and performance measures for the 2008 Action Agenda. Puget Sound Partnership, Olympia, WA.
Newton, J., and K. Van Voorhis. 2002. Seasonal patterns and controlling factors of primary production in Puget Sound's central basin and Possesion Sound. WA Department of Ecology, Olympia, WA.
Newton, J. A., S. L. Albertson, k. V. Voorhis, C. Maloy, and E.Siegel. 2002. Washington State Marine Water Quality, 1998 through 2000. Washington State Department of Ecology, Olympia, WA.
Nightengale, B. J., and C. A. Simenstad. 2001. Overwater Structures: Marine issues. University of Washington, Seattle, Washington.
Noakes, D. J., and R. J. Beamish. 2009. Synchrony of Marine Fish Catches and Climate and Ocean Regime Shifts in the North Pacific Ocean. Marine and Coastal Fisheries: Dynamics, Management, and Ecosystem Science **1**:155-168.
NRC. 2009. Urban stormwater management in the United States. The National Acadaemies Press, Washington, D.C.
O'Neill, S. M., C. F. Bravo, and T. K. Collier. 2008. Environmental Indicators for the Puget Sound Partnership: A Regional Effort to Select Provisional Indicators (Phase 1). Summary Report., National Oceanic and Atmospheric Administration, Seattle, WA.
O'Neill, S. M., and J. E. West. 2009. Marine Distribution, Life History Traits, and the Accumulation of Polychlorinated Biphenyls in Chinook Salmon from Puget Sound, Washington. Transactions of the American Fisheries Society **138**:616-632.
Orensanz, J. M., C. M. Hand, A. M. Parma, J. Valero, and R. Hilborn. 2004. Precaution in the harvest of Methuselah's clams - the difficulty of getting timely feedback from slow-paced dynamics. Canadian Journal of Fisheries and Aquatic Sciences **61**:1355-1372.
Palsson, W. A., T. S. Tsou, G. G. Bargmann, R. M. Buckley, J. E. West, M. L. Mills, Y. W. Cheng, and R. E. Pacunski. 2009. The biology and assessment of rockfishes in Puget Sound. Washington Department of Fish and Wildlife, Olympia, WA.
Penttila, D. 2007. Marine Forage Fishes in Puget Sound. Puget Sound Nearshore Partnership Report No. 2007-03, Seattle, WA.
Phillips, C. H., K. D. Anderson, and T. O. Ketel. 2008. Spartina Eradication Program 2007 Progress Report. Washington State Department of Agriculture.
Pionke, H. P., W. J. Gburek, and A. N. Sharpley. 2000. A crticial source area controls on water quality in an agricultural watershed located in the Chesapeake basin. Ecological Engineering **14**:325-335.
PRISM. 2010. The Puget Sound Regional Synthesis Model Initiative, http://www.prism.washington.edu/home/index. University of Washington, Seattle, WA.
PSSRP. 2007. Puget Sound Salmon Recovery Plan. Shared Strategy for Puget Sound and NOAA Fisheries, Seattle, WA.
Puget Sound Partnership. 2008. Puget Sound Action Agenda, Protecting and Restoring the Puget Sound Ecosystem by 2020. Olympia.
Puget Sound Regional Council. 2009. Vision 2040. Seattle, WA.
Rapport, D. J., H. A. Regier, and T. C. Hutchinson. 1985. Ecosystem Behavior Under Stress. American Naturalist **125**:617-640.
Rashin, E., and C. Graber. 1992. Effectiveness of best management practices for aerial application of forest pesticides. Washington Department of Ecology, Olympia, WA.

Rashin, E., C. Clishe, A. Loch, and J. Bell. 1999. Effectiveness of forest road and timber harvest best management practices with respect to sediment-related water quality impacts. Washington Department of Ecology, Olympia, WA.

Reinelt, L. E., and B. L. Taylor. 2001. Effects of Watershed Development on Hydrology. Pages 69-95 *in* A. L. Azous and R. R. Horner, editors. Wetlands and Urbanization: Implications for the Future. Lewis Publishers, Boca Raton, FL.

Reinelt, L. E., B. L. Taylor, and R. R. Horner. 2001. Morphology and Hydrology. Pages 69-95 *in* A. L. Azous and R. R. Horner, editors. Wetlands and Urbanization: Implications for the Future. Lewis Publishers, Boca Raton, FL.

Reum, J., M. Hunsicker, and C. Paulsen. 2010. Species composition and relative abundance of large medusae in Puget Sound, WA. Northwest Science **84**:xxx-yyy.

Rice, C. A. 2007. Evaluating the biological condition of Puget Sound. Ph.D. dissertation. University of Washington, Aquatic and Fishery Sciences, Seattle, WA.

Richter, A., and S. Kolmes. 2005. Maximum Temperature Limits for Chinook, Coho, and Chum Salmon, and Steelhead Trout in the Pacific Northwest. Reviews in Fisheries Science **13**:23-49.

Roberts, M., J. Bos, and S. L. Albertson. 2008. South Puget Sound dissolved oxygen study interim data report. WA Department of Ecology, Olympia, WA.

Rosenberg, A. A., and P. A. Sandifer. 2009. What do managers need?*in* K. McLeod and H. Leslie, editors. Ecosystem-Based Management for the Oceans. Island Press, Washington, DC.

Ross, P. S. 2006. Fireproof killer whales (*Orcinus orca*): flame retardant chemicals and the conservation imperative in the charismatic icon of British Columbia, Canada. Canadian Journal of Fisheries and Aquatic Science **63**:224-234.

Rothaus, D. P., B. Vadopalas, and C. S. Friedman. 2008. Precipitous declines in pinto abalone (*Haliotis kamtschatkana kamtschatkana*) abundance in the San Juan Archipelago, Washington, USA, despite statewide fishery closure. Canadian Journal of Fisheries and Aquatic Sciences **65**:2703(2709).

Ruckelshaus, M., T. Essington, and P. Levin. 2009. Puget Sound, Washington, USA.*in* K. McLeod and H. Leslie, editors. Ecosystem-Based Management for the Oceans. Island Press, Washington, DC.

Ruggerone, F. G. T., N. E., I. J. L., S., , and P. Hagen. 2005. Seasonal marine growth of Bristol Bay sockeye salmon in relation to competition with Asian pink salmon and the 1977 ocean regime shift. Fishery Bulletin **103**: 355–370.

Ruggerone, G. T., Zimmerman, M. M., N. K. W., and D. E. Rogers. 2003. Competition between Asian pink salmon (*Oncorhynchus gorbuscha*) and Alaskan sockeye salmon (*O. nerka*) in the north Pacific Ocean. Fisheries and Oceanography **12**: 209-219.

Samhouri, J., P. Levin, and C. Harvey. 2009. Quantitative Evaluation of Marine Ecosystem Indicator Performance Using Food Web Models. Ecosystems **12**:1283-1298.

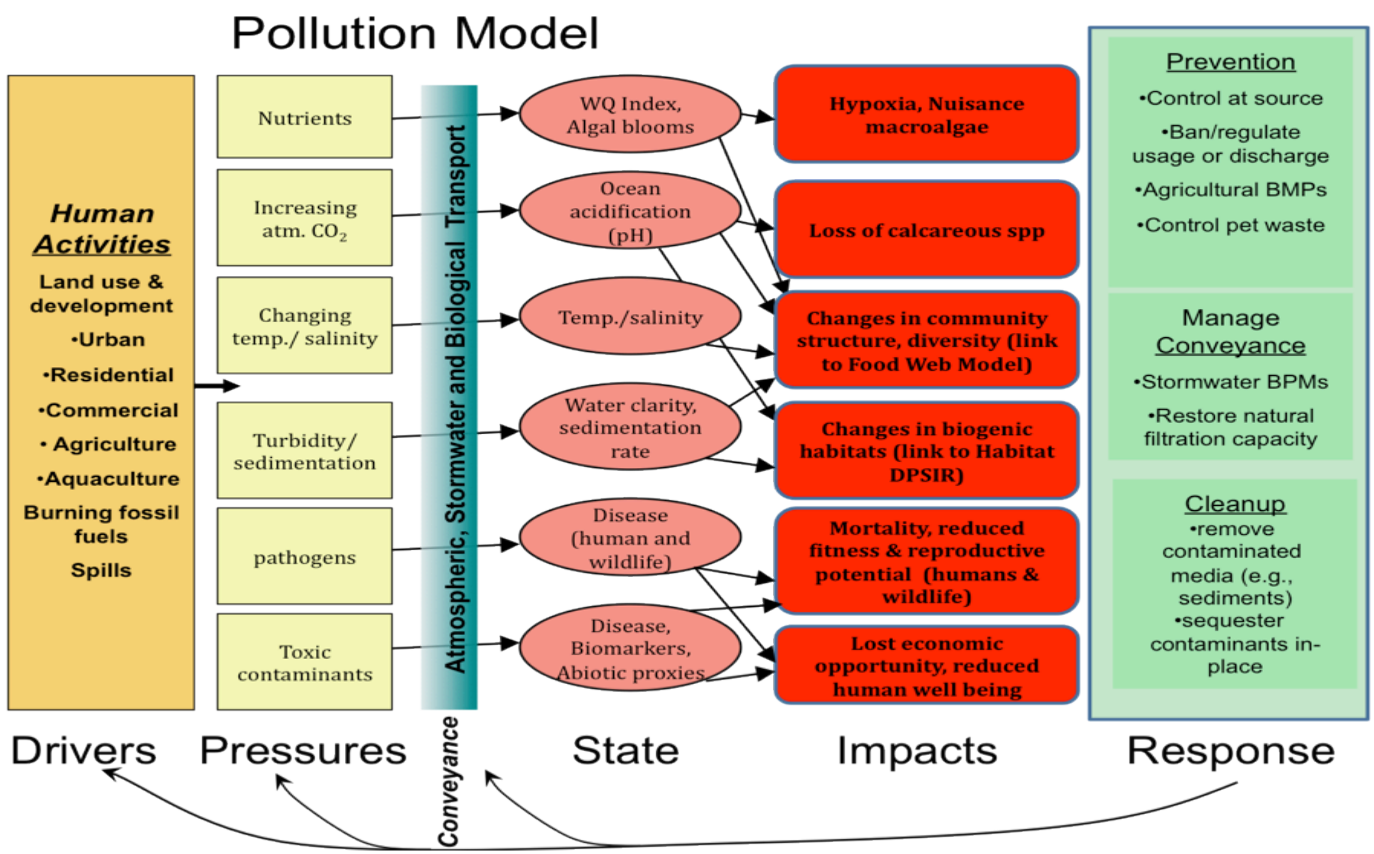
Scheuerell, M. D., R. Hilborn, M.H. Ruckelshaus, K.K. Bartz, K.M. Lagueux, A.D. Haas, and K. Rawson. 2006. The Shiraz model: a tool for incorporating anthropogenic effects and fish–habitat relationships in conservation planning. Canadian Journal of Fisheries and Aquatic Sciience **63**:1596–1607. .

Scheuerell, M. D., and D. E. Schindler. 2003. Diel vertical migration by juvenile sockeye salmon: Empirical evidence for the antipredation window. Ecology **84**:1713-1720.

Schneider, L. 2004. Quality Assurance Project Plan: BEACH Program. Washington State Department of Ecology, Olympia, WA.
Shackeroff, J. A., E.L. Hazen, and L. B. Crowder. 2009. The oceans as peopled seascapes.*in* K. McLeod and H. Leslie, editors. Ecosystem-Based Management for the Oceans. Island Press, Washington, DC.
Shared Strategy for the Puget Sound. 2007. Puget Sound Salmon Recovery Plan. Seattle, WA.
Sharpe, A. 1999. A survey of indicators of economic and social well-being., Background paper prepared for Candian Policy Research Networks, Ottowa, Canada.
Simkanin, C., I. Davidson, M. Falkner, M. Sytsma, and G. Ruiz. 2009. Intra-coastal ballast water flux and the potential for secondary spread of non-native species on the US West Coast. Marine Pollution Bulletin **58**:366-374.
Smith, C. T., W.D. Templin, J.E. Seeb, and L. W. Seeb. 2005. Single Nucleotide Polymorphisms Provide Rapid and Accurate Estimates of the Proportions of U.S. and Canadian Chinook Salmon Caught in Yukon River Fisheries. North American Journal of Fisheries Management **25**:44–953.
Stark, K., S. Mickelson, and S. Keever. 2009. Water Quality Status Report for Marine Waters, 2005 - 2007. King County Department of Natural Resources and Parks, Seattle, WA.
Starr, P., and R. Hilborn. 1988. Reconstruction of harvest rates and stock contributions in the gauntlet salmon fisheries: Application to British Columbia and Washington sockeye (*Oncorhynchus nerka*). Canadian Journal of Fisheries and Aquatic Sciences **45**:2216-2229.
Stewart, I. T., D. R. Cayan, and M. D. Dettinger. 2005. Changes toward earlier streamflow timing across western North America. Journal of Climate **18**:1136-1155.
Stick, K. C., and A. Lindquist. 2009. 2008 Washington State Herring Stock Status Report. Stock Status Report No. FPA 09-05, Olympia, WA.
Stinson, D. W. 2005. Washington State status report for the Mazama pocket gopher, streaked horned lark, and Taylor's checkerspot. Washington Department of Fish and Wildlife, Olympia, WA.
Stout, H. A., B. B. McCain, R. D. Vetter, T. L. Builder, W. H. Lenarz, L. L. Johnson, and R. D. Methot. 2001. Status review of Copper rockfish, Quillback rockfish and Brown rockfish in Puget Sound, Washington. NOAA Technical Memo, U.S. Department of Commerce.
Trainer, V., B.-T. Eberhart, J. Wekell, N. Adams, L. Hanson, F. Cox, and J. Dowell. 2003. Paralytic shellfish toxins in Puget Sound, Washington State. J Shellfish Res **22**:213 - 223.
U.S. Environmental Protection Agency. 2006. Puget Sound Georgia Basin ecosystem indicators report: technical background document. U.S. Environmental Protection Agency Region 10.
United States Geological Survey. 2010. Provisional data for Washington.
Urban Ecology Research Lab. 2009. Puget Sound Future Scenarios. Seattle, WA.
USEPA. 2002. Onsite Wastewater Treatment System Manual. U.S. Environmental Protection Agency, Office of Water, Washington, DC.
USEPA. 2005. National Management Measures to Control Nonpoint Source Pollution From Forestry. U.S. Environmental Protection Agency, Nonpoing Source Control Branch, Washington, DC.
Walsh, C. J., A. H. Roy, J. W. Feminella, P. D. Cottingham, P. M. Groffman, and R. P. Morgan, II. 2005. The urban stream syndrome: current knowledge and the search for a cure. Journal of the North American Benthological Society **24**:706-723.

Washington Invasive Species Council. 2009. Annual Report. Seattle.
Washington State Department of Ecology. 2010. Water Resources, Instream Flows in Washington. Olympia, WA.
WBC. 2007. Washington's Biodiversity: Status and Threats. Washington Biodiversity Council, Olympia, WA.
WDOE. 2010. Overview: Threats – Saving Puget Sound, http://www.ecy.wa.gov/puget_sound/threats.html. Washington State Department of Ecology, Olympia, WA.
WDOH. 2005. Nitrogen Reducing Technologies for Onsite Wastewater Treatment Systems. Washington Department of Health, Olympia, WA.
Welsch, H., and J. Kuhling. 2009. Using Happiness Data for Environmental Valuation: Issues and Applications. Journal of Economic Surveys **23**:385-406.
West, J. E., S. M. O'Neill, and G. M. Ylitalo. 2008. Spatial extent, magnitude, and patterns of persistent organochlorine pollutants in Pacific herring (Clupea pallasi) populations in the Puget Sound (USA) and Strait of Georgia (Canada). Science of The Total Environment **394**:369-378.
White, J., J. L. Ruesink, and A. C. Trimble. 2009. The nearly forgotten oyster: *Ostrea lurida* Carpenter 1864 (Olympia oyster) history and management in Washington State.(Report). Journal of Shellfish Research **28**:43(47).
Whitely Binder, L. C., J.K. Barcelos, D.B. Booth, M. Darzen, M.M. Elsner, R. Fenske, T.F. Graham, A.F. Hamlet, J. Hodges-Howell, D.D. Huppert, J.E. Jackson, C. Karr, P.W. Keys, J.S. Littell, N. Mantua, J. Marlow, D. McKenzie, and M. Roginson-Dorn. 2009. Preparing for Climate Change in Washington State.*in* M.M Elsner, J. Littell, and L. W. Binder, editors. The Washington Climate Change Impacts Assessment,. Center for Science in the Earth System, Joint Institute for the Study of Atmosphere and Ocean, Seattle, WA.
Wickham, J. D., R. V. O'Neill, K. H. Riitters, E. R. Smith, T. G. Wade, and K. B. Jones. 2002. Geographic targeting of increases in nutrient export due to future urbanization. Ecological Applications **12**:93-106.
Winder, M., and D. E. Schindler. 2004. Climatic effects on the phenology of lake processes. Global Change Biology **10**:1844-1856.
With, K. A. 2002. The Landscape Ecology of Invasive Spread. Conservation Biology **16**:1192-1203.
Wonham, M. J., and J. T. Carlton. 2005. Trends in marine biological invasions at local and regional scales: the Northeast Pacific Ocean as a model system. Biological Invasions **7**:369-392.
Zickfeld, K., M. Granger Morgan, D. J. Frame, and K. D.W. 2010. Expert judgments about transient climate response to alternative future trajectories of radiative forcing. Proceedings of the National Academy of Sciences, in press.

Appendix C. Example of a Driver-Pressure-State-Impacts-Response conceptual model (for pollution) in the Salish Sea ecosystem from Chapter 3. Note that in a full assessment, human well-being and human health states would be included in the conceptual model so that trade-offs in strategies affecting both natural and human system objectives could be evaluated.



Appendix B. Status and key findings of biophysical components reviewed in Chapter 2A.

Habitats	Key Findings	Primary References
Kelp	Annual aerial surveys of floating kelp conducted by the Washington Department of Natural Resources show that floating canopies have increased in outer coastal areas in the western Strait of Juan de Fuca. Floating kelp canopies in the eastern Strait of Juan de Fuca showed no statistical change over the same period.	(Berry et al. 2005)
Eelgrass	Sharp, local declines in eelgrass abundance have been reported at some sites.	(Berry et al. 2003, Mumford 2007, Gaeckle et al. 2009)
Tidal Wetlands	Current abundance of tidal wetland habitat is reported to be much lower than historic levels. Forthcoming analyses by the Puget Sound Nearshore Partnership (PSNERP) stand to shed more light on the extent and nature of current and historic wetland alterations in Puget Sound.	(Collins and Sheikh 2005)
Species and Food Webs		
Jellyfish	Existing data are not sufficient to assess spatial and temporal patterns of jellyfish abundance in Puget Sound.	(Rice 2007, Reum et al. 2010)
Pinto Abalone	Pinto abalone are in severe decline in Puget Sound and are presently at densities where they may not be self-sustaining.	(Rothaus et al. 2008)
Bivalves	Geoduck clams are very long-lived, rendering them potentially susceptible to overexploitation. Published accounts of Sound-wide estimates of population status and trends of geoducks are lacking. Abundances of Olympia oysters have been very low in Puget Sound since the 1940s despite the fact that they are no longer targeted by fisheries.	(Bradbury et al. 2000, Orensanz et al. 2004, White et al. 2009)
Dungeness Crabs	Fishery-independent assessments of Dungeness crab abundances in Puget Sound are lacking.	(Dethier 2006, Fisher and Velasquez 2008)
Bentho-pelagic fish	In Puget Sound, Pacific Hake, Pacific cod and walleye Pollock were all once reported to be common and now apparently much less abundant despite the fact that fishing pressure has been relieved. The direct causes for the declines and for the lack of rebounding are not well understood.	(Gustafson et al. 2000)
Rockfish	In Puget Sound, rockfish abundances have decreased substantially since quantitative monitoring began in the 1970's. Because of the diversity in habitat use, ecology and life history, single-species approaches to rockfish management in Puget Sound are currently being considered.	(Stout et al. 2001, Palsson et al. 2009)
Forage Fish	Because of their reliance on near-shore habitats, the continued viability of forage fish stocks depends on the preservation of this habitat. Data on population status are most extensive for Pacific Herring stocks, where current status and trends are mixed. The previously large Cherry Point stock is severely depressed from historic population levels.	(Penttila 2007, Stick and Lindquist 2009)

Salmonids	The number of Chinook salmon in Puget Sound has increased since being listed in 1999 although population numbers are still well below target abundances. Hood Canal Summer Chum abundances have increased since their listing, yet only two extant spawning aggregations show long-term positive growth rates. Steelhead trout also show declining trends, particularly in southern Puget Sound.	(Good et al. 2005, Fresh 2006, Hard et al. 2007, PSSRP 2007)
Harbor Seals	Harbor seal populations in Washington State have recovered since the 1970s and population sizes may be near a stable equilibrium, perhaps reflective of the carrying capacity of the environment. Because monitoring was discontinued after 1999, current population levels are not known.	(Jeffries et al. 2003, Carretta et al. 2007)
Marine Birds	Multiple species of marine birds that overwinter in Puget Sound have shown declines in abundance over the past two decades. These declines have occurred across diverse taxonomic groups and feeding guilds.	(Eissinger 2007, Bower 2009)
Killer Whales	Human removal of Southern Resident Killer Whales appears to have driven population declines prior to the 1970s, yet 35 years after the removals for live capture ended, population numbers remain low. Data on transient killer whale populations are lacking.	(Krahn et al. 2004, Kriete 2007)
Water Quality		
Harmful Algal Blooms	Harmful algal blooms in Puget Sound have been variable over the past two decades but appear to be increasing since the Washington Department of Health began monitoring in 1957. While there is emerging concern about blooms of *Heterosigma* and Ulvoid algae, data that address these concerns currently are lacking for Puget Sound.	(Trainer et al. 2003)
Marine Fecal Bacteria	Considerable monitoring effort contributes to the assessment of fecal bacteria in Puget Sound. No single area or basin was identified as consistently having the highest fecal bacteria levels.	(Newton et al. 2002, Schneider 2004, Determan 2009, Stark et al. 2009)
Marine Dissolved Oxygen	Identifying the ultimate causes of hypoxia and policy responses that might mitigate them remains a high priority. Valuable species such as geoduck clams and Dungeness crabs may be adversely affected by hypoxic conditions.	(Albertson et al. 2002, Roberts et al. 2008)
Marine Eutrophication	Ongoing research is working to develop detailed biophysical models of Puget Sound that will be useful for gauging the contributions of human activities to changes in nutrient levels in Puget Sound and for identifying the most effective policy interventions to prevent worsening conditions. Surveys of local experts suggest moderate to high levels of eutrophication throughout Puget Sound.	(Albertson et al. 2002, Newton and Van Voorhis 2002, U.S. Environmental Protection Agency 2006, Bricker et al. 2007, Stark et al. 2009)

Toxic Contaminants	In Puget Sound, PBT chemicals are present in apex predators such as Killer Whales as well as their primary food sources (salmon and herring) in concentrations that may harm their health and impair recovery of populations that are depressed. Juvenile life stages of fishes may be particularly susceptible to PAH toxicity. Reproductive effects of endocrine-disrupting compounds have been detected in benthic Puget sound fish, but the consequences of exposure at the population level and long-term trends are not known.	(Ross 2006, Hart Crowser 2007, Johnson et al. 2008, Myers et al. 2008, West et al. 2008, O'Neill and West 2009)
Water Quantity		
Instream Violations	All streams showed violations of instream flow rules, mostly commonly occurring in August and September.	(United States Geological Survey 2010, Washington State Department of Ecology 2010)
Seven-Day Low Flow	Decreasing trends were revealed for seven of the fourteen gauging stations analyzed.	(Mote et al. 2005, United States Geological Survey 2010)
Flow Timing	Despite significant variation in the flow timing data, four of the fourteen streams analyzed showed that flow timing has become earlier in the water year.	(Stewart et al. 2005, Barnett et al. 2008, United States Geological Survey 2010)
Daily Average Flow	There was some evidence for changes in transitional river systems over time, indicated primarily as decreasing magnitude of the spring snowmelt peak flows.	(Barnett et al. 2008, United States Geological Survey 2010)
Annual Flow	The Cedar River showed a decrease in annual flow while all other locations analyzed did not show any temporal trends.	(United States Geological Survey 2010)

Appendix A. A subset of the over 200 indicators ranked in results tables in Chapter 1A. The numerical value that appears under each of the considerations represents the number of evaluation criteria supported by peer-reviewed literature. For example, Killer whale trends has peer-reviewed literature supporting 3 out of 5 Primary Considerations criteria.

Guild	Indicator	Primary Considerations (5)	Data Considerations (8)	Other Considerations (5)	Summary Comments
Mammals	Southern Resident killer whale population trends	3	4	3	Overall good indicator of species (e.g., vital sign) but may not be best indicator of ecosystem structure & function. Also, does not respond predictably to management actions.
Mammals	Toxics in harbor seals	4	7	3	Good indicator but more sites are needed for Puget Sound.
Mammals	Backyard wildlife population trends	3	1	1	May be a good species indicator, although evidence for management relevance is lacking (but may be used to encourage) citizen action). Monitoring data sources are likely to be widely dispersed and patchy in time.
Key Fish	Total run size of salmonids (hatchery & wild)	5	8	4	Overall good indicator; peer-reviewed literature supporting most criteria.
Key Fish	Pacific herring status & trends	4	1	0	Theoretically-sound and relevant, but difficult to determine whether forage fish populations are responding to management actions or pressures or environmental conditions. Highly sensitive to uncontrollable environmental conditions. Good data for many Puget Sound stocks.
Birds	Peregrine falcon nesting surveys	3	3	4	Does not appear to be a good indicator (theoretically-unsound); lack of data in Puget Sound and variations in abundance not well understood.
Birds	Bald eagle status & trends	5	3	2	Overall good species indicator (e.g., vital sign) although data coverage and variability not well documented in Puget Sound.
Birds	Pigeon Guillemot nesting colony trends	0	0	0	Poor indicator. Difficult to find any peer-reviewed literature on pigeon guillemot population numbers or nesting colony trends.
Shellfish & other invertebrates	Dungeness crab harvest	2	6	4	May be a good indicator b/c theoretically-sound and relevant to management, but year-to-year variation in harvest is not well-understood. Long-term data available from harvest report cards.

Guild	Indicator	Primary Considerations (5)	Data Considerations (8)	Other Considerations (5)	Summary Comments
Shellfish & other invertebrates	Jellyfish	4	3	2	Theoretically-sound – jellyfish should be reliable indicators of trophic energy transfer & community composition. Responds predictably to actions and pressures, and may be especially relevant to understanding the status of forage fish. Historical data is limited, although still a promising indicator.
Plants	Phytoplankton biomass	3	1	1	Good indicator of pelagic ecosystems, especially nutrient cycling and the amount of primary production. Only limited amounts of historical data available. Provides similar information as chl a so choose one to avoid redundancy.
Marine habitat	Eelgrass status & trends	2	4	2	Theoretically-sound but difficult to determine what causes changes in abundance (natural vs. anthropogenic).
Marine habitat	Aggregation/deposition zones	3	5	1	Theoretically-sound. Could be a good leading indicator of habitat forming processes.
Interface habitat	Riparian habitat	5	6	3	Very good indicator of riparian ecosystem health including habitats and species. Evidence that restoration increases riparian habitat area. Good data for Puget Sound. May best be used as part of an integrative assessment of habitat change in the region.
Water quality	Dissolved Oxygen marine	5	4	4	DO levels affect marine species. Selected areas of low DO in Puget Sound are of great management concern. Management actions may have some impact on anthropogenic nutrient inputs to PS. Generally clear reference points and targets though may vary depending on historic conditions. Some areas of localized coverage, though not good historical record.
Water quality	Violations of DOE instream flows	3	8	3	Good indicator of management effectiveness. Instream flow rules may not be proctective of ecology. Good range of possible management responses. Good flow data. Instream flow rule only established on limited number of streams in Puget Sound. Somewhat redundant with 7-day Average Low Flow and Number of Minimum Day Flows per Year