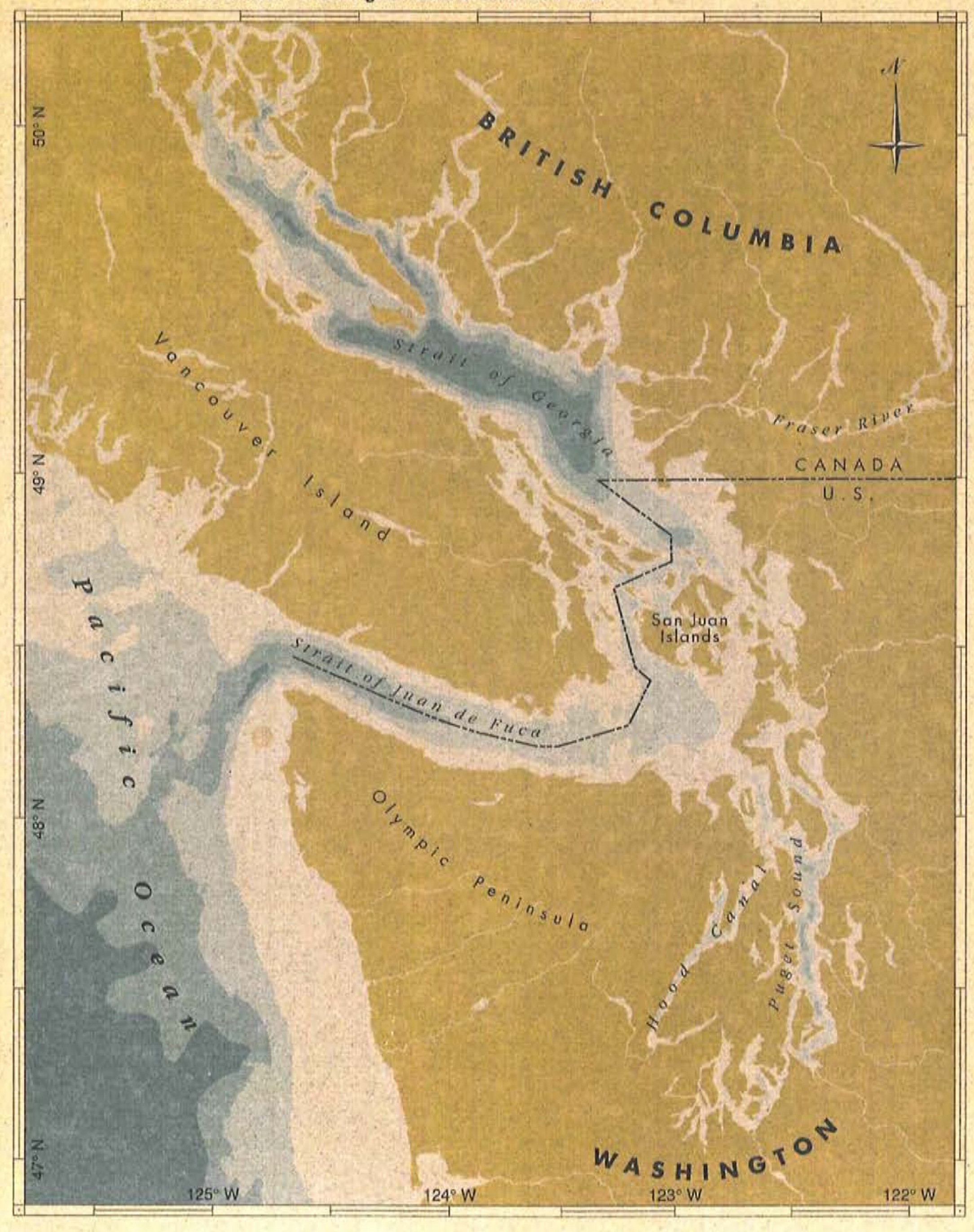
The Shared Marine Waters *of* British Columbia *and* Washington

Report to the British Columbia / Washington Environmental Cooperation Council by the British Columbia / Washington Marine Science Panel



The Shared Marine Waters of British Columbia and Washington

A Scientific Assessment of Current Status and Future Trends in Resource Abundance and Environmental Quality in the Strait of Juan De Fuca, Strait of Georgia, and Puget Sound

Report to the British Columbia / Washington Environmental Cooperation Council by the

British Columbia / Washington Marine Science Panel

August, 1994

Province of British Columbia   The State of Washington

British Columbia / Washington Marine Science Panel

Chair:

Dr. Andrea Copping, Washington Sea Grant Program and
Pacific Northwest Regional Marine Research Program,
University of Washington, Seattle, WA

Dr. Richard Beamish, Department of Fisheries and Oceans,
Pacific Biological Station, Nanaimo, BC

Dr. Curtis Ebbesmeyer, Evans-Hamilton, Inc., Seattle, WA

Dr. Chris Garrett, School of Earth and Ocean Science and
Department of Physics and Astronomy,
University of Victoria, Victoria, BC

Dr. Bruce McCain, National Marine Fisheries Service,
Northwest Fisheries Science Center, Seattle, WA

Dr. Tom Pedersen, Department of Oceanography,
University of British Columbia, Vancouver, BC

Report Prepared In Association with
Richard Strickland, School of Oceanography,
University of Washington, Seattle, WA

This publication was funded in part by the Pacific Northwest Regional Marine Research Program, grant #NA26RM0180, and Washington Sea Grant Program, grant #36RG0071, from the National Oceanic and Atmospheric Administration, Office of Sea Grant and Extramural Programs, U.S. Department of Commerce. The views expressed herein are those of the authors and do not necessarily reflect the views of NOAA or any of its subagencies.

Table of Contents

Preface

The Formation, Activities and Mandate of the Marine Science Panel

On May 7, 1992, Premier Mike Harcourt and then–Gov. Booth Gardner signed the first Environmental Cooperation Agreement between British Columbia and Washington state. The agreement stated that "...environmental concerns and impacts respect neither physical nor political boundaries..." and that the province and state will "...promote and coordinate mutual efforts to ensure the protection, preservation and enhancement of our shared environment for the benefit of current and future generations."

The British Columbia/Washington Environmental Cooperation Council was formed shortly thereafter. This body identified water quality in the Georgia Basin/ Puget Sound region as a high-priority issue requiring immediate and joint attention. The Council directed formation of the Puget Sound/Georgia Basin Work Group, a group of representatives from state, provincial and federal water quality agencies, with a mandate to recommend and implement efforts on information sharing, monitoring and research for transboundary waters. On April 5, 1993, Premier Harcourt and Gov. Mike Lowry agreed to establish a joint panel of Canadian and United States marine scientists to evaluate the marine waters. The Environmental Cooperation Council selected the Marine Science Panel members (the authors of this report) from a group of nominees in July 1993.

The British Columbia/Washington marine science panel was asked to collaborate with the Work Group in organizing a scientific symposium, which was held in Vancouver, B.C., on January 13 and 14, 1994. The symposium featured 13 invited presentations by Canadian and American scientific experts on a broad range of topics concerning the shared waters, including physical oceanography, point source loadings and trends, nutrients and plankton, sediments, birds and marine mammals, shellfish and invertebrates, benthos, fish stocks, habitat loss, toxic algae and bacteria, and human health concerns. The meeting was attended by about 200 people from

Canadian and U.S. government agencies, universities, non-governmental organizations and industry. Presenters at the symposium and their co-authors prepared a series of excellent scientific review papers, which has been published as a separate technical report, and which forms an important basis for this report (Wilson et al., 1994).

To obtain further information beyond that presented at the symposium and in the review papers, the panel solicited written and oral briefs from a broad range of individuals and groups. Briefings were held at the University of British Columbia on January 19, at the University of Washington on January 20, and at the University of Victoria on February 18. The panel also drew on scientific journals and books and a range of technical reports that had been prepared previously for various levels of government.

The panel was specifically charged by the Environmental Cooperation Council to produce an independent scientific report on the current condition of, and trends in, the marine waters shared by the province and the state. Our report comprises this preface and eight chapters. Chapter 1 lays out some of the principles that the panel followed in reaching its conclusions, and Chapter 2 briefly describes the region. Subsequent chapters review specific aspects of the marine environment and provide the science used to formulate the recommendations of the final chapter.

The panel's work and this report focused on several questions posed by the Environmental Cooperation Council about natural processes, resource populations, contamination and future trends in the shared waters. These questions are posed below, along with the chapters in which they are addressed. To address the questions fully, some material has been repeated in several chapters.

Questions Posed by the Environmental Cooperation Council

1) What transport mechanisms exist for transboundary exchange of human-caused contamination between the Strait of Georgia, Puget Sound and Juan de Fuca Strait? To what extent can spills or discharges to these waters be transported across the international border and cause harm? (See Chapter 3.)

2) What do we know about the status of the transboundary population of invertebrates, finfish, birds and mammals of the Strait of Georgia, Puget Sound and the Strait of Juan de Fuca? Are there long-term trends in the populations, and if so, what are the likely causes? (See Chapter 4.)

3) To what degree do the biological resources of the Strait of Georgia, Puget Sound and Juan de Fuca Strait move across the international border? Biological resources include invertebrates, finfish, birds and marine mammals. (See Chapter 4.)

4) What evidence is there for harm from transboundary pollution and other anthropogenic influences to the habitats, aquatic biota, human uses or public health of the Strait of Georgia, Puget Sound and the Strait of Juan de Fuca? As compared to five or 10 years ago, is the severity of harm greater, less or the same? (See Chapter 5.)

5) Given forecasts of human population increases for the lands that drain to the Strait of Georgia, Puget Sound and the Strait of Juan de Fuca, and assuming little or no change to the current level of pollution control, harvest management and land use management activities, will the amount or severity of harm from transboundary pollution to the habitats, aquatic biota, human health or public health be greater, less or the same in 20 years? Are the transboundary populations of biological resources associated with the Strait of Georgia, Puget Sound and the Strait of Juan de Fuca anticipated to increase, decrease or stay the same in 20 years? (See Chapter 6.)

6) What components of the transboundary marine ecosystem appear to be the most sensitive to harm from human activities? (See Chapter 6.)

7) What types of harm appear to be most serious and should be the focus of monitoring, research and management activities over the next 10 years? (See Chapter 7.)

8) What indicators are recommended for future state-of-the-environment reporting for the transboundary marine ecosystem? (See Chapter 7.)

9) Which types of human activities (for example, discharges or spills of toxic compounds, nutrients, pathogens, physical land modification) need the most management attention? (See Chapter 8.)

The panel's efforts are proceeding in parallel with a similar process operating under the North American Free Trade Agreement (NAFTA). The environmental side agreement to NAFTA created a Council for Environmental Cooperation composed of senior environmental officials from the United States, Canada and Mexico. According to Article 10 of this side agreement, the council has many functions resembling those of the British Columbia/Washington Environmental Cooperation Council. These functions include (paraphrased): establishing expert working groups, seeking advice of outside experts, serving as a forum for transboundary environmental issues, promoting transboundary cooperation and information exchange on environmental issues, recommending actions to further transboundary environmental protection and research, and advising on transboundary environmental disputes and legal actions.

Acknowledgments

The panel gratefully acknowledges the help we received from the authors of the papers presented at the January symposium on the BC/WA Marine Environment in Vancouver. Without the efforts and expertise of these 37 scientists, we could not have pulled together the information necessary to prepare this report. Similarly we wish to thank those who took the time and trouble to prepare written and oral briefs for the panel. The authors and the titles of their papers, and those who prepared briefs, are listed at the end of this report. We received helpful comments on our draft report from John Armstrong, Karl Banse, Ralf Brinkhurst, John Calambokidis, John Dohrmann, Ben Kangasniemi, Blair King, Paul Harrison, Lyndal Johnson, Colin Levings, Mary Mahaffy, Chris Prescott, Jake Schweigert and members of the Puget Sound/Straits of Georgia Working Group. We appreciate the efforts of Lynn Bailey, John Dohrmann, Brendan Holden, Carol Jolly, Ben Kangasniemi and Wendelin Fraser for organizing and taking care of the logistic details of the Vancouver symposium and the briefing sessions. We want to thank the members of the Environmental Cooperation Council, Tom Gunton and Mary Riveland, for their wisdom in setting this process in motion, and the Honourable Moe Sihota, British Columbia minister of the environment, for his insights at the January symposium. Finally, we are grateful to each of our respective organizations and to our colleagues for their support and enlightened discussions.

Summary

Background

The British Columbia/Washington Marine Science Panel was created in 1993 under the 1992 Environmental Cooperation Agreement between British Columbia and Washington state. The panel was asked to evaluate the condition of the marine environment in the Strait of Georgia, Strait of Juan de Fuca and Puget Sound region on both sides of the international boundary. For purposes of this report, this region is called *the shared waters*, and the area in the immediate vicinity of the international boundary is called *the transboundary waters*.

The panel reports to the British Columbia/Washington Environmental Cooperation Council, which was formed as part of the Environmental Cooperation Agreement and which identified water quality on both sides of the boundary as a high-priority issue requiring immediate and joint attention. To guide its inquiries, the panel addressed several questions about natural processes, resource populations, contamination and future trends in the area. In early 1994, the panel participated (with a Work Group supporting the Environmental Cooperation Council) in a scientific symposium featuring invited presentations by Canadian and U.S. scientific experts on a broad range of topics. The scientific review papers from this symposium have been published as a separate technical volume and form an important basis for this report.

The panel based its recommendations about conditions in the shared waters and proposed remedial actions on scientific evaluation of actual harm done and on the risks that harm will be done, rather than on popular perceptions or political considerations. Where insufficient information is available to evaluate harm and risks, a precautionary approach and additional research are recommended.

Estuarine Waters

The shared waters constitute a system of estuaries—embayments where fresh water enters salt water. In most of the shared waters, on average, there is a two-layered pattern of seawater flow typical of estuaries. Water in the surface layer flows gradually seaward along the surface, carrying fresh water from rivers, and water in a subsurface layer flows gradually landward, carrying saline water from the Pacific Ocean. The high-energy actions of winds, tidal currents and mixing in narrow and shallow passages complicate this average picture. This circulation pattern creates a vigorous exchange of water, salt, plant nutrients and plankton within the shared waters and across the international border. Dissolved, floating and neutrally buoyant contaminants discharged by humans at the sea surface, in the water column and along the seafloor also are carried by this exchange.

The two-layered flow in the shared waters gradually replaces resident water with river and ocean water, and so flushes waterborne contaminants to sea over time scales of about one month to one year. The rate of basin flushing is largely determined by river discharge, which provides the basic force for the estuarine circulation, and by tidal exchange. Dissolved contaminants, such as dioxins, furans and associated compounds, may accumulate in poorly flushed basins close to major contaminant sources, but in most of the shared waters, flushing power is sufficient that human input of most contaminants causes negligible harm.

Because of abundant natural supplies, dissolved nutrients do not limit plant growth in most of the shared waters. Therefore, human nutrient discharges (mainly in sewage effluent) do not appear to cause overgrowth of algae that impairs water quality, except in certain poorly flushed embayments. In addition, because of abundant natural supplies of dissolved oxygen, human discharges of substances generating Biological Oxygen Demand (BOD) do not deplete oxygen supplies to a degree that impairs water quality, except in certain poorly flushed embayments. The predominant discharges of nutrients and BOD into the shared waters are municipal sewage effluents from Seattle and Vancouver. Even in the waters off Victoria, the local sewage contribution is estimated to be only about 5 percent of that from the two larger cities.

Four areas of caution regarding the condition of the open water column are indicated, however.

1) Diversion or alteration of river flow and other land uses could affect temperature and salinity conditions for marine biota in the shared waters. These changes also might alter water movements and flushing times in the basins in ways that have not been studied. Diversions could harm both habitats and biota in watersheds.

2) The vigor of exchange processes in the shared waters means that oil spilled in large quantities anywhere in the transboundary waters, including along the outer coast of Washington, is likely to be spread widely throughout the system before cleanup can be implemented.

3) Relatively little is known concerning human bacteria, viruses and protozoan pathogens discharged from both sewage outfalls and nonpoint sources. Untreated human fecal material entering marine waters near swimming and shellfish harvesting beaches merits additional research and monitoring, until science is able to identify, and render harmless, potentially virulent pathogens.

4) The forces driving exchange in the shared waters are known to fluctuate over cycles of 10-20 years. These cycles are likely to affect river flows and biological production in the shared waters. They are also likely to make it more difficult to manage fish, shellfish, birds, mammals and the natural food webs supporting them because existing management regimes typically presume that environmental conditions are constant.

Status of Marine Biota

Most marine populations are healthy and abundant in the shared waters, notably commercial and recreational fishes, marine birds and waterfowl, and marine mammals. However, several species are threatened or in danger of extinction, including numerous Puget Sound runs of salmon and steelhead, the marbled murrelet, and the Steller sea lion. Species with depleted populations include several salmon stocks in Puget Sound and chinook salmon in the Strait of Georgia, marine fish such as lingcod and rockfish on both sides of the border, Pacific hake in Puget Sound, harlequin ducks, harbor and Dall's porpoise, and raptors such as osprey. Important prey species also merit concern, including baitfish such as herring and smelt, intertidal and shallow subtidal invertebrates, and plankton.

Most salmon stocks in the Strait of Georgia are healthy. However, chinook catches declined in the 1980s, despite efforts to rebuild the stocks, and numbers of wild coho surviving to spawn have declined recently. In Puget Sound, about half of all the wild salmon stocks that can be assessed are considered healthy. Of the other half, about 80 percent are considered depleted, and 20 percent are critically low. In both the Strait of Georgia and Puget Sound, possible explanations for declines in wild salmon returns include freshwater and estuarine habitat loss, changing environmental conditions and direct effects of fishing pressure. Indirect effects related to hatch-

ery fish, such as competition between stocks and higher reproductive survival of hatchery fish, may be confounding efforts to rebuild wild stocks.

Stocks of Pacific herring are abundant in the Strait of Georgia, but their abundance fluctuates in Puget Sound and is now at low levels. Lingcod, which have been overfished and are now at critically low levels in both Puget Sound and the Strait of Georgia, might benefit from a program of habitat reserves to relieve fishing pressure. Other species of concern are hake and pollock in Puget Sound, and rockfish, Pacific cod and some flatfish in both areas. Declines in Puget Sound hake and rockfish appear to be the result of overfishing. There is concern that rockfish also are being overfished in the Strait of Georgia.

Most non-game invertebrate populations are believed to be sustaining their populations in the shared waters, although less is known about these species than about species that are harvested recreationally or commercially. Some nongame shellfish species recently have become the targets of unregulated harvesting. Traditionally harvested invertebrates also are generally sustaining their populations, but some areas of concern exist. The major problem on both sides of the boundary is the closure or restriction of harvesting on bivalve shellfish beds because of human health concerns related to contamination by fecal coliform bacteria. This problem is spreading as a direct result of poor residential and agricultural waste handling practices by the expanding human population. In addition, abalone populations are low, and abalone fisheries have been closed in British Columbia, apparently because of overfishing. Geoducks need to be managed carefully to prevent similar problems. Some signs of overfishing of shrimp and prawns are present in a few areas of the Strait of Georgia.

Some bird populations have increased in recent years (Canada geese, glaucous-winged gulls, ring-billed gulls, caspian terns, pelagic and double-crested cormorants, bald eagles, peregrine falcons and osprey), and some remain relatively unchanged. A few are depleted, including harlequin ducks and marbled murrelets, as well as common murres and tufted puffins, for reasons that may include habitat destruction and incidental capture in gillnet fisheries.

Most marine mammal populations appear healthy, with harbor seal, California sea lion, elephant seal and orca populations increasing. Nevertheless, marine mammals are vulnerable to the impacts of human disturbance and habitat loss and may be killed incidental to commercial fishing operations. Humans may be disturbing lesser-known species such as harbor and Dall's porpoises, but the effects are uncertain because these species receive disproportionately little research attention.

The vigorous exchange of marine waters within the area might be expected to sustain populations of marine biota by transporting organisms from areas where they

are abundant to areas where they are depleted. The migratory patterns of some species, apart from water movements, do foster such exchanges. For example, there is some exchange of migratory wild and hatchery-reared salmon stocks between Puget Sound and the Strait of Georgia. Marine birds, shorebirds, and waterfowl move freely through the shared waters, which are located on the Pacific flyway. Marine mammals also freely cross the border.

However, distinct populations of some species do not appear to mix among the straits of Juan de Fuca and Georgia and Puget Sound. Hake and herring stocks, for example, are depleted in Puget Sound and apparently are not replenished by Canadian fish. Transport across the boundary could occur, however, and be masked by predation or other factors. Most adult invertebrates cannot cross the border, and although many of these animals have planktonic larvae that are seemingly susceptible to transboundary exchange, there is little evidence that these life stages successfully settle across the international boundary.

Contaminated Sediments

Most chemical contaminants entering the shared waters bind to particles, which accumulate on the seafloor within their basin of origin. There appears to be little natural transport of contaminated sediments between basins or across the international boundary, but dredge spoil disposal does spread contaminated material to some extent. As a result, significant contamination is confined to sediments close to contaminant sources such as point source discharges (for example, industrial facilities and sewage treatment plants) and collective discharges of nonpoint source contaminants (for example, storm drains and combined sewer overflows). High concentrations of toxic contaminants are found mainly in nearshore sediments near urban areas in British Columbia and Washington.

Chemical contaminants are found in bottomfish and their prey organisms within the areas of contaminated sediments. These fish suffer an increased incidence of liver tumors and other liver damage and may not be able to reproduce normally. The effects of these conditions on fish populations basin-wide are uncertain, however. Salmon migrate through areas having contaminated sediments, but contaminants are not known to harm salmon populations significantly in the shared waters because declines in salmon populations have been similar in both contaminated and relatively uncontaminated areas. Prey species in the shared waters show an abnormal community structure in contaminated areas, frequently being dominated by hardy,

opportunistic organisms. These same sediment areas, in their natural state, contain the greatest diversity and abundance of organisms.

Available data are not definitive, but conditions appear to be improving at some industrialized areas in Puget Sound. Contaminant levels and liver damage in English sole from Elliott Bay (Seattle) have declined over the last decade, suggesting that more stringent regulation of combined sewer overflows, hazardous waste disposal and industrial point sources has succeeded. High concentrations of contaminants have been found in the past in harbor seals (from southern Puget Sound), harbor porpoises and orcas. While the effect of these contaminants on local marine mammals is uncertain, they have been linked to reproductive failure and suppression of the animals' immune systems elsewhere in the world. Chlorinated hydrocarbon levels in eggs from great blue heron and selected cormorant species monitored in the Strait of Georgia have declined from maximum levels in the 1970s.

The incidence of chemical contamination and fish disease in Elliott Bay remains among the highest in the United States, however, suggesting that sediments recover from contamination slowly. Furthermore, aromatic hydrocarbons (byproducts of petroleum use) from nonpoint sources pose continuing problems because they may be increasing with the human population and urbanization. At non-urban sites in Puget Sound, sediment contamination and fish disease levels appear unchanged over the past 15 years, but toxicants probably will increase moderately as the human population increases.

Urban and/or industrialized areas pose the greatest possibility of human health effects resulting from chemical contamination of seafood, but actual health risks from this source appear to be small or undetectable in the overall human population. Shellfish beds are widely contaminated by human fecal discharges and toxic algal blooms (apparently not related to human activities). Both problems appear to be increasing—fecal pathogen contamination is spreading in rural areas with little or no sewage treatment, failing septic fields and runoff from agriculture or storm water. Large areas of the shared waters are monitored and closed to shellfish culture and harvesting, and under this management, human health risks are low.

Fish and Wildlife Habitat

The destruction or degradation of natural habitats consistently appears as a probable cause for depleted populations of marine organisms. The habitats most vulnerable to disturbance, and those suffering the most harm, are those in closest

proximity to human activities. Ironically, scientists believe that these are also some of the most critical habitats in the basin for threatened fish and wildlife populations.

Nearshore estuarine wetland habitat—primarily vegetated intertidal and shallow subtidal habitat near river mouths—has been most severely affected, primarily in urban areas and secondarily in suburban and rural areas. Estuarine wetlands are critical feeding and nursery habitats for numerous species of fish, including salmon, bottomfish, and herring and other baitfish, as well as waterfowl and shorebirds. They support critical links in the marine food web for the entire estuarine system. Destruction of wetlands has been extensive in Puget Sound (estimated at 58 percent), and less so in the Strait of Georgia (18 percent). Habitat losses have been much greater, however, in urban bays such as the North Arm of the Fraser estuary (96 percent), and the Duwamish and Puyallup estuaries (99 and 100 percent, respectively). Even when such habitat is not destroyed outright by careless shoreline development, it may be degraded by contamination and human disturbance.

Other habitats in the shared waters also are vital to specific organisms, for example submerged rocky reefs (for lingcod and rockfish) and open waters (for diving birds such as murres and mammals such as porpoises). While these habitats are less susceptible to outright destruction, they also may be degraded by contamination and human disturbance. In addition, key organisms depend on habitats in the rivers feeding the shared waters and in the watersheds of those rivers. For example, diversion of rivers and poor forest practices are believed to cause serious harm to salmonid populations. The marbled murrelet, a seabird that nests in old-growth forests, has been declared a threatened species in the United States because of habitat degradation.

The relative sensitivity of ecosystem components to harm from human activities is evaluated in Table 1. Overall, habitat for fish and wildlife is judged to be most sensitive, and marine biota, sediments and benthic organisms also are judged to be quite sensitive to harm. In contrast, under most conditions the open water column of the shared waters and human health are judged to be relatively insensitive to harm from human activities.

SUMMARY TABLE 1

Components of the shared waters most sensitive to harm from human activities

SENSITIVITY	COMPONENT
HIGH	Fish and wildlife habitat
↑	Marine biota
	Sediments and benthic organisms
	Marine water column
LOW	Human health

The Shared Waters in 2014—"Business as Usual" Scenario

Table 2 presents a synopsis of present conditions of key ecosystem components on both sides of the border. The conditions range from very good to very poor, depending on component and location. Table 2 also presents the panel's judgment about how these conditions will have changed 20 years hence given little or no change in the current level of pollution control, harvest management and land use management. Current management programs are responsible for maintaining the good quality of some components of the shared waters system, such as human health. We emphasize that our judgments are qualitative *projections* of existing population, contamination and resource use trends, and not necessarily *predictions* of actual conditions in 2014.

The scenario reflects a pessimistic outlook because projected increases in human population would appear to outweigh the trend toward lower per capita discharges of many contaminants and uses of many resources. The improving trend in sediment contamination may diminish or even reverse over the next 20 years, for

example, as nonpoint source inputs increase with population growth. The conditions of wild salmonid and marine fish populations in Puget Sound, and of estuarine wetland and upstream riverine habitats around Puget Sound, are projected to be "slightly" rather than "much" worse by 2014 only because they cannot get much worse than they already are.

Furthermore, no one of these types of harm exists in isolation from the others. In reality, the effects of multiple environmental stresses are cumulative. Examining types and magnitudes of harm separately rather than cumulatively within an ecosystem paints an over-optimistic picture.

Loss of habitat is the single most serious threat, although irreversible changes to the regional ecosystem also could arise from the inadvertent introduction of exotic species, from continued overharvesting of fish and wildlife or from river diversion projects. Conditions in British Columbia are generally better than in Washington, and probably will continue to be, because the Canadian portion of the shared waters has a larger surface area, longer shoreline, and smaller human population. However, some habitats and populations in British Columbia are as heavily affected as those in Washington.

Because present management practices have not prevented depletion of many wild salmonid and marine fish populations in Puget Sound, they offer little prospect of restoration. Reduced shellfish populations in the shared waters, such as abalone, are unlikely to recover under present management, and many other populations that are now healthy will decline without more vigilant management. A continued lack of regulation of harvesting will lead to declines of non-game marine invertebrate species as well.

Human activities affecting birds, especially disturbance of nesting colonies and loss of habitat, are likely to become more severe in the next 20 years, taking a toll on some populations. Marine mammals are affected by variations in food supply and by food competition and disturbance from humans, the latter being on the increase. It is difficult to project marine mammal populations 20 years hence, but to the extent that their absence may result from disturbance, harbor porpoises probably will not return to Puget Sound. Populations of harbor seals and California sea lions throughout the region are likely to stop increasing due to limiting food supplies or disease.

Some issues probably will not grow significantly worse by 2014. For example, present management appears adequate to minimize human health risks from contaminants and algal toxins in seafood, even as populations expand. Most waterborne contaminants in the future will probably continue to cause significant problems only in local areas.

SUMMARY TABLE 2

Current and projected status of components in the shared waters:
"Business as usual" scenario[1] and "optimal future" scenario[2]

	PRESENT STATUS		"BUSINESS AS USUAL" Status Change, 1994-2014		"OPTIMAL FUTURE" Status Change, 1994-2014	
COMPONENT	WA	BC	WA	BC	WA	BC
AQUATIC HABITATS						
Vegetated shores	very poor	good	slightly worse	much worse	unchanged	unchanged
Unvegetated shores	acceptable	good	much worse	slightly worse	unchanged	unchanged
Rivers upstream	poor	acceptable-good	slightly worse	slightly worse	unchanged	unchanged
Subtidal	good	good	unchanged	unchanged	slightly better	slightly better
Urban sediments	very poor	poor	unchanged	unchanged	slightly better	slightly better
Water column	very good	very good	unchanged	unchanged	unchanged	unchanged
LIVING RESOURCES						
Salmonids	very poor	acceptable-good	slightly worse	slightly worse	slightly better	slightly better
Marine fish	very poor	good[3]	slightly worse	slightly worse	slightly better	slightly better
Bottomfish in urban bays	poor	good[4]	unchanged	unchanged	slightly better	slightly better
Commercial/recreational invertebrates	good	good	slightly worse	slightly worse	slightly better	slightly better
Birds	mixed[5]	mixed	slightly worse	slightly worse	slightly better	slightly better
Marine mammals	mixed[6]	mixed	slightly worse	slightly worse	slightly better	slightly better
HUMAN HEALTH						
Safety from direct contaminant and pathogen exposure	very good	very good	slightly worse	slightly worse	unchanged	unchanged
Safety from contaminated seafood	good	good	slightly worse	slightly worse	slightly better	slightly better
Safety from toxic algae	good	good	slightly worse	slightly worse	slightly worse	slightly worse

[1]This simplified scenario assumes that management measures to reduce contamination and resource depletion are instituted and enforced immediately.

[2]This ideal scenario assumes that management measures to reduce contamination and resource depletion are instituted and enforced immediately.

[3]Except lingcod [4]Except portions of Vancouver Harbor [5]Except common murres and marbeled murrelets [6]Except Dall's and harbor porpoise

SUMMARY TABLE 3

Recommendations for actions and effective management to protect the shared waters (ranked in order of priority)

PRIORITY	ACTIONS
Highest	Minimize estuarine wetland habitat losses
	Establish marine protected areas
	Protect marine animals and plants
	Minimize large fresh water diversions
	Minimize introduction of exotic species
	Control toxic wastes
	Prevent large oil spills

PRIORITY	EFFECTIVE ENVIRONMENTAL MANAGEMENT
Highest	Strategic planning
	Comprehensive program review
	Monitoring/research/ management framework
	Increased public and scientific communication
	Freedom of scientific communication

However, a major oil spill is statistically likely in the next 20 years and would almost certainly cause significant harm to shoreline habitats and wildlife (especially birds) on both sides of the boundary, some of which would still be evident 20 years afterward. In addition, problems associated with nonpoint source contamination (from urban runoff and agricultural and domestic sources), overharvesting, toxic algal blooms and multiple-use conflicts are expected to continue or intensify in the next 20 years.

One or more issues about which little is known today also may emerge as important in the next 20 years. Possible examples include tributyl tin (TBT), surfactant compounds, contaminants in the sea surface microlayer and the introduction of exotic organisms. Furthermore, the effects of multiple environmental stresses are cumulative and may interact in unforeseen ways to exacerbate existing conditions or hinder recovery.

The Shared Waters in 2014—Optimum Future Scenario

Table 2 also presents an optimum future scenario for the state of the shared waters in 20 years. This "best-case" scenario supposes that appropriate management measures are taken immediately to reduce contaminant input and resource depletion significantly and to allow the system to recover by natural processes. This scenario does not account for the time that elapses in the normal process of decision-making, nor for the time needed to build or improve facilities that enhance water quality. These activities can span time intervals of the same order as those required for the recovery of the natural system once action is taken—i.e., decades.

Appropriate management measures could arrest or even reverse the present downward trend in the condition of many components of the shared waters. For example, if conservative management strategies were adopted, depleted marine fish stocks in U.S. waters and stressed salmonid populations could recover at least partially, to the extent that natural environmental variability permits. Harvest limits also could allow recovery of depleted abalone populations and prevent depletion of nongame invertebrates and of long-lived recreational and commercial species that recover slowly, such as geoducks.

There are limits, however, to what even effective management could accomplish in the next 20 years. Minimizing habitat destruction and degradation, for example, would still do little more than to preserve the troubled status quo. Furthermore, even if overharvesting, habitat destruction and river diversion were to be eliminated, prospects for restoring depleted Puget Sound wild salmon populations over the next 20 years are limited, given losses of genetic resources. Stocks of some long-lived rockfish that currently are very low on both sides of the border also probably would take longer than 20 years to recover. Furthermore, the prospect of cyclical or long-term changes in climate may alter the ability of the environment to support some fish and wildlife populations.

If habitat loss and disturbance of bird colonies could be controlled and a large oil spill can be prevented, healthy bird populations should remain so, and depleted populations could recover substantially. With similar controls, most marine mammal populations may remain healthy for 20 years, although to the extent that their absence may result from disturbance, it seems unlikely that harbor porpoises will return to the Sound.

With proper management, largely by control of nonpoint sources of contaminants, the improving trend in sediment contamination could be extended despite population growth. Contamination and community alteration of bottomfish and invertebrates could, in turn, recover substantially in urbanized areas if contamina-

tion of their habitats is reduced. Shellfish will purge chemical and pathogenic contaminants very quickly if sources are controlled. Source controls, monitoring and education could further reduce the limited threat to public health posed by contaminated sea water, sediments and seafood, although they cannot prevent naturally occurring toxic algal blooms.

Finally, so long as oil is transported through the shared waters, even very vigorous preventive efforts cannot ensure that a large accidental oil spill will not happen. Conservative management of habitat, harvest and contaminants would minimize the potential cumulative effects resulting from these stresses combined with an oil spill. Although evidence of a large oil spill would disappear from most parts of the shared waters within 20 years, harm from such a spill might still be evident in sheltered estuarine wetland habitats and in already stressed populations of diving birds such as common murres and tufted puffins.

Management Priorities and Recommendations

The panel's ranking of marine environmental issues in the shared waters, in descending order of priority for managment action, is shown in Table 3. In ranking these issues and making specific recommendations to address them, the panel gave primary importance to *recovery time*—the period required for the ecosystem to respond to control measures and for harm to be adequately reduced. Recovery times of less than three years are *short*, three to 30 years are *medium*, more than 30 years are *long*; if there is no recovery over a century or more, harm is *irreversible*. Harm that is irreversible or requires a long recovery period demands immediate and conservative management attention to minimize all further impacts.

Where gaps remain in our knowledge of processes, resources and problems or potential problems, we cannot judge the degree of harm or risk without further research. In the meantime, we must proceed with caution when allowing degradation or contamination in the shared waters, following our best understanding of how long the system will take to recover from potential harm. Additional exploratory research and monitoring in these areas is essential.

Some sources of contamination cause only minor environmental harm that is quickly repaired and/or is beyond our capabilities to remedy. We can afford to study such minor problems before action is necessary. Significant expenditures of public funds on such problems should be based strictly on the cost-effectiveness of the proposed remedial actions.

Two additional criteria also played a role in the panel's evaluations: preventability of harm and cost required to restore or mitigate loss of a resource. Activities deserving the most attention are those that cause the longest-lasting and greatest harm, are most preventable and are most expensive to remedy.

The following specific recommendations are listed in order of priority.

·*Preventing destruction of nearshore estuarine habitat* is accorded the highest priority because it causes significant, irreversible harm, is technically preventable and is extremely expensive or impossible to restore. Attempts to create new habitat to offset losses are not yet reliable. To sustain marine fish, invertebrate, bird and mammal populations, the panel recommends that existing natural fish and wildlife habitat—including estuarine and upland wetlands, watersheds and river flows—be preserved to the maximum extent possible.

·*Establishing marine protected areas,* which would set aside a portion of each major type of marine and nearshore habitat in the shared waters from human activities, is recommended as a measure to protect both habitat and biota. These protected areas would most effectively guard against further human encroachment, permit recovery of depleted fish stocks, and provide refuge for marine mammals and birds.

·*Protecting fish and shellfish* populations is necessary, especially in the case of depleted or threatened stocks, whose recovery may be very slow or impossible and very costly. Although such population declines should be highly preventable, existing harvest restrictions have not prevented widespread losses, so more extensive measures are necessary to protect both populations and their habitats.

·*Preventing major diversions of fresh water* is urged because these diversions are a form of habitat destruction and could cause changes in estuarine circulation. In addition to harming salmonids, river diversions might cause unforeseen effects on water conditions and movements and marine biota in the shared waters.

·*Minimizing the introduction of exotic species,* which can unpredictably and irreversibly alter natural species abundances and degrade habitat, is necessary in order to maintain the ecological viability of natural communities. Implementing very conservative measures in the short term could avert very expensive consequences in later years.

·*Minimizing toxic contamination of marine sediments and biota,* which occurs at present from ongoing discharges of toxic wastes from point and nonpoint sources, is necessary to avoid deleterious effects to marine biota and to assure a safe seafood

supply for human consumption. The cost of eliminating all toxic discharges would be prohibitive, but reduced levels of contamination can be reached by careful controls on toxic sources.

·*Preventing large oil spills* promises to be much less expensive and much more effective than the alternative of shoreline cleanup after the fact. The shared waters would recover over a medium time scale from the harm caused by a large spill, but the harm could be extensive in the short term and is unnecessary and preventable.

Recommendations for More Effective Environmental Management

The best prospects for implementing the actions recommended above, and approaching the optimum future scenario for the shared waters in the year 2104 (Table 2), would be realized if both British Columbia and Washington federal, state and local agencies and the public would communicate freely and work jointly in planning, research and monitoring, and resource management.

·*Strategic planning* for the region's resources, encompassing all aspects of the marine environment and the lands and human actions affecting it on both sides of the boundary, is essential for enhancing the condition of the shared waters. No new bureaucracies need be created; instead, by joint cooperative action, clear guidelines can be established clarifying the responsibilities and authority of each of the multitude of provincial, state, federal and regional/local government entities.

·A *comprehensive programmatic audit* is recommended to review the goals, accomplishments and resource allocations of programs and management activities influencing the shared waters and resources. Such an audit is needed immediately to determine why existing policies have failed to protect critical resources. The audit should be conducted by an independent body, to be free of influence and the potential to capitalize on its findings. The body could be selected from or modeled after examples such as the U.S. National Research Council or General Accounting Office or Canada's Office of the Auditor General.

·A *coordinated research, monitoring and management framework* could both answer research questions and supply the long-term data sets needed to answer ecological questions and assess the state of the transboundary waters. Habitat preservation, fish and wildlife protection, and waste disposal are priority subjects for this monitoring and research effort. The goals of this monitoring research and the proto-

cols for collecting data should be clearly and publicly defined. The resource management framework must be guided by scientific principles of risk and cost-benefit, not political dictates. An external, independent peer review of all monitoring, research and management programs must be scheduled at five-year intervals, and quality control of all data collected by both public and private entities must be strictly enforced.

·*Increased communication* across the border—among scientists and between scientists and the public—should characterize the planning, monitoring, research and management processes. The future of the shared waters can be greatly enhanced if information is actively exchanged among professionals in both British Columbia and Washington and disseminated to the public. The informational environment should be cultivated through numerous joint activities including research, regular scientific conferences and educational programs. Scientists should be encouraged to share their findings and views with the widest possible audiences.

·*Freedom of discussion* is needed so that scientists are not constrained in voicing their scientific opinions, even on controversial issues. Airing of opposing views is an important part of scientific progess and public policy discussion. The public good is not served when senior officials dictate what is acceptable speech by scientists.

1. Philosophy of the Panel

In deliberating the questions from the Environmental Cooperation Council, we have regarded the shared marine waters of British Columbia and Washington as a single integrated system. We also found it important to view the system within a science and resource management framework. This framework establishes terminology, identifies the values guiding us, and formulates goals to be pursued in setting ecosystem management policies. The framework also sets forth objective criteria for judging both the relative vulnerability of each part of the ecosystem and the value that humans place on those parts of the ecosystem.

In all cases the judgments presented in this document represent the consensus of the panel rather than individual opinions. In most cases throughout this report, we have cited as our primary sources of information the presentations at the January 1994 symposium in Vancouver, B.C., and the subsequent published proceedings (Wilson et al., 1994). The articles in these proceedings reviewed the state of knowledge of the environment and resources of the shared and transboundary waters. Further information can be found in references cited in these review articles.

Because of limitations on the quality and quantity of information available for review, there were many aspects of conditions in the shared waters that we could not evaluate. For example, we could not assess the cumulative effects of toxic chemicals from all sources, because data are inadequate. Much more research and monitoring of almost all aspects of the shared waters and their resources must done before such questions can be answered confidently.

Definitions of Terminology

Shared and Transboundary Waters

The mandate of the panel was to study issues affecting the Strait of Georgia, Strait of Juan de Fuca and Puget Sound on both sides of the British Columbia/Washington border. We use the term *shared waters* to refer to these three bodies of waters

collectively. We use the term *transboundary waters* to refer to the immediate area surrounding the border (eastern Juan de Fuca Strait, Gulf/San Juan Islands and the southern Strait of Georgia), where water is exchanged among the three bodies of water.

Contamination and Harm

We use the term *contamination* to refer to the artificial increase of a chemical above natural background levels (GESAMP, 1993). Unlike the term *pollution*, contamination does not necessarily indicate harm to living resources or hazards to human health (Macdonald and Crecelius, 1994). *Harm* includes adverse effects on health (human, animal or plant) or on the quality of life. Some degree of environmental contamination and harm is commonly tolerated by society as an acceptable or unavoidable effect of economic development.

Risk

Of the many definitions of *risk*, we adopt the definition used by the International Atomic Energy Agency (IAEA, 1993): the probability that a "hazard" will cause harm. Most people tend to see risk and safety as absolute opposites. In reality, they are ends of a spectrum, so that what most people perceive as "safe" corresponds to an acceptable degree of risk. The upper limit of acceptability depends on how the risk is perceived by individuals or the community, and risk management is the process of making and implementing decisions based on this limit.

Commitment and Recovery Time

There are varying degrees of risk and harm, and they are felt for different lengths of time. *Commitment* is a concept that combines the magnitude and duration of the harm, or risk of harm, that arises from a *single* action. Commitment sums the harm or risk from that action to express the cumulative effect, projecting into the future until the harm or risk disappears. An event causing a small amount of harm that persists for a long time may carry a larger harm commitment than an event that is more serious at first but from which the ecosystem recovers quickly. For example, a large oil spill may cause a great deal of ecological harm initially, but most effects disappear in a matter of years. In contrast, if a valuable piece of habitat were lost to development in the same year as the oil spill, it might seem to cause less damage at first, but the ecosystem (and society) would still be harmed by this loss long after all traces of the oil spill had disappeared. The harm commitment from habitat loss, which persists long after the end of the useful life of the development that destroyed

the habitat, may eventually exceed that from the oil spill once we take into account the worth of the habitat to future generations.

This concept of harm commitment emphasizes the importance of *recovery time*, the period required for natural processes in the ecosystem to reduce or eliminate a source of contamination or resource stress, and for the harm done to be eliminated or adequately reduced. We define periods of less than three years as *short* recovery times, three to 30 years as *medium* recovery times, and more than 30 years as *long* recovery times. Harm that persists a century or more we define as *irreversible.*

Values We Place on the Marine Environment

Those who live and work in the watersheds surrounding the shared marine waters of British Columbia and Washington place a high value on the health of the environment, including the marine and fresh waters and the tributary basins. Understanding is growing that all segments of the environment are connected, and that practices on land affect the health and resources of the marine environment. Preventing further environmental degradation may require significant changes in some or many of people's everyday activities.

Concern for the marine ecosystem centers on potential threats to the health of humans and other living components of the ecosystem. Any concerns for the cleanliness of the water, sediments or other physical components of the system are in effect concerns about the harm that alteration or degradation of the physical components might cause to the living components.

Concerns also exist about the integrity and value of public and private property—specifically, about potential damage to shorelines and adjacent property by physical forces, about issues of access and privacy, and about the ability to make a living from the use of those properties.

While the panel is aware of local human health concerns in the shared waters (Kalman et al., 1994), most information indicates that present risks posed to living marine and estuarine resources are much more significant than those faced by humans. Some ethnic groups, notably native peoples and Asians, have a higher proportion of seafood and a different seafood composition in their diets than does the average Washingtonian or British Columbian, and so may face higher health risks from contaminated seafood.

Goals for Our Shared Marine Ecosystem

We believe three factors will dictate the type of marine environment that will evolve in the future: the values that people place on segments of the environment, the willingness of people to change their behavior to support those values, and the ability of scientists and managers to understand and control those changes perceived to be deleterious. We do not presume to speak for the citizens of the shared waters in assigning values to various elements of our marine environment. We have, however, described a series of qualitative goals for the state of the environment. We used these goals to guide us in choosing the type and extent of management actions that should be taken to protect marine environmental quality in the shared waters.

1) **Contamination.** The marine waters should, in all areas, be sufficiently free of contamination to prevent a significant increase in the rate of disability or death in marine organisms, and to protect humans from illnesses caused by seafood consumption or contact with water.

2) **Living resources.** The populations of anadromous fish, marine fish, shellfish, waterfowl, marine birds and marine mammals should approach the levels they reached before exploitation, or at least a significant fraction thereof; recreational and commercial fish, shellfish and waterfowl harvests should not cause these population levels to decline.

3) **Biodiversity.** The health and biodiversity of marine plants and non-commercial, non-game marine invertebrate and vertebrate populations should be protected so as to maintain or restore their historic levels.

4) **Habitat.** There should be sufficient marine and nearshore habitat, as well as interconnected riverine and terrestrial habitat, to support healthy fish and wildlife populations.

5) **Industry.** Water-dependent and water-related industrial, commercial and private shoreline developments should not be permitted unless they show a clear net benefit to society, taking into account their true environmental costs.

The Approach to Evaluating Threats and Harm

In assessing potential threats to the shared waters, we stress the importance of distinguishing between actual and perceived threats to human and ecosystem health.

Actual threats should be distinguished from perceived threats by providing the decision-makers, mass media and public with objective scientific information in a readily accessible form. Accordingly, we adopted a pragmatic, science-based approach to assessing the severity of environmental degradation or impacts, and potential mitigation. In this, we have followed the lead of the National Research Council committee on wastewater management for coastal urban areas (NRC, 1993). This approach is based on two fundamental, related principles that we emphasize throughout this report: one, that management decisions should be based on scientific evaluation of risk and harm, and two, that the most serious types of risk and harm can be those that persist for the longest time.

Risk-Based Management System

Our first principle dictates that management priorities should be based on scientific evaluation of actual risks rather than on perceptions or biases. Risk evaluation is the science of identifying hazards quantitatively, using scientific information, by analyzing the probability that harm will occur and the amount and seriousness of harm that may result. Given finite budgets, society through its governments must make decisions that involve trade-offs among impacts, benefits and levels of risk. Management decisions should not be dictated by political expediency or public emotion, but if they are, that fact should not be disguised with false scientific justifications. The evaluation of risk and harm commitment provides a pragmatic method for weighing such decisions by quantifying the probability and extent of present and future harm.

Where risk cannot be adequately evaluated because insufficient information is available, a precautionary approach is warranted and must be followed in tandem with appropriate scientific inquiry. The panel recognizes that there are uncertainties in our present knowledge and understanding, and that unknown and unforeseen environmental problems, such as unusual synergistic effects, may appear. We do not pretend that all environmental effects or hazards have been discovered, nor that all connections have been defined. Strategic planning for ecosystem stewardship must consider such uncertainties and unknowns; flexibility will be a key to good policy.

Recovery Time

For our second principle, and related to the concept of harm commitment, we give recovery time primary importance in deciding how to assign priorities to various types of harm for management actions. recovery time is the first and most important of four criteria we used in setting priorities for management action. The other criteria are discussed in Chapter 7.

We place the highest priority for attention on harm that is potentially irreversible or requires long recovery times (habitat loss, for example). Conservative management of the environment is essential in such cases. Harm from which the ecosystem recovers quickly, once the insult ceases, is assigned medium to low priority for management action. Medium to low priority problems are not meant to be ignored; quick recovery from harm is not a justification for complacency about the harm. Instead, because recovery is relatively rapid in such cases, society can afford to be less cautious in its approach to the problem. Time can be taken to ensure that the best scientific information has been obtained before resources are allocated for remediation.

A simple example can illustrate the use of risk evaluation and recovery time to guide environmental decision making. Suppose, arbitrarily, that a decision must be made on how to allocate resources between oil spill response and protection of natural habitat. Most biological systems appear to recover relatively quickly from the acute but short-term harm of an oil spill (National Research Council, 1985). By contrast, destruction and degradation of natural habitat harms fish and wildlife over prolonged periods and causes other environmental problems. Thus the harm commitment would be greater in the latter case, and we would accord it a higher priority in allocating resources for preventing environmental harm.

This definition of recovery time includes only a scientific analysis of the time required for the natural environment to clean and rebuild itself. It does not include a political or institutional analysis of the time required for decisions to be made and implemented in society. In the real world, both of these time intervals must be considered when calculating how long it will take to improve the marine environment from its present condition to a desired condition. Nevertheless, in setting priorities for management attention, we give high priority to the harm that is longest-lasting and give low priority to harm that will disappear quickly, whether remedial action is taken immediately or delayed for many years.

We believe that a risk–based approach is most appropriate for the shared waters. The Honourable Moe Sihota, minister of the environment for the province of British Columbia, noted in his address to the Marine Science Symposium in January that his administration intends to support those branches of science involved in collection and interpretation of environmental data, *and* to make good use of the results. The panel recognizes that the data collection and interpretation will require *sustained* monitoring, and the data use must involve scientific risk evaluation. Past policy decisions often have not been based on such a progressive foundation; we hope in the future they will be.

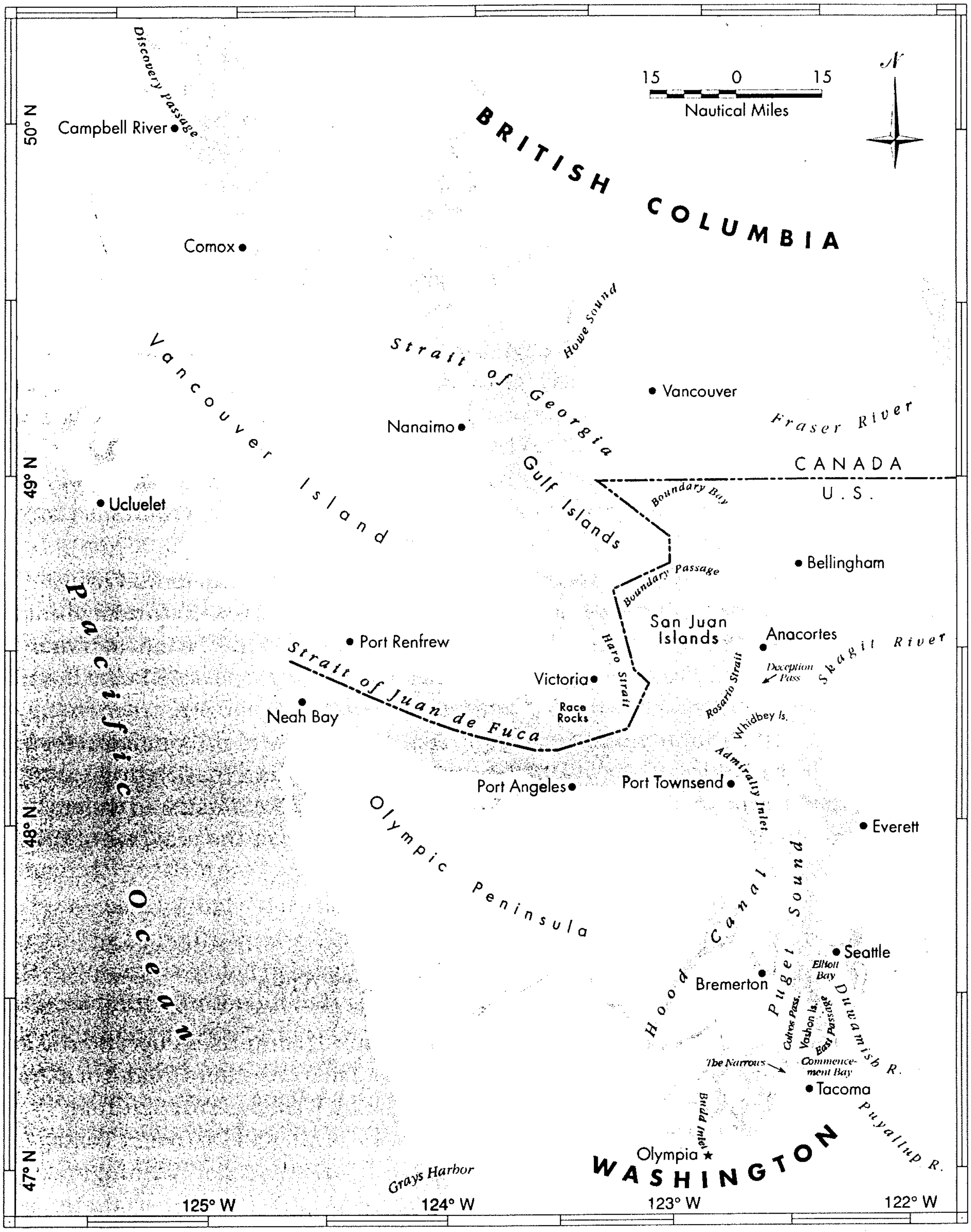
2. The Shared Waters and Ecosystem

The Pacific coast of southwestern Canada and the northwestern United States is one of the fastest-growing North American population centers. The region's physical grandeur is a magnet to new residents. The proximity of the sea, fjords, forests, lakes and rivers, and a rich natural biodiversity are fundamental to the attraction. But, as the British Columbia/Washington Marine Science Panel and participants heard at the Marine Science Symposium in January 1994, all is not well in the shared waters.

Rapid population growth is imposing increasing waste burdens and recreational and commercial demands on marine waters and resources. Natural habitat is disappearing or being degraded, and fish stocks are diminishing. Marine mammal populations are changing—some species (such as the harbor porpoise in Puget Sound) seem to have all but disappeared, while others, such as the harbor seal, are thriving. Episodes of shellfish contamination are apparently becoming more common; closures of commercial and recreational shellfish beds because of contamination by fecal coliform bacteria are now more frequent. These problems, like the shared waters themselves, are not limited to either the state of Washington or the province of British Columbia.

Characteristics of the Transboundary Waters Area

The area studied by the panel, depicted in Figure 1, comprises Puget Sound and the straits of Georgia and Juan de Fuca. It includes all marine waters inland of a line from approximately Cape Flattery (Olympic Peninsula), Wash., to Port San Juan (Vancouver Island), B.C., and northward to Johnstone Strait and Discovery Passage. Contiguous waters, such as those in Howe Sound, B.C., and the outer Washington coast are unavoidably included in the discussion. Large rivers having an important impact



15 0 15
Nautical Miles
BRITISH COLUMBIA
Discovery Passage
Campbell River
50° N
Comox
Howe Sound
Strait of Georgia
Vancouver Island
Vancouver
Fraser River
Nanaimo
Gulf Islands
CANADA
U.S.
49° N
Ucluelet
Boundary Bay
Bellingham
Boundary Passage
San Juan Islands
Anacortes
Skagit River
Pacific Ocean
Port Renfrew
Haro Strait
Deception Pass
Rosario Strait
Victoria
Strait of Juan de Fuca
Neah Bay
Race Rocks
Whidbey Is.
Admiralty Inlet
Port Angeles
Port Townsend
48° N
Olympic Peninsula
Everett
Hood Canal
Puget Sound
Seattle
Elliott Bay
Bremerton
Duwamish R.
Colvos Pass.
Vashon Is.
East Passage
The Narrows
Commencement Bay
Tacoma
Budd Inlet
Puyallup R.
Olympia
WASHINGTON
47° N
Grays Harbor
125° W
124° W
123° W
122° W

Figure 1.

on marine waters, such as the Fraser and the Skagit, and their watersheds are also implicitly included in the study area.

Physical Oceanography

This basin complex may be classified as a system of estuaries, or as a single all-embracing estuary. An estuary is defined as a marine water body, semi-isolated from the open ocean, in which salt water is diluted by freshwater runoff. The system also may be likened to a fjord—a deep, steep-sided high-latitude estuary in which the basin was carved by glacial movement. Fjords are characterized by a sharp difference in salinity between surface and deep waters in the basin and by a shallow area called a sill at the entrance of the basin from the ocean.

Where rivers meet salt water, the less-dense fresh water flows seaward over the denser marine water. Turbulence mixes the two waters to some extent, so that the fresh water flowing seaward entrains some marine water. To replace the marine water carried out to sea in the shallow layer near the sea surface, additional marine water flows at depth toward the river mouth. Overall, this process is referred to as estuarine circulation. Specifically, these flows separate the water column into two layers, a lower layer flowing landward, and an upper layer flowing seaward. Most of the marine waters of Puget Sound, the Strait of Georgia and the Strait of Juan de Fuca exhibit these two layers, though there are exceptions. On average, the inland marine waters as a whole are composed of 90 percent ocean water and 10 percent fresh water.

The estuarine nature of the shared waters highlights the importance of the many rivers entering the basin from surrounding watersheds. System-wide, freshwater runoff is heavily influenced by two large rivers. The Fraser River alone, entering near the international boundary, delivers 80 percent of the fresh water entering the Strait of Georgia and more than half of the fresh water reaching the shared waters (Thomson, 1994). The Skagit River, though much smaller than the Fraser, still delivers approximately two-thirds of the fresh water reaching U.S. inland waters. Flows in both of these rivers are highly seasonal, with prominent runoff peaks caused by snow melt during early summer (May-June) and lowest flows during late summer (August-September). The seasonal flow of the Skagit has been significantly altered by hydroelectric dams, but otherwise its watershed is mainly wilderness and farmland, and its waters are relatively pristine. Changes in the seasonal flow characteristics or total freshwater volume of the Fraser and the Skagit could have major effects on the estuarine circulation of the system.

Aquatic Habitats

Aquatic habitats in the shared waters range widely from deep-water marine settings to upland freshwater environments. In intertidal and shallow subtidal marine waters, unvegetated zones, rocky shores, sand- and mudflats, and eelgrass, kelp, and intertidal algal beds are typical habitats. Many beaches in the basin are covered by various mixtures of sand, cobble and gravel. Lowland environments include marshes, grasslands ("wet meadows") and various types of floodplains. The importance of aquatic nearshore habitats lies in the fact that most species that are considered economic or aesthetic resources in the shared waters depend upon nearshore habitats for part or all of their life history (Levings and Thom, 1994). For example, herring use algae, eelgrass and kelp as spawning substrates for eggs, and outmigrating juvenile chum and chinook salmon fry rely on the rich detrital food web characteristic of certain nearshore soft-bottom habitats.

Unfortunately, severe nearshore habitat loss has occurred in the region, as discussed in Chapter 5. In the North Arm of the Fraser estuary near Vancouver, for example, 96 percent of the brackish marsh habitat has been lost in the past 100 years due to human alteration of the shoreline and nearshore area (Levings and Thom, 1994). In Puget Sound as a whole, an estimated 70 percent of the tidally influenced wetlands have been lost to development, and in the urban estuaries of the Duwamish (Seattle) and Puyallup (Tacoma) Rivers, 99 and 100 percent, respectively, of the wetland areas have been lost (PSWQA, 1992). Alterations to freshwater flow also can cause changes in habitat near river mouths and elsewhere.

Invasions of non-indigenous or exotic species (those imported either inadvertently or purposely) have changed the species composition in some habitats. For example, the remaining brackish marsh communities on the Fraser estuary have been invaded by purple loosestrife, which outcompetes native sedges. Puget Sound has been invaded by species of the cordgrass *Spartina*, which threatens to colonize and alter unvegetated mudflats on a broad scale (Mumford et al., 1991). Such assaults on ecosystems may have irreversible consequences for all species, including humans.

Marine Populations

The diverse habitats, deep, cool water, and access to numerous rivers that make up the shared waters are inhabited by numerous species of fish, invertebrates, birds and marine mammals.

The open waters teem with plankton, both plant (phytoplankton) and animal (zooplankton), which serve as food for fish, birds and mammals. These waters are among some of the most productive in the world and support an intricate web of

living organisms. Invertebrate communities inhabit the intertidal beaches, the bottom sediments and the fringing wetlands of the region. Large invertebrates, including shellfish such as clams, oysters and mussels, live along the shoreline, while crab and shrimp are found farther from shore. The soft muddy bottom of the shared waters supports large populations of tiny worms, clams and crustaceans, which are prey for larger invertebrates, bottomfish and gray whales.

Approximately 220 fish species live in the shared waters (PSWQA, 1991; Schmitt, 1990). A small number of these (including the five salmon species, steelhead, dolly varden and cutthroat trout) are anadromous, spawning in fresh water, moving to salt water to feed and mature, and returning to fresh water to breed. Other fish in the shared waters are marine fish (which spend their whole lives in marine water), including baitfish such as herring; lingcod and Pacific cod; flatfish living near the bottom such as sole, flounder and halibut; and numerous species of distinctly marked rockfish.

Very large populations of seabirds (also called marine birds—those that spend their entire lives at sea), waterfowl (ducks and geese) and shorebirds live in the shared waters in winter, with smaller populations present in summer (Mahaffy et al., 1994; PSWQA, 1990, 1991). Populations of seabirds include many migratory species, as well as five species breeding in Puget Sound and the Strait of Juan de Fuca (rhinoceros auklet, glaucous-winged gull, pigeon guillemot, pelagic cormorant, double-crested cormorant). The same seabirds breed in the Strait of Georgia, along with small breeding populations of tufted puffin and Brandt's cormorants. Winter visitors in the shared waters include common murres, loons and grebes, ancient murrelets and marbled murrelets. Great blue herons are year-round residents in the shared waters, as are several raptors that feed in the nearshore marine wetlands and rivers, including bald eagles and osprey.

Waterfowl living in the shared waters include 26 species of ducks, 10 species or subspecies of geese and three species of swans. While four duck species breed in the shared waters, the others feed here during the winter, with the greatest populations found in the estuaries and bays of Puget Sound and the Strait of Georgia. Dabbling ducks such as mallards and widgeons winter in wetlands along the shoreline, while diving ducks such as scoters, goldeneye and bufflehead are found in deeper water. Numerous shorebirds winter in the estuaries of the shared waters, particularly in the Fraser and Skagit. Dunlin are the most numerous shorebird found, with sandpipers and plovers found in large numbers as well.

Four species of pinnipeds (seal and sea lions) and five species of cetaceans (whales and dolphins) are commonly seen in the shared marine waters, while many

other species of whales, dolphins, and seals are rare visitors (Calambokidis and Baird, 1994; PSWQA, 1990, 1991). The most abundant pinniped, the harbor seal, can be seen hauled out on rocks, small islands, marina floats and buoys throughout the shared waters. California sea lions also are frequently visible to human visitors. Both pinnipeds have been implicated in the reduction of fish runs in Puget Sound and the Strait of Georgia, although there are few definitive studies showing this. The orca whale is a frequent sight in the open waters of the straits of Juan de Fuca and Georgia, although sightings are rare treats for people in the enclosed waters of Puget Sound. Gray whales, recently removed from the endangered species list in the United States, are becoming more frequent visitors to all parts of the shared waters, while harbor porpoises are no longer seen in Puget Sound.

Demographics

In 1980, the human population in the combined Puget Sound and metropolitan Vancouver areas was approximately 3.8 million. That number is expected to rise by more than 60 percent by the year 2010, when it will almost certainly exceed 6 million (B.C. Ministry of the Environment, 1993). The population along the eastern shore of Vancouver Island between Victoria and Campbell River also is expected to continue rising rapidly. So far this rapid growth has been accommodated by steady expansion from the major cities of Vancouver and Seattle into adjacent suburban areas in the corridor between the two centers, on the western margin of Puget Sound, and along eastern Vancouver Island (West et al., 1994). This expansion has essentially ringed the shared waters with urban areas that generate contaminant loads, degrade habitat, divert fresh water and consume resources. Determination of the future effects of the growing waste streams, and the need to prevent further habitat loss, are fundamental considerations in this report.

3. Physical Exchange Mechanisms in the Transboundary Region

QUESTION—What transport mechanisms exist for transboundary exchange of human-caused contamination between the Strait of Georgia, Puget Sound and Juan de Fuca Strait?

A number of mechanisms exchange water among the Strait of Juan de Fuca, the Strait of Georgia and Puget Sound. These mechanisms carry various natural materials, including fresh water, salt and nutrients from the ocean, and plankton and sediment particles. They also bear three major types of materials discharged by humans—sediment particles bearing contaminants, sewage and spilled oil—at the sea surface, in the water column and along the sea floor.

Most of these physical mechanisms can transfer contaminants across the international border. In the following sections, we describe the four major mechanisms that are active in the shared waters: estuarine circulation, refluxing, tidal eddies and wind-driven transport. These descriptions are followed by discussions of the ways that these mechanisms move the three major types of contaminants listed above. These mechanisms and contaminants were selected for their potential to cause harm—losses of some marine organisms, of biodiversity, of aesthetic appeal and of human uses and economic benefit—that persists for several years.

Transport Mechanisms

Estuarine Circulation

Puget Sound, the Strait of Georgia and the Strait of Juan de Fuca encompass a convoluted network of deep basins, long channels, narrow shallow tidal passages, sheltered embayments and islands that connects with the open Pacific Ocean through the Strait of Juan de Fuca (Figure 1). The oceanography of the region is complex, reflecting its topography, the annual cycle of fresh water from rivers, a relatively large tidal range and a marked seasonal cycle in prevailing winds (Thomson, 1994).

Averaged over a long period of time, two-layer estuarine flow is the dominant circulation pattern in the shared waters. The transition between surface outflow and deeper inflow is marked by a depth layer with little net flow, which typically is observed between 75 and 125 meters in the Strait of Juan de Fuca (Thomson, 1994) and at 50 meters or less in Puget Sound and the Strait of Georgia (Thomson, 1994; Cokelet et al., 1990).

This two-layer circulation pattern is highly variable in time and space. Under average conditions in the Strait of Juan de Fuca, a deflection caused by the rotation of the earth piles up the deep inflow on the U.S. (southern) side of the strait, and the surface outflow on the Canadian (northern) side. At any moment, furthermore, the strongest currents observed generally are tidal currents that are superimposed on the average estuarine flow and reverse in direction four times daily. The strength of tidal currents generates other flow features that would not be observed if only the average estuarine flow were present. Tidal currents promote intense mixing as water flows through many narrow channels and across shallow sills, such as those in the Gulf and San Juan islands, that separate the deeper basins. This mixing significantly affects important physical and chemical water properties, including temperature, salinity, density, nutrients and oxygen, and water column contaminants. Tidal currents also interact with the configuration of the shoreline to generate eddies. These features are discussed below.

Gradual replacement of resident water by ocean and river water in the two-layered flow carries water out of and between the basins composing the shared waters. This replenishing of water in a basin is called *flushing*. The rate of basin flushing is largely determined by river discharge and tidal mixing, which power the estuarine circulation. Estimates of flushing times (the time required to completely replace the water in the estuary) in the Strait of Georgia range from 100-200 days in winter to 50-100 days in summer (Thomson, 1994). Deeper waters in the main basin of Puget Sound are replaced about once per month, which is quite rapid compared to rates in

many other fjords (Thomson, 1994). Puget Sound as a whole is estimated to flush about every five months, on average (Cokelet et al., 1991). Flushing times for individual basins within Puget Sound range from less than one month to more than six months. Because flushing times are linked to river discharge, decreases in fresh water inflow that might result from river diversion schemes or climate change could prove detrimental to future water quality in the shared waters.

Refluxing

Over most of the shared waters, vertical mixing between upper and lower estuarine water layers is weak. However, the layers are vigorously intermixed in narrow channels and passages where tidal currents are particularly fast. These channels are generally the sites of sills, where the water is much shallower than in the flanking basins. At the sills, some of the upper-layer water flowing to sea is mixed downward into the lower layer flowing inland, and some of the lower-layer water is mixed into the upper layer. This exchange between layers has been termed *refluxing* (Cokelet and Stewart, 1985). Refluxing increases the flushing time of a basin. The flushing times estimated above account for refluxing in Puget Sound and the Strait of Georgia, and accordingly are longer than they would be in the absence of refluxing.

The fraction of water refluxed between layers varies between 10 percent and 80 percent, with typical values of about 30 percent. For example, about 52 percent of the surface water leaving Puget Sound through Admiralty Inlet (the connection to the Strait of Juan de Fuca, between Port Townsend and Whidbey Island) is mixed downward in the Inlet and recirculates inland into the deep layer of the Sound. In the main basin of Puget Sound, approximately 49 percent of water flowing northward in Colvos Passage (west of Vashon Island) is refluxed around Vashon Island to return southward in East Passage (east of Vashon) (Cokelet et al., 1991). No estimate of refluxing for the Strait of Georgia has yet been determined.

Tidal Eddies

As tidal currents ebb and flood, eddies—rotating current patterns that trap particles and debris—form in the lee of headlands. These eddies often are felt by boaters and seen by beachcombers watching drifting objects. Because of large tidal ranges, eddies are prominent features throughout much of the shared waters.

Tidal eddies may produce currents flowing in directions other than those corresponding to the simple two-layer flow. Currents may flow periodically or consistently onshore, offshore or opposite to the prevailing estuarine flow at selected locations. For example, tidal eddies are particularly prominent along the international border in the eastern Strait of Juan de Fuca. They may retard or even halt the seaward

transport of materials drifting in the surface estuarine flow. Onshore movements in the tidal eddies increase the probability that drifting materials will be beached before reaching the Pacific Ocean. This mechanism can harm the marine environment by concentrating floating materials at particular locations.

Wind-Driven Transport

Winds dramatically affect the movements of both coastal and inland marine waters. They can reverse the prevailing currents at the surface under some conditions and drive water and contaminants out of basins or across the boundary.

A prominent example of surface current reversal caused by winds occurs in the Strait of Juan de Fuca. During winter, southwesterly winds produced by storms off the outer coast raise the sea level at the entrance to the Strait, driving a landward surface flow along its southern shore and reversing the average two-layer flow. These surface inflow events, called oceanic intrusions, may occur up to 25 percent of the time during winter and can persist for many days and are more pronounced on the Washington side. They can be traced by objects known to have drifted inland from the Pacific coast and offshore waters as far as the San Juan Islands and Bellingham (Thomson, 1991).

Temporal Variations of Transport Mechanisms

The transport mechanisms in shared waters were discerned after many years of observations. However, the forces driving the mechanisms (river discharge, tides, winds, and oceanic conditions) are known to undergo cyclical fluctuations with a time scale of approximately 10-20 years (Thomson, 1994). For this reason it is to be expected that the relative strength of the transport mechanisms also will vary over the decades.

In one phase of this decadal cycle (cold, wet years), air and water temperatures are relatively low, river discharge is high, and the strong southerly winds are more frequent in winter. Under these conditions, surface oceanic intrusions may also be more frequent. In the other phase (warm, dry years), air and water temperatures are relatively high, river discharge is low, and northerly winds are more frequent.

Research on the potential effects of this variability on contaminants and marine organisms is just beginning. However, many significant effects of climate variability could be postulated on such ecosystem processes as migration and survival of salmonids, or direction and strength of surface winds and currents and resulting trajectories of spilled oil.

QUESTION—To what extent can spills or discharges to these waters be transported across the international border and cause harm?

Contaminant Transport

Materials from human activities are discharged into both the upper (seaward-flowing) and lower (landward-flowing) layers of the estuary. Once they enter sea water, they may move between layers according to their buoyancy, and this movement will affect their transport. For example, it has been estimated that after sewage effluent is discharged from an outfall, 10 percent is more buoyant than sea water and floats to the surface, 10 percent is less buoyant and sinks, and 80 percent is neutrally buoyant (Word et al., 1990). A similar analysis has been made of discharged dredge sediments: 95-98 percent sink within minutes after release from a barge, and 2 percent-5 percent remain suspended in the water (Hardy and Cowan, 1986). The position and physical state of discharged contaminants determines which of the four transport mechanisms act on them and how the materials are transported.

Particle-Bound Contaminants

Most chemical contaminants bind to particles, regardless of their source—including some of the material from point sources such as sewage effluent and industrial discharges, and from nonpoint sources such as urban runoff. Particles that are denser than sea water sink to the seafloor and generally accumulate in the sediments within the basin receiving the discharge (Macdonald and Crecelius, 1994). In addition, filter-feeding organisms near the surface ingest neutrally buoyant and slow-sinking particles and egest them in fecal pellets, which sink rapidly. These processes, which trap sediments close to their sources, have a dominant effect on determining the distribution of contaminants in the shared waters.

Sediment contamination is severe in some locations close to certain major contaminant sources, such as outfalls from sewage treatment plants, industrial outfalls, pulp mills, storm drains and combined sewer overflows. Sediments at a distance from these sources generally show low levels of contamination. To the extent that contaminants are present far from major contaminant sources, furthermore, evidence suggests that atmospheric transport is more important than waterborne transport, especially for contaminants such as lead and hydrocarbon residues from

automobile exhaust (Macdonald and Crecelius, 1994). Patterns of contamination vary within and between each of the basins of the shared waters, depending on the contaminant input and patterns and rates of sediment movement.

In some cases sediment is transported naturally or artificially within the shared waters. Under limited circumstances—such as in the Point Roberts area, where the border runs through open waters in the southern Strait of Georgia—sediment is transported across the boundary. Some sediment is known to be transported naturally inland along the seafloor (seabed drifters from the Washington coast have been recovered in both the Strait of Georgia and Puget Sound; Barnes et al., 1972). More important, dredging of sediments for nearshore development projects, for navigation purposes, or for removal of contaminated sediments, can spread contaminants from one area to another. Dredge-disposal impacts also occur in the open waters of each of the basins at considerable distance from shore. The areas of greatest contamination, and consequently the most likely to cause harm resulting from dredging and dredge material disposal, are in close proximity to the urban areas of the basin, particularly those near Seattle, Tacoma, Vancouver and Victoria. The issue of harm resulting from contaminated sediments is discussed in detail in Chapter 5.

Waterborne Contaminants

Estuarine circulation transports water and some waterborne contaminants—those that float or are dissolved or neutrally buoyant—into and among the various basins that compose the shared waters. Waterborne contaminants discharged into a basin in the shared waters are gradually flushed out of the system to the Pacific Ocean, but in transit they may be refluxed within their basin of origin and transported into another basin by tidal exchange. This exchange is illustrated by drifting objects that are commonly observed to cross the international border among Puget Sound and the Straits of Juan de Fuca and Georgia (Thomson, 1994; Waldichuk, 1958; Ebbesmeyer and Coomes, 1994).

Waterborne contaminants enter the system from the same types of sources as those bound to particles, including from point sources such as sewage effluent and industrial discharges and from nonpoint sources such as urban runoff. The waterborne contaminants of principal concern are:

1) Nutrients, which can stimulate excess growth of marine plants that later decay and can cause oxygen depletion, foul odors and fish kills.

2) Dissolved organic compounds that are metabolized by bacteria, also causing oxygen depletion. Some organic particles also are metabolized by bacteria and can contribute

to depletion of oxygen in the water column as they sink, as well in the sediments after they sink. The collective potential for nutrients and dissolved and particle-bound organic compounds to cause oxygen consumption by microorganisms is called *Biological Oxygen Demand (BOD)* and is one of the properties monitored in conventional water quality analyses.

3) Potential human pathogenic microorganisms, such as fecal coliform bacteria and some viruses and protozoa, which retain their pathogenicity in salt water for an uncertain length of time and may contaminate swimming and shellfish harvesting beaches.

The scope of potential harm from a sewage discharge depends on the amount of discharge, the size of the basin, the extent of natural mixing and flushing and the prevailing natural nutrient supply. Extensive studies show that in most areas in the shared waters, discharges are too small significantly to alter natural supplies and concentrations of nutrients and oxygen and so have little effect on marine plant growth or dissolved oxygen concentrations (Harrison et al., 1994).

The shared waters are supplied with ample nutrients by upwelling off the outer coasts of Washington and Vancouver Island, which brings nutrient-rich ocean water close to the sea surface, where it is entrained within the deep inflow into the Strait of Juan de Fuca. At present, natural estuarine transport accounts for about 90 percent-92 percent of the total nutrient input to the shared waters (Harrison et al., 1994). The remainder is supplied by rivers (about 5 percent) and sewage discharges (3 percent-5 percent). Furthermore, nutrient supplies near the surface, where plant growth takes place, are naturally maintained at high levels in most of the shared waters by strong vertical mixing.

The substances responsible for creating BOD do consume significant amounts of oxygen in the shared waters. However, the vigorous estuarine transport and refluxing present in most basins of the shared waters provide large amounts of oxygen that prevent oxygen depletion. In most basins, flushing of deep waters by oxygenated water from the Pacific Ocean, and injection of further oxygen into this deep water as it passes through mixing and refluxing zones, are sufficient to offset oxygen consumption and maintain satisfactory water quality.

Municipal Effluents

Some instances of harm from excess nutrient and BOD discharge have been observed locally. In poorly flushed and mixed Budd Inlet, Puget Sound, for example, natural surface nutrient supplies are seasonally low in summer (PSWQA, 1993). Nutrients and BOD in sewage effluent from the urban areas of Lacey, Olympia.

Tumwater and Thurston County have been blamed for overgrowth of phytoplankton (free-floating microalgae) and resulting anoxic episodes and fish kills. Because of this problem, a high level of sewage treatment is currently being implemented.

The much larger discharges from the cities of Vancouver and Seattle, in contrast, show little or no effect on naturally high nutrient and oxygen levels and phytoplankton growth in the large and well-flushed main basins of the Strait of Georgia and Puget Sound (Harrison et al., 1994). Incoming ocean water contributes significantly greater amounts of nutrients than sewage discharges, and supplies phytoplankton in open waters with more nutrients than they can use. Flushing and mixing also supply oxygen. These volumes of effluent have caused water quality problems, however, when discharged into rivers that feed marine waters (West et al., 1994). Seattle has taken steps, and Vancouver is planning steps, to reduce harm from contaminants in sewage discharged to rivers entering the shared waters.

The Victoria metropolitan area discharges screened but otherwise untreated sewage effluent to a segment of the open Strait of Juan de Fuca that experiences some of the strongest currents and mixing processes in the entire shared waters. This effluent disperses quickly, contributing negligible quantities of nutrients and BOD to an already nutrient-rich area of the estuarine system. There has been some concern that floatable materials and pathogens—much of which may originate from surface runoff such as storm sewers rather than from the offshore subsurface sewage discharge (West et al., 1994)—may be trapped in persistent surface tidal eddies observed off Victoria and accumulate on beaches (Thomson, 1994), posing a possible threat to local residents, but causing little harm beyond the immediate area. Recently, Victoria has acted to clean up these intertidal discharges and has greatly reduced local contaminant levels (Taylor, personal communication).

A computer model has been built to simulate estuarine circulation in Puget Sound and the Strait of Juan de Fuca (Cokelet et al., 1991). The model contains representations of the two flow layers, the numerous basins and the refluxing between layers and basins. It also includes a hypothetical dissolved chemical that behaves conservatively (i.e., its abundance depends only on input from land and water movement and is not affected by chemical or biological processes within the water). The validity of the model has been verified by comparing modeled and actual transport of dissolved copper (Paulson et al., 1993), and it can be used to study the transport of water and waterborne contaminants (but not particle-bound contaminants).

The model has been adapted to trace the theoretical amount of dissolved constituents in sewage effluent in various Puget Sound-area basins that originates from three municipal discharges (Victoria, Vancouver, Seattle) (Cokelet, 1994). As applied

in this example, the model does not include other sources of sewage effluent. The model also does not account for any chemical or biological transformations that the dissolved effluent may undergo as it is transported, nor for floating or particle-bound contaminants in sewage effluent. The latter mainly remain in their basin of origin.

In the Strait of Juan de Fuca, the model estimates dissolved effluent concentrations of 100, 83 and 9 parts per million (ppm) from Vancouver, Seattle and Victoria, respectively. Thus the model shows that waters off Victoria theoretically could contain about 20 times as much dissolved sewage effluent from Vancouver and Seattle as from Victoria itself. This finding supports the conclusion that dissolved material in sewage discharges from Victoria have a negligible effect on the shared waters.

Material originating in Seattle dominates the dissolved effluent content within Puget Sound in the model because Seattle discharges directly into the Sound. However, an estimated 22 percent of the dissolved sewage effluent from Victoria and Vancouver theoretically enters Puget Sound because of tidal mixing and refluxing in the Gulf and San Juan Islands, the Strait of Juan de Fuca, and Admiralty Inlet. In the model on average, all layers in Puget Sound contain dissolved sewage effluent from Seattle at a theoretical concentration of approximately 455 ppm, from Vancouver at 67 ppm and from Victoria at 6.3 ppm. The theoretical total concentration of Canadian dissolved effluent in Puget Sound is about 16 percent of that from Seattle. Unfortunately, the model at present does not include detailed dynamics of the Strait of Georgia; therefore, the transport into the Strait of Georgia from Puget Sound cannot be computed.

Spilled Oil

Crude oil is a complex mixture of related but differing organic chemicals. When spilled into sea water, the oil separates into several fractions, the most familiar of which is buoyant and floats on the sea surface. While at the surface, it is subject to the surface processes operating in the estuary, including transport by currents and winds, trapping by eddies and refluxing. Some fractions of crude oil evaporate or are broken down by sunlight, while others dissolve in sea water and travel with it. Still other fractions may become denser than surface sea water and sink to a subsurface layer or to the sea floor. Sometimes refined oil containing a single fraction (such as fuel oil) is spilled, simplifying the understanding of its fate.

A mathematical model has been developed that divides the inland waters into many cells and incorporates the effects of tides, winds and runoff (Bolton et al., 1983; Crean et al., 1988; Stronach et al., 1993a&b). This model was verified by comparing predicted and observed currents and tides. In particular, the model compared well

with observed tracks of objects drifting around eddies in the eastern Juan de Fuca Strait (Thomson, 1994). It can be used to predict where drifting materials such as spilled oil will reach the shoreline.

Oil spilled in British Columbia and Washington waters has been tracked on a number of occasions, providing examples of all modes of transport and exchange. Diesel fuel spilled from a refinery dock at Anacortes, Wash., in 1971 was tracked seaward into Juan de Fuca Strait, and undoubtedly some was transported across the boundary (Vagners and Mar, 1972). Some of the spilled diesel fuel also was observed inland in the subsurface layer of the Whidbey basin, indicating that estuarine refluxing, exchange between vertical layers and transport inland at depth were occurring (Ebbesmeyer et al., 1979). Subsurface sinking and transport of heavy fuel oil also were observed from a barge spill off Anacortes in January 1988.

Oil also can be transported into the system from coastal waters. Fuel oil from a barge spill off Grays Harbor, Wash., in December 1988 reached the outer shores of Vancouver Island a few days later, and a small amount was transported into the Strait of Juan de Fuca and various bays on Vancouver Island by intrusions (Thomson, 1994). Although the outer coast generally has few contaminant sources, it is clear that, under certain conditions, oil spilled off the coast could be carried in large amounts by oceanic intrusions to the entrances of Puget Sound and the Strait of Georgia. Transport is more pronounced along the Washington side of the strait. At this point refluxing would likely cause some of the oil to be transported northward and southward into these two water bodies in the lower layer of the estuarine transport mechanism.

These examples illustrate that spilled oil readily crosses boundaries between nations and between basins in the shared waters. The high volume of oil transshipped along the outer coast and through the Strait of Juan de Fuca creates a significant possibility of a large spill at a location where transport mechanisms could carry oil over wide areas of the inner basins in the shared waters. The potential harm from spilled oil is a complex subject that is discussed in Chapters 6 and 7.

4. Movements, Status and Trends of Transboundary Biological Resource Populations

QUESTION—What do we know about the status of the transboundary population of invertebrates, finfish, birds and mammals of Strait of Georgia, Puget Sound and the Strait of Juan de Fuca? Are there long term trends in the populations, and if so, what are the likely causes?

Living marine resources in the shared waters have value to humans as commercial and recreational resources, and they have ecological value because they support the marine food web and maintain regional and global biodiversity. The loss of a marine invertebrate species in a critical part of the food web could threaten regional biodiversity as much as the loss of entire salmon runs, the marbled murrelet or other endangered species. Species at all levels of the food chain are equally important for biodiversity and resource production, and are equally important to protect. Management activities historically have focused only on commercial and recreational species, but they are beginning to protect prey items of these species as well.

Status and Trends in Marine Biota

In most cases in the shared waters, we have few direct measurements of fish populations. Instead, fish abundance is monitored using the numbers of fish that are caught in recreational and commercial fisheries, and population trends are assumed

to follow trends in fish catch per unit of fishing effort. Populations of species that are not intensively fished typically are not monitored at all. Thus the discussion of fish abundance must be conducted using catch data rather than population counts, and the discussion of causes of abundance trends traditionally focuses on how these trends relate to management practices rather than to changes in the environment.

All natural populations fluctuate in abundance to a greater or lesser degree, and constant production or population levels cannot be expected. Thus, it is important to differentiate between natural changes in abundance and those that may result from human activities. For example, even in cases when overfishing might be known to cause declines in fish populations, the inability to halt such declines by reducing fish harvests could indicate that natural changes are also occurring. Understanding the reasons for abundance changes is essential for sound management, but in many cases, the abundance changes observed among marine organisms in the shared waters cannot be fully explained. There is a need for additional research on causes of changes in marine populations and on interactions between marine biota and the oceanic and estuarine environments. There also is a need for ongoing monitoring of exploited and non-exploited marine populations.

Some evidence of population fluctuations related to climatic fluctuations already exists (Wooster and Fluharty, 1985). For example, during the warm–dry phase of the decadal cycle (Ebbesmeyer et al., 1991), adult salmon returns to West Coast rivers decline, juvenile salmon survival in rivers drops as runoff decreases, distributions and migrations of other fishes are anomalous, and the outer coastal Oyster Condition Index (an indicator of oyster growth) decreases (Schoener and Tufts, 1987). These biological effects are most dramatic on the outer coast but are also evident in inland waters to some extent. The effects may indicate changes in primary production, which supplies food for animals, as well as in temperature. During warm-dry phases, there also is evidence of increased populations of predators at the top of the food chain—such as large fish, birds and mammals (Wooster and Fluharty, 1985). It follows that animals at middle levels of the food chain may suffer, providing one possible explanation for the declining fish stocks and oyster harvests.

Accordingly, fishery regulations imposed under cold-wet phase conditions would be too liberal for use during the warm-dry phase and would tend to lead to overfishing. Recent studies have fostered the concept of a “carrying capacity” of the ocean for fish populations that is not constant, but fluctuates with climatic conditions (Pearcy, 1992). Under this concept, fishing limits should shift with climatic conditions rather than remaining fixed. Such flexible management regimes have been slow to evolve, however.

Salmonids

Salmon production in the Strait of Georgia supports a major recreational and commercial industry. Virtually all the pink, chum and sockeye salmon production in the Strait of Georgia comes from the Fraser River. Catches and escapements (numbers of fish that survive to spawn in rivers) are close to the historic high levels of the late 1930s for these species in the Strait of Georgia. The high abundance is believed to result from increases in natural survival. However, unlike the abundant salmon stocks prior to the first half of this century, a large proportion of the salmon in the shared waters today are hatchery-reared.

Chinook salmon catches in the Strait of Georgia increased in the early 1970s then declined in the 1980s. Despite efforts to rebuild chinook stocks, their abundance appears to have remained almost constant. The reasons for the inability to rebuild stocks are not clear but may be related to fishing pressure and a decline in the natural carrying capacity for chinook. Coho salmon catches in the Strait of Georgia have fluctuated since 1970, but the average catch from 1970 to 1993 has not changed. Wild coho escapements have declined recently, which gives cause for concern. The reasons for the decline are unclear but may be related to freshwater habitat loss, fishing pressure and interactions of wild stocks with hatchery stocks.

In Puget Sound, about half of all the wild salmon stocks that can be assessed are sustaining acceptable population levels. Of the other half, about 80 percent are considered depleted, and 20 percent are critically low (Schmitt et al., 1994). Clearly, a substantial number of wild salmon populations are in jeopardy; the status of others is unknown. The causes for the declines are debatable, but poor ocean conditions, freshwater habitat loss, overfishing, variable flow in rivers and interactions between wild and hatchery-reared salmon appear to be most important (Schmitt et al., 1994). It is not clear whether declines may be related to contamination in the watersheds around Puget Sound (although it could be a contributing factor in some cases), because declines are even worse in the relatively uncontaminated waters along the coast. However, harm to individual salmon from contaminated Puget Sound rivers has been documented in laboratory studies (Varanasi et al., 1993).

It is not clear why large annual Puget Sound releases of hatchery-reared smolts (60 million-70 million chinook, 60 million-80 million chum, and 40 million coho salmon [Schmitt et al., 1994]), which were intended to support populations by compensating for loss of at least some of the wild smolt production and sustain fishable populations, have not prevented these declines. For example, it is believed that more than 5,600 kilometers of river habitat are underutilized by coho, indicating that wild coho stocks could be rebuilt. This question might be clarified by additional research

on the habitat needs of salmonids in fresh water and on the carrying capacity of the estuaries and the Pacific Ocean.

Salmonid migrations and fisheries interceptions complicate harvest management and may contribute to the decline of some populations. According to the equity principle agreed to by Canada and the United States, there must be some compensation in salmon for the interceptions of fish produced in each country. Recently, the United States announced severe measures to protect chinook and coho salmon off the coast and in Puget Sound. Closures and very restricted fishing times were believed to be necessary for protecting wild stocks, despite (or perhaps because of) the relatively large numbers of hatchery-reared salmon. There is concern about the fishing of U.S.-origin stocks in Canadian waters and about the possibility that lower Strait of Georgia stocks may become depleted as well.

In 1993, approximately 4,000 Atlantic salmon were reported caught in fisheries in the Strait of Georgia. These Atlantic salmon are grown in aquaculture operations and escape accidentally. No evidence of harm resulting from these Atlantic salmon introductions has been presented, but studies that might reveal such harm or the risk of harm are needed.

Marine Fish

The most valuable non-salmonid fish stock in the marine waters is Pacific herring, which also plays an important role in the food web. In the Strait of Georgia, herring stocks are sustaining acceptable population levels, perhaps reaching historic high levels of abundance. In the late 1980s and early 1990s, there have been a number of very successful spawnings that have produced strong year classes. In Puget Sound, catches have fluctuated since 1944. They are now at low levels, principally because of the decline of the historically largest stock, which is located in U.S. waters of the southern Strait of Georgia. This stock has not rebuilt despite the closure of the fishery (Schmitt et al., 1994), suggesting that in recent years that factors other than overfishing are affecting stocks or that stocks were fished below a critical population level.

Lingcod have been overfished on both sides of the border (Schmitt et al., 1994). Stocks in both Puget Sound and the Strait of Georgia began declining in the 1970s and are now at critically low levels. Mature lingcod are territorial, and their populations might benefit from a program in which protected areas were set aside to spare at least a minimum spawning stock from fishing pressure. Very young lingcod are highly migratory, so it is possible that protected areas could "seed" other areas with young lingcod.

Pacific hake is another important midwater fish in the Strait of Georgia and Puget Sound. Abundance estimates vary and appear to be approximate, but the estimated 120,000 metric tons (mt) of adult hake in the Strait of Georgia, where they are the most abundant fish species, represent approximately 240 million fish. Hake appear to have been about 10 times more abundant in the Strait of Georgia than in Puget Sound, where the maximum biomass was approximately 15,000 mt in 1983 and now is about 5,400 mt. There is good evidence that the stocks were overfished in Puget Sound in the early 1980s, resulting in a total closure in the late 1980s. Additional monitoring and research studies could help determine the reasons that these populations have not recovered and might suggest ways to restore them.

Other species of concern are rockfish in both areas, pollock in Puget Sound, Pacific cod in both areas and some flatfish in both areas. The reasons for the concern vary. In some cases population declines may result from natural population cycles, but declines in rockfish in Puget Sound appear to result from overfishing (Schmitt et al., 1994). Despite efforts to restrict fishing, overall marine fish populations in Puget Sound have failed to recover, and harvests are at the lowest levels in 55 years. There is additional concern that rockfish will become as seriously depleted in the Strait of Georgia as in Puget Sound, for similar reasons. Rockfish are long-lived, and stocks rebuild slowly. Unless catches are monitored closely, it is probable that overfishing of some species will occur. A system of protected areas also could help shelter a rockfish spawning stock to sustain viable populations.

The marine fisheries or groundfish and pelagic fisheries do not appear to be as extensively managed as the salmon fisheries. In part, the reason appears to be that there are more species, but there also has been less concern about these stocks than for salmon because of the considerably higher harvest value of salmon. Many of these non-salmon species are important to the recreational fisheries and as a result may be quite valuable. Some government agencies may not have adjusted to the reality that the non-salmon fisheries that still sustain normal population levels will continue to be a valuable resource to the non-commercial sector. Our knowledge of marine fish ecology, habitat requirements and population dynamics is not extensive. Additional research is needed.

Invertebrates

Large and sustained populations of invertebrates are found throughout the shared waters, including small benthic invertebrates living in the soft-bottom sediments, intertidal snails and limpets, and subtidal animals such as sea stars and sea urchins (Brinkhurst et al., 1994). Many species of invertebrates are harvested com-

mercially and recreationally, while others are not used by humans. Traditionally harvested invertebrates include bivalve shellfish, crab and shrimp, sea urchins, and sea cucumbers. In recent years, non-traditional harvests have targeted other invertebrates, including small clam species, snails, chitons and shore crabs.

Invertebrate stocks that are harvested commercially, and most recreationally harvested stocks, are generally sustaining their population levels but face many threats (Bourne and Chew, 1994). In the Strait of Georgia, crab catches are generally at high levels, and populations appear to be robust in Puget Sound as well. In some areas of the Strait of Georgia, shrimp populations are average or even low, but prawn catches remain high. In a few areas of the Strait of Georgia there are signs of overfishing on shrimp and prawns, and there is also evidence of natural abundance fluctuations (Bourne and Chew, 1994). In Hood Canal (Puget Sound) there is an important recreational fishery for prawns, which continues to sustain an adequate population.

Bivalve shellfish resources and marine aquaculture operations are currently facing problems that either curtail use or prohibit expansion of operations. The major problem in both areas is not the depletion of stocks but an expanding human population that introduces conflicts regarding use and contaminates nearshore areas. In Puget Sound, more than 30 percent of shellfish growing areas have been classified downward to conditional or restricted use because of fecal coliform bacterial contamination (Bourne and Chew, 1994). In the Strait of Georgia, there are approximately 100 areas closed to the harvest of shellfish for the same reason. Management of commercial bivalve resources might become a problem in the future if immature bivalves originate from hatcheries, and stocking beaches may conflict with the desire to maintain natural conditions in intertidal reserves.

The commercial or recreational shellfish species whose population is most threatened is abalone (Bourne and Chew, 1994). All stocks are low in British Columbia, apparently because of overfishing, and fisheries are closed. It is not known when the stocks in British Columbia may be rebuilt and the fishery reopened. Geoduck landings have remained steady or declined slightly over the past 10 years, but the species must be managed carefully because it is long-lived and thus may easily be overharvested (Bourne and Chew, 1994).

The harvesting of non-traditional marine invertebrates (sometimes called nongame marine invertebrates) may be taking an environmental toll on beaches in urbanized areas of British Columbia and Washington. Creel censuses (counts of animals harvested) of invertebrate species and surveys of beaches that have been heavily harvested show that large numbers of small animals are being taken, primarily by Asian immigrants and native peoples (Cummins and Kyte, 1990). Effects of these

fisheries on overall invertebrate populations are unknown. Before effective management of these resources can be put in place, fisheries agencies should undertake further research and monitoring of these invertebrates and the habitats in which they are harvested.

As human populations increase, consideration must be given to excluding more and more shellfish areas from the commercial wild harvest and assigning them to the recreational fishery. Intertidal areas are finite, and as more recreational groups demand use of the areas, there will be conflicts unless strategic plans for use are in place. One possible solution in British Columbia is to create nearshore recreational reserves that could perhaps be managed by local coastal communities. In Washington, parks are set aside for recreational shellfish harvesting, but no similar mechanism currently exists in British Columbia. Enhancement of natural shellfish stocks by planting of hatchery seed is becoming technically possible. However, by affecting the genetics of invertebrate stocks, such enhancements may present a challenge to managers who may also be attempting to preserve natural ecosystems in protected areas.

Birds

Large numbers of marine birds live in the shared waters area. Eighteen species of marine birds, comprising approximately 60,000 breeding pairs, bred within the marine shoreline habitats of Puget Sound and the Strait of Juan de Fuca in 1989. Protection Island in the Strait of Juan de Fuca is a vital and sensitive seabird nesting area that has been set aside as a wildlife refuge. In 1988, breeding populations of seabirds in the Strait of Georgia were estimated to be about 36,500. Recent observations of marine birds at sea were made in the winter. The maximum number of water birds that pass through and use estuaries and beaches in the Strait of Georgia was estimated to be 400,000-500,000. The Fraser River estuary and the Boundary Bay beach contained 70 percent and 93 percent, respectively, of the totals found on the estuaries and beaches,. In all marine waters of Washington state, approximately 500,000 to 600,000 birds are present in winter, compared to about 120,000 to 135,000 in summer (Mahaffy et al., 1994).

The Fraser River estuary has one of the largest wintering and migrant shorebird populations in the transboundary area. Various species migrate through the estuary to feed. For example, between 500,000 and 1 million sandpipers are found in the estuary during late April (Mahaffy et al., 1994).

Birds in the shared waters in most cases are sustaining their populations. A number of populations have increased in abundance, some have remained about

constant, and a few are depressed. Populations of Canada geese, glaucous-winged gulls, ring-billed gulls, caspian terns, pelagic and double-crested cormorants, bald eagles, peregrine falcons, and osprey are increasing. In Puget Sound, bald eagle populations have increased dramatically from 114 nesting territories in 1975 to 459 in 1992. Peregrine falcon nests in the San Juan Islands increased from one territory in 1980 to nine in 1992. Osprey nesting territories increased statewide in Washington from 168 in 1984 to 373 in 1989, with dramatic increases in the Puget Sound area. In British Columbia, bald eagle populations also increased approximately 30 percent between 1974 and 1987, with 97 occupied nests in 1987 (Mahaffy et al., 1994).

Marbled murrelet, common murre, and tufted puffin populations are low, prompting concern. Although accurate population counts are lacking, marbled murrelet abundance is low, possibly because of nest predation and the loss of nesting sites in old-growth forests. Murrelets are classified as threatened in the United States. Washington's total common murre population has decreased from about 30,000 individuals in 1979-82 to approximately 3,500 in 1993 (U. Wilson, personal communication). In 1993 and possibly in 1992, they experienced reproductive failure, which is thought to have resulted from a number of natural and human causes. Tufted puffins have been scarce recently at most sites in the eastern Strait of Juan de Fuca and the San Juan Islands. The low abundance is thought to result mostly from human disturbance (U. Wilson, personal communication).

The most serious threat to the health of marine bird populations probably is degradation and destruction of habitat resulting from human population growth and development. Large numbers of birds spend the winter in the transboundary area. In Puget Sound, approximately 70 percent of the tidally influenced emergent wetlands have been lost to development (Mahaffy et al., 1994). More than 75 percent of the marshes of the Fraser River delta and almost 32 percent of the former estuarine marshland on Vancouver Island now lie behind dikes, and it is important that these feeding areas be protected.

Incidental capture in salmon gillnet fisheries is also a cause of bird mortality. Accurate estimates of the numbers and species affected are not available, but some experts believe that more birds are killed in U.S. fisheries than in Canadian fisheries. It has been suggested that such a difference might result from the use of nearly invisible nylon monofilament nets by U.S. fishers (Kaiser, 1993; Troutman et al., 1991).

Mammals

Nine major species of marine mammals occur in the shared waters, and several other species are occasional visitors. Most marine mammals in the shared waters

seem to be sustaining their population levels. Harbor seals are the most abundant (Calambokidis and Baird, 1994), and their populations are increasing at 10 percent-15 percent per year. Harbor seals breed at numerous locations in the shared waters, and their high rate of increase may result from the removal of a bounty in the early 1960s, federal and state protection in U.S. waters since the early 1970s and possibly an abundance of food.

California sea lion and elephant seal populations also have increased steadily in the shared waters, although neither breeds in these waters (Calambokidis and Baird, 1994). California sea lions breed on islands off Baja, Mexico, and Southern California, with males migrating to the shared waters primarily to feed. California sea lions consume Pacific hake, walleye pollock, Pacific herring, and spiny dogfish. Northern elephant seals occur in small numbers, but little is known of their feeding habits.

Steller sea lions are year-round residents in British Columbia and seasonal visitors to Washington waters. Breeding populations in Alaska and California have declined drastically over the last 30 years, but those in British Columbia have remained stable in recent years. Steller sea lions are listed as threatened in the United States. (Calambokidis and Baird, 1994).

The best known local marine mammal is the orca (killer whale). In the transboundary area there is a transient and a resident population, the latter being one of the most studied whale populations in the world. The resident population contains 96 individuals and has been increasing at about 1 percent-2 percent per year since live capture was stopped in 1977. The transient population may contain approximately 160 individuals (Calambokidis and Baird, 1994). In contrast, other species, such as harbor and Dall's porpoises, receive less attention. Their populations appear to be declining, but little is known about their population dynamics. These species merit research on abundances and mortality rates.

Large numbers of gray whales migrate along the outer coasts of Washington and British Columbia, and a few come into the shared waters for about four months each summer to feed in shallow water on small organisms living in the bottom. Many of the dead gray whales that wash up on beaches appear to be undernourished, and other causes of death include entanglement in gillnets, boat collisions, and orca attacks (Calambokidis and Baird, 1994).

Despite the increasing populations of most species, marine mammals remain vulnerable to human activities. Perhaps the greatest immediate threat to the abundance of marine mammals comes from commercial fishing or intentional killings. Harbor seals, California sea lions, and Steller sea lions occasionally are shot by fishers. Aquaculture operations in British Columbia can legally shoot harbor seals and Califor-

nia sea lions. Gillnets set for salmon will catch and kill porpoises in the transboundary area, although the number killed is unknown.

> ***QUESTION—To what degree do the biological resources of the Strait of Georgia, Puget Sound and Juan de Fuca Strait move across the international border? Biological resources include invertebrates, finfish, birds and marine mammals.***

Transport of Living Resources

Despite the exchange of water among Puget Sound and the straits of Juan de Fuca and Georgia, there appears to be a barrier to the movement of some animals among these segments of the transboundary area. The nature of this barrier is not understood, and the barrier does not exist for all animals, but there are clear indications of distinct populations of some similar species in the shared waters that do not mix.

Fish

Perhaps the most obvious example of stock separation is provided by Pacific hake, which are depleted in Puget Sound. Hake are more abundant in the Strait of Georgia, and if there were an exchange between the Strait of Georgia and Puget Sound stocks, there should be some signs of recovery in the Puget Sound stock, but there are not. If pelagic eggs and larvae, or young or adult hake, find their way alive from Canadian waters into Puget Sound in significant numbers, they may be suffering from predation, habitat loss or other factors during or after the transfer. Additional research is needed to determine why Puget Sound stocks are not recovering.

Pacific herring stocks in Puget Sound and the Strait of Georgia also appear to be separate, despite a migratory pattern that results in movements in and out of the Strait of Juan de Fuca and possible intermingling of the two stocks in the offshore feeding grounds. Like hake, herring have a pelagic larval stage that might be expected to result in some movement into Puget Sound. However, the two stocks appear to maintain their separation, even with a common water body. Stocks in Canadian waters may be at historic high levels, while the stock inhabiting the U.S. portion of the Strait of Georgia is depleted (Schmitt et al., 1994). There is some evidence of localized

exchange of herring larvae across the border in this region (Levings, personal communication).

There is some exchange of salmon stocks between Puget Sound and the Strait of Georgia. There is movement of hatchery-reared coho and chinook salmon from Puget Sound into the Strait of Georgia. Releases from U.S. hatcheries total approximately 60 million-70 million chinook and 40 million coho salmon, and possibly 20 percent of these releases may find their way into the Canadian zone. Canadian hatchery releases into the Strait of Georgia may account for approximately 30 million chinook and 10 million coho, some of which move into Puget Sound.

Natural migration patterns of wild salmon stocks also cross the international boundary. The majority of pink and sockeye salmon reared in the Fraser River pass through U.S. waters when they return as adults. One million-3 million sockeye salmon caught by U.S. fishers in Puget Sound and roughly 50 percent-75 percent of U.S. pink salmon catches,originate from the Fraser River (Schmitt et al., 1994). Canadian fisheries intercept about 44 percent of chinook salmon produced in Puget Sound and 62 percent and 42 percent of the coho salmon produced in the north and south regions of Puget Sound, respectively (Schmitt et al., 1994). Extensive monitoring of salmon stocks in the shared waters continues. Research that will aid survival of wild stocks is still needed.

Invertebrates

Most adult invertebrates would not be expected to undergo extensive exchange across the border. The larvae of many of these animals are planktonic, however, and susceptible to transboundary exchange. Nevertheless, for most species there is little evidence of natural exchange of invertebrate populations between Puget Sound and the Strait of Georgia (Bourne and Chew, 1994). This lack of evidence may result from lack of data, because large numbers of planktonic larvae almost certainly are carried by the strong tidal exchange. There probably are exchanges between areas such as Boundary Bay and either Puget Sound or the Strait of Georgia, but some factor (possibly predation, for example) seems to limit the survival of planktonic larvae exchanged through the Strait of Juan de Fuca and therefore creates an apparent barrier to free natural exchange of the planktonic stages.

A lucrative Dungeness crab fishery occurs on both sides of the transboundary area and is probably the exception among invertebrate populations. Young crabs settle in this area from the larval stages that are found in the plankton. In recent years, abundance has remained high, suggesting that adequate spawning is occurring. Plankton studies in the Strait of Georgia indicate that large quantities of larval crabs

are produced. Thus, the crab populations on the mudflats in the transboundary area may contribute young crab to populations in other areas of the shared waters.

The exchange of invertebrates across the border, intentionally or unintentionally, might become a serious issue, however, because it could foster the spread of exotic species introduced somewhere within the shared waters. Recent studies have shown that larval and spore stages of many organisms can be transported great distances across ocean basins in ballast waters, as well as by other mechanisms. There already have been extensive introductions of invertebrates into the Strait of Georgia (Levings, personal communication). Nevertheless, introductions of new species are still a cause for concern. Several plant species, including *Spartina* species and invertebrates such as the oyster drill have been identified locally. Precautions are necessary to prevent the careless introduction of additional marine invertebrates into the area. Careful monitoring is needed to track the introduction and spread of exotic species, while research studies may develop strategies to enable indigenous species to outcompete the invaders.

Birds

Of all animals, marine and water birds would be expected to move most freely across the border. The shared waters are located on the Pacific flyway connecting Alaska and the Arctic with wintering areas to the south. Bird migrations along this flyway are well documented. Wintering bird populations in the shared waters tend to be much larger than summer breeding populations. Species diversity also varies greatly between seasons and reaches its peak in winter. Monitoring and research on birds will better determine areas of critical importance to resident and migratory birds in the shared waters.

Mammals

All of the nine major species of marine mammals in the transboundary area move across the international border. Harbor seal stocks breed locally. California sea lion and elephant seal males migrate to the shared waters area primarily to feed. Steller sea lions are seasonal visitors to the area from central and northern British Columbia waters. Harbor porpoise and Dall's porpoise are found in the area, but little is known about their migrations or population dynamics. In the shared waters there is a transient and a resident population of orca whales. Large numbers of gray whales migrate along the outer coasts of Washington and British Columbia during spring and summer as part of their migrations between winter breeding grounds in Baja, Mexico, and their summer feeding grounds off Alaska. A few come into the shared waters

each year, generally staying about four months and moving readily across the transboundary area and throughout the shared waters (Calambokidis and Baird, 1994). Research studies on marine mammal population dynamics and movements are needed to understand future threats to their populations.

5. Anthropogenic Impacts on the Ecosystem and Humans

QUESTION—What evidence is there for harm from transboundary pollution and other anthropogenic influences to the habitats, aquatic biota, human uses or public health of the Strait of Georgia, Puget Sound and the Strait of Juan de Fuca? As compared to five or 10 years ago, is the severity of harm greater, less or the same?

Ample evidence indicates that pollution and habitat changes in the Strait of Georgia (near Vancouver) and Puget Sound (around Seattle-Tacoma-Everett) are now adversely affecting individuals and populations of certain marine and anadromous fishes and invertebrate species. However, effects on entire *community assemblages* of marine biota—that is, on the total numbers of organisms present and on their ability to sustain those numbers—are often very difficult to quantify. Changes in fish and wildlife populations almost always have multiple causes, such as environmental conditions (e.g., temperature and wind velocity), variability in recruitment of young to the adult population, harvest rates, food supplies, predation, and effects of toxic chemicals and/or habitat changes on individual organisms. A great deal more research is needed in this area.

Effects of Habitat Destruction and Alteration on Aquatic Biota

Importance of Habitat

The connection between abundant high-quality nearshore and subtidal habitat and the health of fish and wildlife populations is well known. Habitat is a resource that every organism requires and that occurs in a finite supply. A majority of the commercial, recreational and ecologically important organisms in the shared waters either depend critically on nearshore habitat at some stage of their life cycle or depend on other organisms that themselves have such a dependency.

Although scientists have begun to trace the linkages between specific habitats and certain species, it is clear that fish and wildlife populations require habitat for feeding, rearing and refuge from predators. Elaborate food webs support animals ranging from salmon to ducks, with phytoplankton, seaweeds, seagrasses and detritus providing energy sources. Juvenile fish find safe refuge and plentiful food while gaining strength before venturing into open water; waterfowl find food and protection from storms; and primary production is processed through bacteria and invertebrates and passed on to fish and wildlife in the basin's nearshore habitats. Many nearshore and terrestrial wetlands also retain storm water and release it slowly, minimizing coastal flooding, and nearshore and upland vegetated wetlands improve water quality by filtering out contaminants. Continued research and monitoring will help bring to light the importance of specific habitats to marine organisms.

Habitat Loss and Degradation in the Shared Waters

Habitat is degraded or destroyed mainly by physical alteration for forestry, agriculture, and building and land development. Chronic chemical inputs and larger spills of oil and other chemicals also degrade habitat quality and affect many organisms directly. Invasions of non-indigenous exotic species (most notably the cordgrass *Spartina*) also are changing the functions of many coastal habitats.

Degradation of habitat occurs both along saltwater shorelines and upstream in watersheds. Logging, dam-building, land clearing for development and other land uses can do significant harm to riverine habitats for anadromous fishes. In addition, these activities can cause harm downstream in the estuary.

Logging may cause scouring of river channels and thereby increase sedimentation. Land clearing for agriculture and other kinds of development can increase erosion and sedimentation in much the same way. In addition, agriculture and residential development may increase loadings of chemical contaminants, such as fertiliz-

ers, pesticides and household hazardous wastes, that reach coastal habitats. Commercial and industrial developments, as well as roads and streets, create impervious surfaces from which storm water runs quickly, adding additional scour and toxic chemicals to coastal habitats.

Damming reduces river flows and decreases the supply of sediment to the coastal environment. Reduced sediment input by rivers also can accelerate erosion and destruction of coastal habitat. Erosion problems could be especially troublesome given both the existing steady rise in sea level observed in inland marine waters and the acceleration in sea level rise projected under scenarios of global warming (Peltier and Tushingham, 1989; Houghton et al., 1990). Permanent changes in river flow may alter patterns and seasonal variations of the coastal salinity field in the water column and could affect both surface currents and estuarine circulation rates. Such changes might have widespread effects on the flushing of contaminants, the quality of nearshore habitat and the life cycles of marine organisms that are sensitive to water salinity and transport.

Habitat loss is particularly troublesome to organisms because the loss is incremental and cumulative. Areas of marshland, for example, usually are not lost suddenly, but rather gradually by encroachment or by indirect, sometimes remote alteration of the landscape, which affects the water balance in the marsh. Thus protection of an area must be viewed on a larger scale than that defined by its immediate boundaries. Today, various remediation measures are attempted in association with sites of present or past habitat destruction. However, sites where artificial habitat restoration is attempted often are not monitored over the long term, so the level of success of the remediation effort is not well known. There is a great deal more to be learned from research on habitat remediation techniques.

A variety of marine habitat types critical to the survival of various life history stages of a number of fish species have declined over the last several decades in the shared waters as a result of human activities. Dredging and filling associated with harbor and port development have destroyed extensive areas of eelgrass. Intertidal eelgrass habitats are essential to herring (as spawning substrate) and Dungeness crab (for protection of megalops stages). Juvenile chum and fall chinook salmon, and to a lesser degree, pink and coho salmon, are highly dependent upon eelgrass beds and estuarine wetlands. Losses of such wetlands have been extensive in Puget Sound, with an estimated loss of 58 percent, whereas losses in the Strait of Georgia have been less (18 percent) (Levings and Thom, 1994). The rate of loss of habitat in the Georgia Basin during the last five to 10 years has not been thoroughly quantified. Losses of habitat in urban bays have been far above the basin-wide averages. In the North Arm of the Fraser estuary near Vancouver, for example, 96 percent of the brackish marsh

habitat has been lost in the last 100 years (Levings and Thom, 1994) as a result of human alteration of the shoreline and nearshore area. In the urban estuaries of the Duwamish (Seattle) and Puyallup (Tacoma) rivers, 99 percent and 100 percent, respectively, of the wetland areas have been lost (PSWQA, 1992).

Effects on Salmonids: Habitat Loss and Contamination

Degradation of freshwater habitats has harmed a large number of stocks of Pacific salmon, steelhead trout and dolly varden. Dams block the passage of returning adults in a number of rivers. Stream simplification (e.g., channel straightening) and loss of stream complexity (e.g., by siltation and scouring) are other important types of habitat changes that affect salmonid survival (Bisson et al., 1992). Few studies have linked these latter types of alterations with declines in specific salmon populations. In one study, however, the long-term effects of forestry practices on a stream system in British Columbia were evaluated with a series of models. The models were used to determine the parts played by various forces in the variability in adult returns of coho and chum salmon. The forces examined were climatic variability in the stream and ocean, variations in fishing mortality and changes in stream conditions caused by logging. The results suggested that chum salmon were adversely affected by logging activity, whereas coho salmon were not as affected (Holtly and Scrivener, 1989).

Like English sole, outmigrating juvenile chinook salmon feed on sediment-dwelling organisms as they move through urban estuaries. During their relatively short residency of two to eight weeks, the salmon bioaccumulate significant concentrations of toxic chemicals. When salmon from a contaminated estuary in Seattle were held in tanks with flow-through seawater for a period of several months, they exhibited increased mortality and reduced growth in comparison with salmon from a non-urban estuary (Varanasi et al., 1993). Juvenile salmon from this urban estuary also showed evidence of immune dysfunction. Suppression of immune function could weaken the fish's resistance to pathogens and increase vulnerability to a variety of diseases and could have accounted in part for the decreased survival of juvenile salmon from urban estuaries during laboratory holding.

These studies strongly point to the need to further evaluate the effects of chemical contaminant exposure as a potential contributing factor affecting salmon returns. For example, returns of adult native Chinook salmon to the Puyallup River, which enters highly contaminated Commencement Bay in Tacoma, have been at critically low levels in recent years (Washington Department of Fisheries, 1993).

Effects of Contaminants on Marine Bottomfish

Toxic contaminants are present at high concentrations in sediments at a number of sites in Puget Sound and Vancouver Harbor. Elevated concentrations of these contaminants also can be found in bottomfish from most of these sites. Fish from contaminated areas not only show elevated levels of chemicals in tissue and body fluids, but also show other physiological changes that indicate biological responses to contaminant exposure.

When organisms are exposed to pollutants, effects on biochemical processes are the first to be observed. One of the earliest changes is increased activity of certain liver enzymes. These enzymes break down aromatic hydrocarbons (compounds associated with the use of fossil fuels, such as oil) and a variety of other toxic compounds. Binding of chemical carcinogens to DNA in the liver, a genetic alteration that is thought occur early in the sequence leading to cancer induction, is another type of early change. Both of these types of biochemical alterations have been found in a variety of bottomfish species from several areas in Puget Sound with elevated sediment contaminant concentrations. In addition, DNA damage in the liver is positively correlated with other indicators of pollutant exposure, such as tissue levels of PCBs, and with prevalences of certain liver diseases (Johnson et al., 1994).

Reproductive Problems

Some bottomfish appear to suffer impaired reproduction in contaminated areas of Puget Sound. Ovaries in contaminated female English sole from Puget Sound are less likely to develop normally, and levels of the hormones necessary for ovaries to mature decrease on exposure to extracts of contaminated sediments in laboratory studies (Johnson et al., 1994). Even when ovaries do mature in these specimens. the fish may suffer other problems such as reduced egg and larval viability.

Although there are indications that contamination may affect the ability of an English sole population to reproduce, it is not clear whether their average spawning success is related to the level of contamination in the spawning area. Preliminary field studies suggest that contaminants also may alter reproduction in rock sole and flathead sole, but not as severely as in English sole. Further investigations are needed.

Little information is available on the impact of environmental contaminants on reproductive function in fish from British Columbia embayments, although effects similar to those observed in Puget Sound English sole may occur in fish from heavily contaminated sites such as those in Vancouver Harbor. Fish residing in areas adjacent to pulp mills may also be at risk: studies in eastern Canada have shown that

bleached kraft mill effluent may disrupt or alter reproduction function in several freshwater fish species (Munkittrick et al., 1991). However, there is little likelihood of such problems occurring at non-urban sites that have been sampled thus far in the transboundary region along the U.S.-Canada border, as sediment contaminant levels in these areas are quite low (PSWQA, 1992).

Liver Abnormalities in Marine Bottomfish

English sole from a number of chemically contaminated areas in the vicinity of Seattle, Tacoma and Vancouver also exhibit liver cancers, precancerous liver lesions and chemical changes in the blood indicating liver damage. Although the cancers are more dramatic, the precancerous conditions are much more prevalent and are found in animals at both moderately and heavily contaminated sites. Lesions and cancers are consistently correlated with contaminant exposure, and exposing fish experimentally to toxicants and contaminated sediment extracts can induce lesions (Johnson et al., 1994).

There is some evidence of similar conditions in the transboundary area. English sole and other flatfish in Victoria Harbor and in the vicinity of two British Columbia pulp mills show some contaminant-related liver lesions, but additional sampling and documentation of contaminant exposure are needed to determine the degree of harm (Johnson et al., 1994).

A connection between liver lesions and the death rate of English sole has not yet been demonstrated (Johnson et al., 1994). Computer models have been used to explore the potential impact of liver lesions and reproductive impairments on English sole populations. The model predicted declines in reproductive output similar to those observed in fish from contaminated sites and indicated that such declines could decrease the growth rate of English sole populations in Puget Sound if a significant proportion of the population resides in contaminated areas (Johnson et al., 1994).

Anthropogenic Effects on Invertebrates

A number of studies have shown that some sediment-dwelling, or benthic, invertebrates in some areas of urban embayments and near certain industrial sites in the shared waters have elevated tissue levels of potentially toxic contaminants. Moreover, the laboratory evidence to date indicates that sediments from contaminated environments in the shared waters may be toxic to representative infaunal members

of the benthic community. Toxic effects range from sublethal changes, such as growth inhibition, to mortality (Brinkhurst et al., 1994). Whelks (a type of snail) in the shared waters have shown reproductive problems caused by the contaminant tributyl tin (TBT), which was routinely used in boat-bottom paint (Alvarez and Ellis, 1990).

The characteristics of benthic invertebrate communities (e.g., species richness, diversity, abundance) have been investigated at numerous sites in the shared waters; evidence so far indicates that aberrant communities are found primarily near urban centers and industrial sites. Although it is often difficult to link these changes to specific anthropogenic inputs, a few studies have demonstrated links between certain sediment-associated contaminants and species richness. In addition, benthic invertebrate communities in contaminated areas are frequently dominated by hardy organisms, such as certain species of polychaete worms, that are able to live in highly stressed environments (Brinkhurst et al., 1994). In Howe Sound, some shellfisheries were closed because of high tissue levels of dioxins, but these levels appear to be declining (Bourne and Chew, 1994). Considerably more research is needed in this area.

Another anthropogenic factor that has impacted commercially and recreationally important bivalve populations has been the accidental introduction of pests and diseases, such as the Japanese oyster drill and certain other parasitic organisms.

Effects of Contamination on Marine Birds and Mammals

Historical evidence indicates that populations of marine birds have been adversely affected by anthropogenic factors, such as habitat alteration and pollution (Mahaffy et al., 1994). Successful bird reproduction appears to be sensitive to contaminants. Since 1977, Canadian scientists have used eggs from great blue heron and selected cormorant species to monitor trends in environmental contaminants in the Strait of Georgia. Levels of PCBs, DDE, dieldren, heptachor epoxide, PCDFs and PCDs, and other chlorinated hydrocarbons were high in the 1970s but have fallen since.

Based on results of monitoring contaminants in several waterfowl species, a health advisory regarding the human consumption of livers from Western grebes and common mergansers was issued in British Columbia in 1990. The few studies conducted on contaminant concentrations and shell thinning in eggs of marine birds in Washington's inland marine waters indicated that eggs with the highest contaminant concentrations and greatest egg shell thinning were found in urban and industrial

centers and agricultural areas. Further research is needed to determine whether birds are at risk from newly introduced pesticides and other synthetic chemicals. Birds are also at risk from oil and hazardous material spills, entanglement in commercial fishery nets, and other human disturbances (Mahaffy et al., 1994). However, the greatest harm to waterfowl, seabird and shorebird population in the shared waters is caused by loss of nesting and feeding habitat.

Among marine mammals, highest concentrations of contaminants have been found in harbor seals (from southern Puget Sound), harbor porpoise and killer whales (Calambokidis and Baird, 1994). Determination of the impacts of these contaminants on marine mammals in these waters has been inconclusive, though in other areas of the world, contaminant exposure has been linked to reproductive failure and immunosuppression. Several grey whale deaths have occurred in Puget Sound in recent years, but despite some reports linking these deaths to contamination, most of the evidence points toward other causes (Calambokidis and Baird, 1994), although there is a continuing need to monitor contaminants in marine mammals. Marine mammals also are vulnerable to disturbance and habitat loss, and a small number may be killed incidental to commercial fishing operations.

Temporal Changes in Contaminant Levels and Biological Effects

Available data on disease and contaminant levels in fish are not sufficient to provide a definitive picture of long-term changes in fish health in the waterways of Washington and British Columbia. However, conditions appear to be improving in certain industrialized areas in Puget Sound. Data collected over the past 10 years show a decline in the levels of aromatic hydrocarbons and their derivatives in English sole from Elliott Bay (Seattle). This trend is paralleled by a decrease in the prevalence of certain early liver lesions in fish collected from these sites (Johnson et al., 1994).

These findings suggest that regulatory measures instituted in Elliott Bay over the past several years, such as restrictions on hazardous waste disposal, reductions in the number of combined sewer overflow events and pre-treatment of industrial wastes before discharge to sewage plants, have had positive effects in the marine environment. However, levels of chemical contaminants and fish disease in Elliott Bay are still among the highest measured in the United States. Moreover, although input of certain types of industrial wastes such as PCBs and DDTs has certainly declined since they were removed from the Canadian and U.S. markets in the 1970s, these compounds are persistent in the environment and may exert their effects for some time.

The input of aromatic hydrocarbons from nonpoint sources may be increasing as the population and degree of urbanization increases in coastal Pacific Northwest and represents a continuing unresolved problem. Available data suggest that at non-urban sites around Puget Sound, contaminant concentrations and disease levels in fish appear to have remained relatively constant over the past 15 years, but it is likely that toxicant levels in such areas will increase at least moderately as a result of increased human population density.

Human Health Risks

Humans can face possible health threats from the marine environment through two major exposure routes: direct contact with contaminated seawater or sediment, or consumption of contaminated seafood. Water contact recreation in the shared waters is minimal in most locations because of cold water temperatures. The most likely pathway for this type of contamination is the ingestion of contaminated water or sediment by small children, and some contact with contaminated waters by sailboarders, divers and boaters. This is clearly not a major health threat to a widespread segment of the population. Seafood can be contaminated with pathogens or chemical contaminants or both. Seafood becomes tainted when the marine organisms ingest and concentrate contaminants from seawater, sediment or prey. The human health risk posed by contaminated seafood is considered to be low for most local residents (Kalman et al., 1994) but may be higher for some ethnic groups with higher seafood consumption rates, such as Native Americans and Asians.

Human health risks projected from current levels of chemicals from all sources in the marine environment are small or undetectable (Kalman et al., 1994). However, point and nonpoint source discharges of infectious microorganisms from agricultural and domestic sources may contaminate clams, oysters and other shellfish species used for human consumption (Bourne and Chew, 1994). This risk to human health has prompted the closing of 40 percent of commercial acreage (PSWQA, 1992) on Puget Sound and local areas of the Strait of Georgia to shellfish culture and harvesting. Under these precautions and other current management practices, however, the human health risks continue to be relatively low.

Toxic algal blooms represent an additional threat to human health in the shared waters, most notably from paralytical shellfish poisoning (PSP) and amnesic shellfish poisoning (ASP, caused by the toxin domoic acid) (Taylor and Horner, 1994). Certain species of toxic phytoplankton episodically bloom and are eaten by shellfish,

which concentrate the toxins. These toxins can be fatal in small doses to humans and other warm-blooded animals. Incidences of toxic algal blooms in the shared waters have been more frequent in recent years (as they have worldwide), but there is no clear evidence that human activities play a role in their prevalence or distribution.

6. Ecosystem Sensitivity and Future Scope of Anthropogenic Impacts

QUESTION—What components of the transboundary marine ecosystem appear to be the most sensitive to harm from human activities?

Sensitive Ecosystem Components

Our judgments of the components of the shared waters most sensitive to harm from human activities are presented below. The components are discussed in order of decreasing sensitivity, with the most sensitive component (fish and wildlife habitat) presented first, and the least sensitive (human health effects from the marine environment) presented last.

Fish and Wildlife Habitat

When pristine habitat is abundant, it is resilient and can tolerate considerable localized disturbance. Today, however, certain types of natural habitat are scarce, and disturbances are ubiquitous in the shared waters. The remaining fish and wildlife habitat can be harmed by physical alteration, resource overuse and disturbance. The habitats most vulnerable to disturbance, and those that have suffered the most harm, are those in closest contact with human activities. Scientists believe that these are also the habitats in the basin that are the most critical for the survival of threatened fish and wildlife populations. Ironically, we have very poor inventories of nearshore habitats in British Columbia and Washington; further research and monitoring are needed.

Nearshore estuarine habitat has been most severely affected, primarily in urban areas, and secondarily in suburban and rural areas. Upland wetlands are being irreversibly filled and degraded in the basin. Subtidal habitats in general are less at risk mainly because they are further removed from human activities. There is a general correlation between the distance from major population and development centers and the condition of the habitat, although poor forest practices and freshwater diversions have radically altered habitat in many remote areas.

Fish, Shellfish, Birds, Mammals and Marine Plants

Loss of critical habitat, fishing pressure (including unintentional bycatch of many species including birds and mammals), human disturbance (especially of bird nesting grounds) and other inadvertent human impacts take the greatest toll on the basin's living marine resources.

The most vulnerable species are those whose populations would not rebound quickly if environmental stresses were reduced. The maximum possible protection should be extended to species considered threatened or in danger of extinction, regionally or globally. In the shared waters, these include several Puget Sound runs of salmon and steelhead, the marbled murrelet, and the Steller sea lion.

The next level of protection should be afforded to those populations that are depressed or depleted. This list would include several salmon stocks in Puget Sound and chinook salmon in the Strait of Georgia, marine fish such as lingcod and rockfish on both sides of the border, Pacific hake in Puget Sound, harbor porpoise, harlequin ducks and raptors such as osprey.

The third priority for protection should extend to species that provide important linkages in the marine food web and whose absence could cause wide spread die-offs of other species. These species also may pass contamination up the food chain from their own body burden of chemicals. This group would include baitfish such as herring and smelt, intertidal and shallow subtidal invertebrates, and plankton.

Sediments and Benthic Organisms

Contaminants bound to sediment particles sink to the bottom close to their points of origin except where they are spread by dredging and dredge spoil disposal. Accordingly, the areas of greatest contamination and impacts by dredging and dredge material disposal are in close proximity to the urban areas of the basin. Shallow subtidal estuarine habitat areas are observed to support the greatest diversity and abundance of organisms. Many of these very productive and diverse habitats are close to sources of contamination in and around the urban bays. The threat to bottom

dwellers from toxic contamination decreases with distance from each source. Animals living in, on or close to bottom sediments, generally small invertebrates and fish, are at greatest risk from contamination. Animals that are near the top of the food chain may be vulnerable to accumulating contaminants as well.

Marine Water Column

Most of the shared waters are strongly tidally mixed and flushed. They generally are not at risk for the accumulation of chemical contaminants or excess nutrients. However, these materials may build up in localized areas within poorly circulating bays and close to strong contaminant sources. Because most chemical contaminants bind to particles, the principal toxic chemicals of concern in the water column are those few that remain dissolved in seawater, such as dioxins, furans and associated compounds. Recent studies have suggested that some contaminants may accumulate at the sea surface, dissolved in oils and greases (Word et al., 1990). Further investigations in this area are needed.

Unlike most of the major developed estuaries of the world, the shared waters do not exhibit limited phytoplankton growth as a result of dissolved nutrients. Therefore, discharges of nitrogen and phosphorus do not contribute to additional algal growth, eutrophication or fish kills on a basin-wide scale (Harrison et al., 1994). However, some caution is needed in controlling nutrient inputs to poorly flushed embayments, because marine phytoplankton in these areas are "starved" for nutrients during parts of the summer and may begin to grow rapidly with the addition of nutrients, later dying and robbing the water of oxygen.

Pathogenic organisms are generally believed to be rapidly diluted and killed in sea water, with buildups occurring only in poorly circulating areas. However, little is known about many human pathogens, particularly viruses and protozoans, so there is a need to keep untreated human fecal material out of poorly circulated swimming and shellfish areas until additional research can verify that risks are low from potentially virulent pathogens.

Human Health

Because the most chemically contaminated sediments, water and organisms tend to occur in urbanized and/or industrialized areas, these areas provoke the greatest concern for human health effects of seafood contamination. Fecal contamination is most prevalent in shellfish collected from areas with little or no sewage treatment, in the vicinity of failing septic fields, and in waters receiving agricultural or stormwater runoff. These areas often are rural, although waters off towns and cities without adequate sewage treatment also may be contaminated.

Despite the geographic spread and more frequent observation of toxic algal blooms in the shared waters over the last decade, there is little evidence that local blooms result from human activities. Some types of these blooms are more frequent or more intense in certain areas; these areas are the focus of increased monitoring by public health officials in British Columbia and Washington. Additional research on toxic algae also is needed.

> ***QUESTION—Given forecasts of human population increases for the lands that drain to the Strait of Georgia, Puget Sound and the Strait of Juan de Fuca, and assuming little or no change to the current level of pollution control, harvest management and land use management activities, will the amount or severity of harm from transboundary pollution to the habitats, aquatic biota, human health or public health be greater, less or the same in 20 years?***

> ***QUESTION—Are the transboundary populations of biological resources associated with the Strait of Georgia, Puget Sound and the Strait of Juan de Fuca anticipated to increase, decrease or stay the same in 20 years?***

The Shared Waters in 2014—A Projection of Current Trends

The condition of the shared waters in 20 years will depend on a number of natural and human factors. The primary natural factor is the recovery of each component of the ecosystem from each type of contamination or resource use. Ideally, the system can respond to these stresses and can recover from any harm done. Within limits set by circulation, for example, contaminants can be safely diluted and flushed out of the system or buried in sediments. Likewise, if losses from exploitation and contamination do not exceed reproductive capacity, plants and animals can sustain their populations.

There are a few situations, however, in which no use occurs without some harm, recovery is very slow or impossible, and harm therefore becomes essentially permanent. For example, once altered or destroyed, fish and wildlife habitat recovers to its original state so slowly that the harm is essentially irreversible. Likewise, fish, bird or mammal populations that are depleted below a certain critical level may not recover for decades, if ever.

The primary human factors that will determine the condition of the shared waters in 20 years are the total human population of the region, the average level of fresh water and other resource use and the amount of waste disposal. Recent years have seen significant efforts on both sides of the border to reduce the amount of contaminants entering the system and to manage living resources more carefully. However, as the human population expands, greater efforts will be needed—not only to relieve existing problems of contamination and resource depletion, but also to prevent those problems from actually growing worse.

Relative Risks, Cumulative Impacts, and Uncertainty

If present management practices are not improved, marine resources in the shared waters will suffer significant additional harm over the next two decades. Some of this harm, while apparently serious, would be remedied quickly once the causes were removed. More serious harm is done by gradual, incremental changes that are essentially irreversible and deprive future generations of options. Loss of habitat is the most pervasive change of this kind, although irreversible changes to the shared waters also could arise from introductions of exotic species or from major river diversion projects. Threats that are unknown today—such as harm caused by new forms of chemical contaminants—also may arise. Monitoring and basic research must be maintained to provide the earliest possible warning if such problems arise.

We have listed numerous types of harm individually. We also must point out that no one of these exists in isolation from the others. If we consider types of harm individually, rather than looking at how they affect an ecosystem collectively, we paint an over-optimistic picture. In reality, the effects of multiple environmental stresses are *cumulative* and in some cases may cause effects that are more than additive. The ability of the ecosystem to recover from a single source of harm is diminished if the system is suffering additional stress from other sources—which, given the wide spectrum of harm outlined above, is often the case. In addition, the complexity of the ecological linkages is poorly understood in the shared waters. This fact makes assessment of cumulative effects very difficult.

TABLE 6.1

Current and projected status of components of shared waters: "Business as usual" scenario[1]

	PRESENT STATUS		STATUS CHANGE 1994 to 2014	
COMPONENT	WA	BC	WA	BC
AQUATIC HABITATS				
Vegetated shores	very poor	good	slightly worse	much worse
Unvegetated shores	acceptable	good	much worse	slightly worse
Rivers upstream	poor	acceptable-good	slightly worse	slightly worse
Subtidal	good	good	unchanged	unchanged
Sediments in urban bays	very poor	poor	unchanged	unchanged
Water column	very good	very good	unchanged	unchanged
LIVING RESOURCES				
Salmonids	very poor	acceptable-good	slightly worse	slightly worse
Marine fish	very poor	good[2]	slightly worse	slightly worse
Bottomfish in urban bays	poor	good[3]	unchanged	unchanged
Commercial/recreational invertebrates	good	good	slightly worse	slightly worse
Birds	mixed	mixed	slightly worse	slightly worse
Marine mammals	mixed	mixed	slightly worse	slightly worse
HUMAN HEALTH				
Safety from direct contaminant and pathogen exposure	very good	very good	slightly worse	slightly worse
Safety from contaminated seafood	good	good	slightly worse	slightly worse
Safety from toxic algae	good	good	slightly worse	slightly worse

[1] Assumes (1) existing management programs continue unchanged; (2) no change in current per capita contaminant discharge, resource consumption and land use; and (3) population grows at current rates.

[2] Except lingcod

[3] Except portions of Vancouver Harbor

Furthermore, it is relatively easy to evaluate the time scale for resource recovery following (for example) elimination of contaminant discharge or harvesting pressure. It often can be very expensive or logistically difficult, however, to implement and enforce these remedial measures. Outside the realm of scientific evaluation, these realities complicate the task of forecasting marine environmental quality conditions two decades from now.

Status of Shared Waters

The existing levels of harm visible in components of the shared waters have been reviewed in previous chapters. Table 6.1 presents a synopsis of conditions of these components on both sides of the border at the present time. The conditions range from very good to very poor, depending on the component and the location.

Alongside the present condition column in Table 6.1 is the panel's judgment about how this condition will have changed in 20 years. This "business as usual" scenario assumes that existing management programs continue unchanged. In some cases the harm caused by contaminant discharge or resource use is maintained acceptably low as a result of these existing programs. This scenario also assumes that there will be little or no change in the current *per capita* levels of contaminant discharge, resource consumption and land use. Current upward trends in population growth are assumed to continue.

The judgments in this scenario are qualitative, without detailed calculations of population, contamination, or resource use trends. Furthermore, the judgments are not *predictions* of what the actual state of the system will be in 2014; they are *projections* of existing trends into the future, recognizing that if any of those trends change in the interim, the outcome may differ.

It is immediately evident that no condition is projected to improve. This pessimistic scenario results despite the current trend toward lower per capita discharges of many contaminants and uses of many resources. For example, sediments and bottomfish in urbanized areas are becoming less contaminated as cleaner sediments are being deposited. The panel fears, however, that this decline in most cases would be outweighed by the effects of the projected rate of population increase. Current pollution and resource management practices would appear—at best—only to compensate for the resource contamination and depletion resulting from projected increases in population around the shared waters.

In some cases current pollution and resource management practices do not appear adequate to prevent significant ongoing environmental harm under today's conditions. Wild salmonid and marine fish populations in Puget Sound, for example,

are in severe decline for reasons that are not understood, and there is little prospect of restoration under current management. Their condition is projected to become "slightly" rather than "much" worse by 2014 only because their condition cannot get much worse than it already is unless the stocks become extinct.

Conditions in British Columbia are generally better than in Washington state and probably will be for the foreseeable future because the Canadian portion of the shared waters has a larger surface area, longer shoreline and smaller human population. Localized habitats in British Columbia are as heavily affected as those in Washington, however, and some biological populations are suffering stresses similar to those in Puget Sound. British Columbia has the opportunity to learn from Washington's experience and prevent the conditions in its waters from deteriorating to a comparable extent.

Aquatic Habitats

Shoreline and riverine habitats in the shared waters area have suffered variable degrees of harm from human activities, with a serious degree of harm done to vegetated estuarine wetlands and rivers in the Puget Sound basin. Although the rate at which harm continues to be done to these habitats is decreasing, the harm is cumulative and essentially irreversible. Continued proposals for large shoreline developments, freshwater diversions and dams, poor forestry practices in the watersheds, and building of shoreline homes, septic tanks and seawalls all will take their toll on natural habitats. Therefore, if present trends continue, losses of these types of habitat will become more serious over the next 20 years. So much vegetated estuarine wetland and riverine habitat around Puget Sound already has been lost or degraded that even continued destruction of the remainder at the present rate would make the situation only slightly worse.

Subtidal habitats away from urban areas show low levels of contamination and probably will not be affected much by changes over the next 20 years. Chronic sediment contamination problems do exist in many urban embayments on both sides of the border (MacDonald and Crecelius, 1994). These problems generally are responding to reduced discharges from point sources, as cleaner sediments are deposited, and there is a downward trend in surface sediment contamination. These gains may diminish or reverse over the next 20 years, however, as nonpoint source inputs increase with population growth.

At present, the water column habitat on a basin-wide scale appears to suffer negligible harm from waterborne contaminants, loadings of which (West et al., 1994) appear to be well within the self-cleansing capacity of the shared waters system,

coupled with management programs that treat sewage, maintain septic tanks, and otherwise decrease waste streams. Transboundary harm to the water column habitat caused by these contaminants is likely to remain minimal in 20 years, despite incremental increases above present discharge levels, barring serious spills of oil or other harmful chemicals. Some localized harm now occurs to the water column in confined basins, but if response measures already under way are continued, these problems should be controlled. There is the possibility that extensive freshwater diversions could affect salinity and circulation in the water in unforeseen ways.

One transboundary problem that is statistically probable in the next 20 years under current practices is the occurrence of one or more large oil spills of more than 1,600 cubic meters (10,000 barrels; 420,000 U.S. gallons) (Wolverstan, 1994, and original sources quoted therein). A large spill would certainly cause significant immediate harm to the shoreline habitats with which it came into contact, as well as to many other valued aspects of the marine environment. The probability of such spills can be greatly reduced by various measures, including many recommended by the BC/States Task Force on Oil Spills (Wolverstan, 1994). However, there are times when the wind is strong enough to drive an inwards surface flow of ocean water onto the southern shore of the Strait of Juan de Fuca, carrying with it any oil spilled in the outer Strait or off the coast of Washington. The deep estuarine inflow could also transport submerged oil back into the inland shared waters. Even if oil transshipment into the Straits and Puget Sound were discontinued, there would still be some risk of a fuel oil spill from the large marine vessels plying the inland shared waters. If such a spill were to occur today, and not again, most habitats would have recovered by 2014, although oil residues might remain in some sheltered, muddy shores.

Furthermore, persistent, chronic discharges of oil products from sources such as surface runoff, atmospheric transport and boat motors, also may cause widespread and lasting low-level contamination. The amount of harm that may be caused by such diffuse sources of petroleum hydrocarbons is not well studied.

Fish

As reviewed in Chapters 4 and 5, many fish populations in the shared waters are reduced or threatened, at least partially because of overharvesting. If present practices continue, depleted fish stocks are unlikely to recover, and many fish populations that are now robust will decline.

Salmon populations have declined because of harm caused by habitat degradation and loss (from poor upland land use practices, freshwater diversion and destruction of estuarine habitat), by overfishing, by possible interactions between wild and

hatchery-produced salmon, and by natural fluctuations in oceanic conditions. The losses have been much greater on the U.S. side of the border. Depleted salmon populations appear unlikely to recover in the next 20 years, given the difficulty of restricting harvest and of restoring lost habitat and genetic resources.

Salmon populations in the region also undergo significant natural fluctuations due to interannual changes in freshwater discharge and in marine conditions that affect food availability and predation (Schmitt et al., 1994). In recent years, salmon population declines have been attributed partly to reductions in river flow and coastal upwelling, but it is difficult to project how these climate-related conditions will change in 20 years.

Part of the difficulty in managing salmon harvest has arisen because of conflicts over harvest of fish originating in one nation by fishers of another nation. Years of negotiation between Canada and the United States have failed to produce a satisfactory agreement as critical wild stocks have continued to decline. The panel takes no position on the relative merits of the positions of the parties to these negotiations and prescribes no cure for the ongoing difficulties. If the conflicts are not adequately resolved in a short time, however, all the parties—and especially the resource—will be losers.

Other fish species do not cross the boundary to the same extent as salmonids. Most commercial and recreational fish stocks in U.S. waters are significantly depleted (Schmitt et al., 1994) and likely to remain that way unless current practices change. Rockfish and lingcod stocks are depleted in the Strait of Georgia as well.

Invertebrates

As reviewed in Chapters 4 and 5, most commercially and recreationally valuable invertebrate populations in the shared waters are healthy but face some threats. Many populations of non-game marine invertebrates may decline sharply if management measures are not instituted. If present practices continue, depleted stocks are unlikely to recover, many populations that are now healthy will decline, and contamination from nonpoint sources is likely to be more widespread.

Despite the potential exchange of planktonic larval stages, many invertebrate stocks in Puget Sound and the Strait of Georgia appear to be distinct, separated by the waters of the Strait of Juan de Fuca (Bourne and Chew, 1994; Brinkhurst et al., 1994). There are, however, a number of common problems in the region associated with industrial, agricultural, and domestic pollution; overharvesting; and multiple use conflicts. These problems are expected to continue in the next 20 years, and they may intensify in the absence of appropriate management strategies.

Birds

Most marine bird populations are being sustained in the shared waters, despite a small number of populations that are declining in number, such as those of common murres and marbled murrelets, and other populations that are very sparse, such as harlequin ducks. The overall rating of "Mixed" reflects the differences in population health among bird species. Even though some species are in good condition, there is still a need to attend to problems that threaten other species. Human activities affecting birds include commercial fisheries (food competition and net entanglement), spills of oil and other hazardous materials, contaminant discharges from point and nonpoint sources, disturbance of bird colonies by humans (and their pets), and especially habitat loss (Mahaffy et al., 1994). All these sources of stress are likely to become more severe in the next 20 years as the human population increases. The statistical likelihood of a major oil spill in the future also could threaten stressed populations of diving birds that nest and feed along tanker routes and shipping lanes.

Bird populations fluctuate greatly in response to natural changes in climate and food abundance and availability, and these changes are not very predictable. Migratory bird stocks also are affected by natural and anthropogenic changes in distant places. These distant influences need to be taken into account in any management strategy.

Mammals

Most marine mammal populations are being sustained in the shared waters, although numbers of some species, such as Steller sea lions, are low. Harbor porpoises have disappeared from Puget Sound for reasons that are uncertain but probably related to human disturbance, which also appears to have affected Steller sea lions. Some of the mammals in the shared waters are affected by bioaccumulated contaminants, and others are affected by incidental mortality in various fisheries. How these factors are affecting mammal populations is uncertain (Calambokidis and Baird, 1994).

Marine mammals also are affected by poorly predictable natural variations in food availability, and in many instances they compete with man for food. It is thus difficult to predict what the population levels of marine mammals will be in 20 years' time, although it seems unlikely that harbor porpoises will return to Puget Sound. Recent increases in the populations of harbor seals and California sea lions throughout the region are likely to level off, if only due to limited food supplies. Human disturbance of marine mammals is likely to increase in the absence of increased regulation and public education, and it is unknown at what point this could reach

critically low population levels. The main human impacts on marine mammals probably will continue to arise from competition for foodfish. The poor status and continuing decline in marine fish populations bode poorly for the pinnipeds and small cetaceans that use marine fish, and the declining status of salmonids could have severe impacts on orca whales. In addition, the statistical likelihood of a major oil spill in the future could threaten mammal populations that are already suffering other stresses.

Human Uses and Public Health

Direct human exposure to waterborne and particle-bound contaminants and pathogens is generally slight, but the incidence of exposure will increase as human populations expand. Despite considerable incidence of contaminants and algal toxins in seafood, present management efforts are generally sufficient to keep human exposures low. The problems have the potential to become incrementally more difficult to manage if present trends of human population growth and contamination continue.

Potential Future Problems

Large-Scale Environmental Change

Additional harm to marine resources in the shared waters, beyond the types and magnitude now occurring, also may result from environmental changes that could occur in the next 20 years. Although most of these are beyond human control, an awareness of, and preparedness for, these changes can mitigate the harm they cause to marine resources.

Regional climate change, whether caused by natural variability or by possible human alteration of the global climate, also could lead to widespread harm to the marine environment within the next 20 years. Changes in water temperature would affect the abundance of some temperature-sensitive species, would alter the distribution of migratory marine organisms and might increase the incidence of the outbreak of toxic algal blooms (Nishitani et al., 1988). Any changes in prey abundance or availability could affect higher animals and disrupt the food chain. The effects of climate change, including those from sea level rise and reductions in freshwater discharge, would be likely to trigger or magnify a number of the other marine impacts listed above.

These potential climatic impacts are, by and large, unavoidable through actions taken within the region. However, the harm would be greatly aggravated if marine resources were already suffering stresses that reduced the resilience of the system, and if management activities to protect these resources do not relieve some those stresses.

A major earthquake is expected in this region at any time in the next few hundred years. Such a quake could cause shoreline flooding and erosion from a tsunami and might involve up to several meters of rapid shoreline uplift or submergence, causing the collapse of coastal bluffs and artificial structures. Fossil evidence shows that large earthquakes have occurred and are likely again both off the outer coast, with most impacts sustained along the coast, and along a fault crossing Puget Sound, with significant impacts seen along inland shorelines (Atwater, 1987; Bucknam et al., 1992).

These natural effects of seismic activity are unavoidable. However, damage to buildings and other facilities in the nearshore zone is, in theory, preventable with appropriate precautions. Such damage could cause harm to the marine environment if contaminants are discharged from such sources as ruptured pipelines and damaged storage facilities on land.

Emerging Problems

The panel recognizes the strong possibility that further research and monitoring may reveal problems that are currently only suspected or completely unforeseen. Among the former, a number of anthropogenic chemicals are found to disrupt endocrine function in marine organisms and humans, causing impacts as serious as, or more serious than, those of cancer induction.

The anti-fouling agent tributyl tin (TBT) is one example of a chemical known to be capable of disrupting reproductive functions and development in marine snails (Alvarez and Ellis, 1990). TBT use is presently banned for boats of less than 25 meters in length in Canada and the United States. Evidence of further impacts may dictate more stringent restrictions. Surfactant compounds, widely used in industrial and domestic detergents and discharged to the marine environment, also are prompting concern because they mimic natural reproductive and developmental hormones (MacDonald and Crecelius, 1994). These chemicals may prove a significant problem for marine biota in 20 years unless their discharge is controlled.

A number of contaminants may be entering the ecosystem and concentrating in the sea surface microlayer, the upper millimeters of the water column. Contaminants in this layer may harm the floating eggs and larvae of many marine animals.

Such contaminants might affect adult organisms as the layer traverses the intertidal zone on an ebb tide, or as breaking waves and bubbles create potential "toxic pills" that could be ingested. Part of the input of contaminants to this layer is thought to originate from airborne emissions such as automobile exhaust, wood smoke and industrial emissions. If this is verified to be a significant environmental problem, remedial actions could require reduction of discharges to the atmosphere by human transportation systems, industry and even wood stoves.

A major continuing external threat to shared waters arises from the introduction of new marine organisms from other parts of the world. The ballast water often discharged by merchant ships approaching ports in the region appears to be the major source of these exotic species. Other exotic species are introduced intentionally or unintentionally in packaging and live marine animals exhibits and experiments. If present practices do not change over the next 20 years, it is possible that the region will see the introduction of one or more exotic species that could produce substantial alterations in the local food chain structure.

7. Degree of Harm and Management Priorities

QUESTION—What types of harm appear to be most serious and should be the focus of monitoring, research and management activities over the next 10 years?

In our criteria for identifying priorities for management action (Chapter 1), we stressed the primary importance of recovery time. This is the time it would take for the ecosystem to respond to reductions in human activities causing harm and for any accumulated harm to be eliminated or reduced to acceptable levels. The recovery may take place by entirely natural processes, or where practicable it may be accelerated by restoration activities. We categorize recovery times as follows:

SHORT: recovery time less than about three years

MEDIUM: recovery time about three to 30 years

LONG: recovery time greater than 30 years

IRREVERSIBLE: recovery time extremely long (centuries or more) with or without remediation

A second criterion for identifying priorities for management action is the amount of harm caused by a human activity. We assign harm a secondary role and recovery time the primary role because recovery time includes an estimation of the environmental "harm commitment"—the total future harm, as well as the immediate effect—entailed by some present action. An action that causes a small but persistent harm may entail a greater environmental harm commitment than one that does more harm in the short term but from which the environment recovers quickly.

In addition to recovery time and harm, we used two more criteria—preventability and cost—to assign priorities for management action. These criteria relate more to

the magnitude and technical feasibility of management actions than to the natural responses of the ecosystem. Priority is given to actions that may be taken easily to prevent or to mitigate harm, and to types of harm that would necessitate a high cost and a long time to clean up or restore.

Seriousness of Harm and Management Needs

The panel's ranking of various marine environmental issues, using the four criteria above, is shown in Table 7.1, in order of descending priority for management response. The details of these issues and their rankings are discussed in the sections that follow. Research, monitoring and management activities over the next 10 years should focus on those ecosystem components that are most vulnerable and should be chosen to meet the four criteria described above.

Human activities that damage the ecosystem in ways where recovery times are potentially very long or harm is irreversible, and where remediation is prohibitively expensive, are assigned high priority and demand immediate corrective action. Activities from which the environment recovers quickly, once the insult ceases, are assigned medium to low priority for management action. In these instances, decisions can be postponed to ensure that the best scientific information has been obtained before action is taken.

Recovery time refers only to the response of the natural environment. We do not account for the time required for decisions to be made and implemented in society. In the real world, both of these time intervals must be considered when calculating how long it will take to improve the marine environment from its present condition to a desired condition. However, it is not our goal to produce a timetable for environmental cleanup. Our goal instead is to set an agenda for management attention by giving high priority to the harm that is longest-lasting and giving low priority to harm that will disappear quickly, whether remedial action is taken immediately or delayed for many years.

Destruction, Alteration or Degradation of Habitat

Prevention of habitat destruction is accorded the highest priority because its impacts are irreversible, the potential harm to the environment is great, and habitat losses are highly preventable while the cost and effort needed to restore the amount of functional habitat are very high.

TABLE 7.1

Criteria for setting priorities in the shared waters

ISSUE	RECOVERY TIME[1]	HARM TO ENVIRONMENT	EASY TO PREVENT?[2]	CORRECTION OR MITIGATION COST	OVERALL PRIORITY
Habitat loss	irreversible	high	yes	very high	very high
Fish & shellfish populations	medium[3]	high	yes	high	high
Exotic species	long/irreversible	low/high	no/yes[6]	high	high
Freshwater diversions	long/irreversible	high	yes	very high	high
Toxics in living resources	short/medium	medium	yes/no[4]	medium/high	medium
Toxics in sediments	medium	medium	yes/no[4]	medium/high	medium
Oil spills	medium (long for some populations)	medium	no/yes[6]	high	medium
Toxic algae	irreversible (short for some populations)	low[5]	no	low	medium
Fecal contamination	short	low	yes	medium	medium
Water column contamination	short	very low	yes	medium	low

1 Accounts only for ecological recovery after action is taken, not time required to choose and implement recovery actions.

2 Accounts only for technical feasibility of prevention, not difficulties in political decision-making or enforcement.

3 Certain stocks may never recover and may be replaced with other stocks.

4 Point source toxic releases can be prevented; nonpoint source control of toxics is considerably more difficult.

5 Except for human health.

6 Total prevention is impracticable, but simple measures can greatly reduce risks.

Quite conservative habitat management practices are necessary. Surprisingly little is known about the quantity and quality of all major habitat types, and there is a need for additional research and monitoring as soon as possible to facilitate habitat protection. Management should concentrate on preserving remaining nearshore estuarine habitat, restoring and enhancing marginally degraded habitat, preventing additional freshwater diversions, controlling exotic (non-indigenous) species and protecting contiguous terrestrial wetlands. Research should focus on nearshore habitat functions and values, food chain linkages, investigations into the impacts and spread of exotic species on nearshore habitat, and the effects of chronic contamination on nearshore and terrestrial habitats. Monitoring efforts should provide accurate inventories of nearshore and adjacent terrestrial wetlands and should track changes in quantity and quality of those areas.

Declines in Fish and Shellfish Populations

Halting further losses of fish and shellfish populations is assigned a high priority because these resources require at least a medium time frame for recovery from impacts, which in some cases may be irreversible, and the high likelihood of harm to the food web. These losses can be prevented with relative ease, and the cost and effort required to rebuild or replace stocks is high.

Very conservative management practices are necessary for many depleted or threatened stocks, while further research and monitoring should continue at an accelerated pace. Management practices should focus on fisheries regulations and practices that minimize impacts on depleted stocks. Research is needed on the basic biology of many marine fish species, fisheries-oceanography interactions, food chain dynamics, interactions among hatchery and wild stocks of anadromous fish, and impacts of escape of Atlantic salmon and other farmed fish on wild stocks. Monitoring should be extended to include better stock assessments of non-commercial marine fish species and non-game marine invertebrates.

Introduction of Exotic Species

Preventing the introduction of exotic species is assigned a high priority because changes from such introductions can be persistent or irreversible, and the range of effects from introduced species can be immense. We have the ability to prevent the introduction of certain exotics, while others may prove more elusive; however, the cost to correct or mitigate invasions of exotic species is extremely high.

Sometimes species are introduced deliberately for beneficial uses, although little attention may be paid at the outset to biological side effects of such introduc-

tions. Some species introduced locally, such as the Pacific oyster, have proved to be highly beneficial, while others, such as the oyster drill and the smooth cordgrass *Spartina*, cause or might cause significant harm. Atlantic salmon, introduced for net-pen aquaculture, have been caught in the fisheries in the Strait of Georgia. No evidence of harm from this escape has yet been established. Elsewhere in the world, there are examples of extreme alteration of aquatic ecosystems by exotic species such as the freshwater zebra mussel, which is fouling water intakes in the central United States (Garton and Haag, 1992), and a ctenophore that has preyed on fish eggs and larvae and devastated fisheries in the Black Sea (GESAMP, 1993).

Monitoring and research must be stepped up to understand the extent and life cycle of exotic species that are already present in our marine waters and along shorelines, and monitoring and management for the early detection and exclusion of new species must be increased. Exchanges of information with adjacent areas and among the world-wide research community are crucial to providing early warning of new threats. A recent example is the information from California researchers that a European green crab is undergoing a population explosion and displacing native subtidal benthos, including harvestable invertebrates (Kuris and Lafferty, 1994).

Freshwater Diversions and Alteration

Minimizing diversions and alterations of fresh water supply is assigned a high priority because their impacts are very persistent or irreversible and the impact on the environment is high. The time span required for recovery of salmonid populations following partial or complete restoration of natural river flow patterns is unknown. Evidence of the severity of impacts in our region is provided by the example of the damming of the Columbia River (Ebbesmeyer and Tangborn, 1992) and, even more drastically, the impending loss of estuarine circulation in San Francisco Bay caused by losses of fresh water (Nichols et al., 1986). We have the ability to avoid large freshwater diversions, and the costs to correct or mitigate the effects of large diversions of fresh water from estuarine and coastal areas are very high.

Large and small rivers and streams must be monitored so that the water flow can be maintained for fish passage and for normal estuarine circulation and salinity. Research is needed to determine the sensitivity of estuarine systems to disruptions of fresh water supply. For example, the proposed diversion of the Nechako River, which joins the Fraser in central British Columbia, could potentially affect the salinity distribution at the distant mouth of the Fraser, causing harm to the estuarine habitat. Management activities that encourage and educate the public about water and energy conservation are needed in order to continue to supply adequate fresh water and hydroelectric power for the needs of the growing human population.

Toxic Contamination of Living Resources

Preventing toxic contamination of living resources is assigned a medium priority because recovery occurs over a medium time frame, although the impact on the environment may be reasonably strong. The ability to prevent toxic contamination of resources is high, and cost and time required to turn off contaminant sources and allow for natural recovery are medium to high.

Management activities should concentrate on controlling contaminant sources and spills. Considerable research is needed to define better the pathways through which contaminants enter organisms and the effects that those contaminants have on individual organisms, populations and marine community interactions. Monitoring activities should delineate the extent and severity of resource contamination and should follow the course of recovery.

Toxic Contamination of Sediments

This issue is considered to be of medium priority because recovery occurs over a medium time frame and because there is a fairly substantial impact to the environment, including the potential for human health problems caused by passage of contaminants through the food chain. Prevention of sediment contamination from point sources is well within our ability, and the cost of source control to allow for natural recovery is moderate, although contamination from nonpoint sources is a problem that is more difficult and expensive to remedy. Recovery time could be shortened through capping, sediment removal and other remediation techniques, although the cost would be considerably higher than that for natural recovery.

Management activities, like those for cleaning up living resources, should focus on source control and the prevention of spills. Additional research is needed on the bioavailability and relative toxicity of chemical contaminants in sediments, the development of robust assays to determine harm to organisms from sediment contaminants, and the chemical alterations that occur when freshwater contaminants reach salt water. Monitoring activities should delineate the extent and severity of sediment contamination and follow the recovery.

Oil Spills

Management of oil spill risks is assigned a medium priority, but we segregate this issue into two separate parts. Recovery from oil spills occurs over a moderate time frame. The overall harm to the environment can be acute in the short term but is considered moderate over the longer term. Certain bird and mammal populations may require a long recovery time to return to historic levels if key habitats are oiled or

if these species are suffering cumulative impacts of other stresses. Preventing oil spills is not completely possible as long as oil is transported, yet preventive measures that are available are much less expensive and more effective than cleanup. Cost-effectiveness of most oil recovery and cleanup efforts after a spill is considered to be low, based on information gathered following cleanup activities after the 1989 *Exxon Valdez* oil spill in Alaska and other spills in the British Columbia-Washington region.

Management activities must focus on oil spill prevention and oil conservation. Although some oil spill response and cleanup activities are warranted, such as skimming and booming to protect vital areas, most large-scale oil spill cleanup is ineffective and may cause additional harm. Management activities that provide for the safe transportation of petroleum products will prevent most major spills, while chronic small spills and discharges, as well as the atmospheric-borne wastes from cars, are best handled by increased technical assistance to the marine industry, boaters and the public. Monitoring and research activities that directly support management of spill prevention and conservation are needed.

Toxic Algae

Response to toxic algal blooms is assigned medium priority because the potential threat to the environment (with the exception of human health risks) is low. Recovery time from a single incidence of toxic algal contamination is short, while the effects of introducing toxic algae to a new area appear to be very persistent or irreversible. Toxic algal blooms are the single chronic problem in the shared waters in which human activities are not conclusively implicated, and as a result our ability to prevent toxic blooms is very low. It is possible that human activities could foster the spread of toxic algal organisms by inadvertent introduction of exotic algal species via ballast water or other mechanisms, although to date there is no evidence that this has happened. Costs for dealing with toxic blooms are low and are largely directed at monitoring and management activities to protect public health.

Management efforts that prevent human and other animal contact with toxic marine products, and which inform the public of the risks, should continue. Research efforts should be increased greatly to determine the source of domoic acid and outbreaks of other toxins that are likely to arrive in our waters and to search for correlations between blooms producing saxitoxins, domoic acid and other toxins, and oceanographic or climatic conditions. Monitoring of marine waters, shellfish and other organisms should continue with an increased emphasis on targeting organisms consumed in non-traditional harvesting.

Fecal Contamination of Seafood

Contamination of water and seafood is assigned a medium priority. The recovery time is short after fecal sources are controlled, and the risk of harm to the environment is low, although there is some human health risk from pathogens in seafood. Our technical ability to prevent fecal contamination is high, although placing limits on nonpoint sources may be expensive, difficult and time-consuming to implement. Sewage treatment plants also are extremely expensive and politically difficult to construct and upgrade.

Management activities should continue to focus on reducing sources of fecal material, including both upgrading some urban sewage and surface runoff treatment systems and controlling non-urban sources such as agriculture and domestic drainage systems in the watersheds. The application of a risk-based approach, as we recommend, may lessen the need for construction or extensive improvement of sewage treatment plants. Research is needed on methods for distinguishing between fecal coliform bacteria of human versus animal origin and for isolating and identifying other bacteria, viruses and protozoans from marine waters and organisms. In addition, research is needed to determine the lengths of time that these pathogens remain virulent once they enter salt water. Monitoring of fecal contamination in marine water and shellfish should continue.

Contamination of the Water Column

Water column contamination is accorded low priority because over most of the shared waters, chemical contaminants, including inorganic nutrients, oil and toxins are dispersed and flushed from the system over a short time frame. Also, the environmental damage from water column contamination is very low, and our ability to prevent such spills is fairly high. Although large sums have been spent to keep human contaminants from the water column, future costs should be low.

Management activities should focus on the prevention of spills and chronic inputs of oil and chemicals. Research on food chain interactions, basic oceanographic processes, and the sea-surface microlayer are needed to better understand the distribution and fate of contaminants and their effects on planktonic larvae, eggs and prey organisms. Monitoring activities should be used to support research efforts and to maintain a watch on poorly circulating embayments where future water column problems will first appear.

Unknowns

There always will be threats to the marine environment and its resources that are not foreseen, and the effects of such threats could range from slight perturbations to system-wide collapses. While we cannot evaluate the priority of these unknown threats, it is vital that some focus and resources always be available for their detection and management.

Some uncertain threats are more familiar to us than others. The potential for earthquakes, tsunamis, and global and regional-scale changes in climatic or oceanographic conditions are real and likely threats to the shared waters, yet we cannot predict or prevent them. Planning for these occurrences can provide us with rapid response abilities to deal with these uncertainties. Research and monitoring activities that scan for and better understand these natural phenomena can provide important clues for managers preparing response plans.

Other unknowns belong in the realm of educated speculation. In the future, we might see new synthetic chemicals posing threats to our resources; a new and virulent exotic species taking over large tracts of marine habitats and outcompeting native species; or any of a host of other possible threats. We cannot guarantee against such threats. We can, however, take reasonable precautions in activities that may contribute to such threats, such as in discharges of new chemicals and of ballast water. We also can mount vigilant monitoring programs and broad-based research programs in hopes of recognizing unknown and emerging threats to the marine environment at an early stage. With foreknowledge, managers can move quickly to respond and minimize impacts of the new threats.

The Shared Waters in 2014—Optimum Future Scenario

Table 7.2 presents an idealized scenario for the optimal state of the shared waters in 20 years as an alternative to the "business as usual" scenario outlined in Chapter 6. This "best-case" scenario supposes that appropriate management measures are taken immediately to reduce contaminant input and resource depletion significantly and to allow the natural or assisted recovery of the system. The degree of improvement possible under such a scenario depends upon the relative rates at which resources in the shared waters recover from the harm discussed in previous chapters.

This scenario does not account for the time that elapses in the normal process of decision-making, nor for the time needed to build or improve facilities that enhance water quality. These activities can span time intervals of the same order as

those required for the recovery of the natural system once action is taken—i.e., decades. As such, we clearly present an idealized, optimistic, "best-case" scenario.

The judgments in this scenario are qualitative, without detailed calculations of population, contamination or resource use trends. Furthermore, the judgments are not predictions of what the actual state of the system will be in 2014; they are projections of existing trends into the future, recognizing that if any of those trends change in the interim, the outcome may differ.

Aquatic Habitats

The condition of vegetated shore, unvegetated shore, and upstream river habitats will change little or not at all in 20 years even if afforded the most enlightened management. Natural recovery is extremely slow or irreversible, and experiments in restoration of natural habitat and artificial creation of new habitat have not yet developed methods that can reliably mitigate destruction of natural habitat. Thus even a radical reduction in the rate of development and degradation of these habitats can do no more than preserve the status quo.

The present downward trend in surface sediment contamination largely results from reduced discharges from point sources (PSWQA, 1993). Given further reductions in contaminant inputs, mainly from nonpoint sources, the system should respond quickly, and the downward trend could be continued despite increases in human populations. Cleaner sediments could cover the seafloor and thus continue to improve the quality of subtidal habitats, especially in urban areas.

Prevention of the building of major new dams would assure the protection of riverine flows and habitats and would maintain the supply of clean sediments to the estuaries. It also would maintain the natural supply of fresh water and natural salinity and circulation in the water column. Water column habitats for the most part are in very good condition and could not be improved much by better management. If further monitoring or research were to reveal an unforeseen problem, the system would recover quickly after appropriate controls were applied.

Water column and shoreline habitats also can be maintained in their present condition over the next 20 years if a major oil spill can be prevented. Even in an optimal scenario, however, an accident is possible and could harm transboundary habitats. If a major spill occurred today, and no more occurred for 20 years, water column and rocky shore habitats would completely recover, and sandy, gravelly and muddy shore habitats would mostly recover within 20 years. The harm caused by persistent small spills is uncertain but potentially involves greater harm commitment over 20 years. If this source of contamination could be reduced, habitats could recover substantially within 20 years.

TABLE 7.2

Current and projected status of components in the shared waters: Optimal future scenario*

	PRESENT STATUS		RECOVERY TIME	STATUS CHANGE 1994 to 2014	
COMPONENT	WA	BC		WA	BC
AQUATIC HABITATS					
Vegetated shores	very poor	good	irreversible	unchanged	unchanged
Unvegetated shores	acceptable	good	irreversible	unchanged	unchanged
Rivers upstream	poor	acceptable-good	irreversible	unchanged	unchanged
Subtidal	good	good	medium	slightly better	slightly better
Urban sediments	very poor	poor	medium	slightly better	slightly better
Water column	very good	very good	short	unchanged	unchanged
LIVING RESOURCES					
Salmonids	very poor	acceptable-good	medium-long	slightly better	slightly better
Marine fish	very poor	good	medium-long	slightly better	slightly better
Bottomfish in urban bays	poor	good	medium	slightly better	slightly better
Commercial/recreational invertebrates	good	good	medium	slightly better	slightly better
Birds	mixed	mixed	medium-long	slightly better	slightly better
Marine mammals	mixed	mixed	medium-long	slightly better	slightly better
HUMAN HEALTH					
Safety from direct contaminant and pathogen exposure	very good	very good	short	unchanged	unchanged
Safety from contaminated seafood	good	good	short-medium	slightly better	slightly better
Safety from toxic algae	good	good	irreversible	slightly worse	slightly worse

*This ideal scenario assumes that management measures to reduce contamination and resource depletion are instituted and enforced immediately.

Fish and Invertebrates

The serious decline in many Puget Sound wild salmon stocks is blamed on habitat degradation and loss (from poor upland land use practices, freshwater diversion and destruction of estuarine habitat), overfishing, possible interactions between wild and hatchery-produced salmon, and natural fluctuations in oceanic conditions. While stocks could generally recover from overfishing alone within 20 years, the irreversible loss of habitat and genetic resources dims the prospect for fully restoring depleted Puget Sound wild salmon populations by 2014. Any hope for recovery also requires that the quantity or timing of freshwater discharge from the Fraser and other rivers not be significantly regulated or altered. Restrictions on catch and habitat loss hold the prospect of sustaining Strait of Georgia salmon stocks at their present levels or better.

Most marine fish in Puget Sound, and some invertebrate populations in the shared waters, are reduced or threatened, at least partially because of overharvesting. Reduction or elimination of catch could lead to recovery for most species within 20 years, although the species composition following recovery might differ from the original. Stocks of some long-lived rockfish species are very low on both sides of the border and could take longer to recover. Contamination problems suffered by bottomfish and invertebrates in the shared waters could be significantly reduced in the next 20 years by rigorous controls, especially on nonpoint sources.

Fish and invertebrate populations also can be maintained in their present condition and allowed to improve over the next 20 years if a major oil spill can be prevented. Even in an optimal scenario, however, an accident is possible that would cause significant ecological harm in the transboundary area. If a major spill occurred today, and no more occurred for 20 years, population levels of some fish and invertebrate species could be affected in the short term, but most would recover to their current levels within 20 years. Greater harm to commercial and recreational uses probably would result from contamination by oil residues, which could still be present at low levels in 20 years in organisms inhabiting sheltered muddy shore habitats.

Recovery of most fish and invertebrate species would require that natural oceanographic and climatic conditions remain favorable, a condition that may not be met even today. All recovery efforts could be less effective if the carrying capacity of the shared waters declines because of externally driven environmental changes.

Marine Birds and Mammals

Marine birds and mammals are affected by commercial fisheries (through food competition and net entanglement), spills of oil and other hazardous materials,

contaminant discharges from point and nonpoint sources, human disturbance of feeding and breeding areas, and habitat loss. If the latter two sources of stress, especially, can be reduced even as human populations grow over the next 20 years, bird and mammal populations can be sustained, and the depleted bird species will have some opportunity to recover. It seems unlikely, even if considerable effort were made to limit human disturbances, that harbor porpoises will return to Puget Sound. Recent increases in the populations of harbor seals and California sea lions throughout the region might be sustained somewhat longer if human competition for foodfish is reduced, but fish stocks already are so low that this effect would probably be minimal. The continued well-being of resident orca whale populations will depend on arresting the decline in salmon stocks.

If a major oil spill can be prevented over the next 20 years, bird populations have a chance of maintaining their current populations. Even in an optimal scenario, however, an accident is possible and could harm transboundary bird stocks. Harbor seals also would be vulnerable to a spill. If a major spill occurred today, and no more occurred for 20 years, harbor seals and most bird populations could completely recover, along with their habitats, as long as they were spared serious stresses from other sources. Particularly sensitive populations of diving birds, such as common murres, marbled murrelets and harlequin ducks, which are now at low levels, probably could not recover from a major oil spill within 20 years.

Human Uses and Public Health

There currently are only limited and isolated threats to public health posed by marine resources. Of these, furthermore, the naturally occurring toxic algae blooms are as significant a threat as those caused by contaminants. Reduced waste discharge and increased treatment of waste that is discharged (including well maintained and better designed septic systems) could prevent the contaminant-caused risk to human health from worsening as populations increase. Also, more vigorous education and monitoring programs could reduce the risks posed by whatever level of contamination is present, including risk from toxic algae.

QUESTION—What indicators are recommended for future state of the environment reporting for the transboundary marine ecosystem?

Ecosystem Indicators

The panel recommends that a full set of environmental indicators be used in future state of the environment reporting. The use of a more limited set of indicators may miss important changes in resources of concern and/or miss the emergence of new threats or changes to the marine environment. Indicators should be chosen that meet the following criteria: 1) They must be scientifically-based and replicable; 2) parameters can be easily and cheaply measured; and 3) indicators are tightly tied to the resources and ecosystem components of greatest concern.

Present monitoring programs in British Columbia and Washington collect many types of information ranging from fisheries stock assessments to population counts of birds and marine mammals, water column and sediment chemistry, and measurements of biological and chemical contaminants in biota. The panel recommends that the Puget Sound/Strait of Georgia Working Group undertake a rigorous assessment of the parameters currently measured, choose those parameters that meet the panel's criteria and seek to institutionalize the collection of those environmental parameters in monitoring programs in British Columbia and Washington.

The panel further recommends that the Working Group consider augmenting monitoring data collection with key measures of ecosystem components that are generally lacking in current British Columbia and Washington monitoring programs, including the monitoring of water column phytoplankton and zooplankton species and benthic community structure; the extent and functional value of subtidal seagrass beds; and the health and numbers of sensitive species of fish, invertebrates, birds and mammals that are not of commercial interest. The Working Group also should look closely at indicators for which a sufficient research base exists to interpret changes in resource populations, habitat functions and contaminant levels. The Working Group should encourage the funding of research to elucidate pathways and relationships among the physical and biological environment that are poorly understood.

8. Recommendations

QUESTION—Which types of human activities (for example, discharges or spills of toxic compounds, nutrients, pathogens, physical land modification) need the most management attention?

The panel has formulated 12 specific management recommendations that address the priority issues outlined in Chapters 6 and 7. These recommendations are summarized in Table 8.1. Seven are specific recommendations on dealing with a particular source of harm, and five are recommendations for increasing management effectiveness and enhancing scientific understanding. These recommendations are to be implemented using two important principles outlined below.

Principles for Sound Ecosystem Management

There are two principles, discussed in detail in Chapter 1, that the panel recommends be used to guide future research, management and monitoring activities in the shared waters.

Risk-based Management System

Management decisions that affect the future health of habitats and resources in the shared waters must be based on an integrated scientific risk-based management system. Risks must be evaluated quantitatively, by analyzing the probability that harm will occur and the amount and seriousness of harm that may result. The duration of risks also must be considered to determine the magnitude of harm to which the environment becomes committed. Frequently, risks must be evaluated using incomplete or inadequate information, because society must act and cannot afford to wait or to pay for more complete information. Under these circumstances, scientific inferences are made, typically presuming, without proof, that properties or condi-

TABLE 8.1

Recommendations for actions and effective management to protect the shared waters (ranked in order of priority)

PRIORITY	ACTIONS
Highest	Minimize estuarine wetland habitat losses
	Establish marine protected areas
	Protect marine animals and plants
	Minimize large fresh water diversions
	Minimize introduction of exotic species
	Control toxic wastes
	Prevent large oil spills

PRIORITY	EFFECTIVE ENVIRONMENTAL MANAGEMENT
Highest	Strategic planning
	Comprehensive program review
	Monitoring/research/ management framework
	Increased public and scientific communication
	Freedom of scientific communication

tions observed at one site can be applied at another. Where risk cannot be adequately evaluated because insufficient information is available, a precautionary approach in tandem with appropriate scientific inquiry is warranted. Strategic planning for ecosystem stewardship must consider uncertainties and unknowns; flexibility will be a key to good policy.

Precautionary Approach

Based on our scientific understanding, we recommend three courses of action, based principally on the potential of various activities to create irreversible harm to the marine environment.

1) **Prevent irreversible harm.** Despite incomplete information, there is persuasive evidence that certain human activities produce irreversible effects on the marine environment. Therefore, we must take a cautious approach and minimize all further harm until we can better understand the vulnerability of these resources. Examples include the protection of remaining nearshore habitat, the protection of runs of British Columbia coho salmon and the protection of several species of marine fish that are at critically low levels.

2) Proceed with caution. Gaps remain in our knowledge of processes such as the potential impact of pathogens on humans and marine biota and the importance of the sea-surface microlayer as a source of contamination to marine and intertidal biota. Other gaps surround new potential problems, such as the introduction of new chemicals, exotic species and other stressors in the marine environment. Still others come from our lack of understanding of cumulative impacts on the environment and resources from several types of assaults, such as physical alterations of habitats and chronic chemical contamination.

We cannot yet adequately judge the severity of these kinds of threats without further research. In the meantime, we must proceed very conservatively when allowing degradation or contamination of these resources, although more leeway might be allowed in cases where the environment would recover quickly from potential harm. Additional exploratory research and monitoring in these areas are essential.

3) Take cost-effective action. Some sources of contamination cause only minor harm to the environment and/or are beyond our capabilities to remedy. Significant expenditures of public funds are not justified in such situations. Examples of actions that are not justified include most measures for cleaning up large oil spills, which have tremendous costs for very little demonstrated benefit. They also include removal of nutrients and BOD from sewage effluent. In the latter case, the treatment required is very costly, and the contaminants do little harm to the environment of the shared waters except in local cases. (Some toxic contaminants may be associated with particles that generate BOD. However, it is better to reduce such toxic inputs sources than to try to reduce them indirectly by removing BOD.) We need not place great emphasis on monitoring and research in these areas nor commit significant resources to their management.

Special Transboundary Issues

The recommendations below reflect special attention given to issues that are particularly transboundary in nature—that is, issues that cannot be adequately managed by separate and uncoordinated actions on each side of the international boundary. Such issues fall into two categories.

1) Contaminants, exotic species or nonliving resources (such as fresh water) that are transported across the boundary.

2) Living resource populations whose migrations or critical habitat requirements straddle and do not recognize the boundary.

Recommendations

In both sections below, the most important recommendations are listed first. The panel feels there is no time to be lost in implementing the key recommendations of this report, and we challenge the provincial and state governments to act quickly. In general, we assign priorities to these recommendations based on reversibility of harm.

Prevent Estuarine Habitat Losses

The extent of natural nearshore habitats along all of the developed and many of the rural shorelines of the region has reached critically low levels, and no further losses can be sustained. Existing mitigation and restoration measures clearly are not adequate to replace these habitats. The beneficial use of the nearshore estuarine areas is an issue of intense public concern; the public must decide how much of this habitat it wants to preserve in order to maintain viable stocks of marine biota.

The panel recommends that a public process be undertaken in British Columbia and Washington at the community level to determine the extent of losses that are acceptable to society. To participate in this process, the public must be armed with the best scientific information available, presented in an accessible and understandable format.

As a guideline until such a process can be undertaken, the panel recommends that any further loss of nearshore estuarine habitat be prohibited in embayments that already have lost more than 30 percent of their historic habitat area. In the absence of scientific guidelines on possible threshold levels of habitat loss that cause biological harm, the 30 percent figure is chosen arbitrarily as a level of destruction at which losses may become significant. The panel further recommends that along shorelines that have not yet been as severely degraded, no net loss of nearshore estuarine habitat be permitted, and that monitored habitat enhancement and restoration be required to compensate for losses due to nearshore development, dredging and other anthropogenic activities. The panel urges that estuarine habitat be the subject of additional research and monitoring efforts. So little is known about these vital areas that wise conservation and management decisions currently are very difficult to make.

Establish Marine Protected Areas

In order to protect both habitat and resource populations, a portion of each major type of marine and nearshore habitat in the shared waters should be desig-

nated as marine protected areas and be set aside from most or all human activities. These protected areas will most effectively protect against further human encroachment, permit recovery of depleted fish stocks, and provide refuge areas for marine mammals and birds. Many fish stocks in particular have reached such a critical status in Puget Sound that limits on catches and seasons are inadequate for safeguarding the resource. Although most fish stocks (except rockfish and lingcod) remain much more abundant in British Columbia, they ultimately will face the same pressures and potentially the same fate unless strong preventive measures are implemented.

Whole embayments or stretches of coastline could be strictly set aside as marine protected areas, or mixed uses could be allowed for portions of an area. To protect lingcod habitat, for example, the seabed and deep waters might be declared off-limits to human activity, while recreational fishing might be allowed in the overlying water column.

Protect Marine Animals and Plants

The vast majority of fish, invertebrate, bird and mammal species in the shared waters are still found in abundant numbers. However, the population sizes of many stocks that are harvested for commercial or recreational purposes, as well as those whose habitats have been severely altered, are alarmingly low. Many of these species no longer can sustain the harvest levels that have been enjoyed by fishers and hunters in British Columbia and Washington. In particular, stocks of salmonids and marine fish species in Puget Sound; lingcod and rockfish in British Columbia; marbeled murrelet, common murre and tufted puffin populations in the Straits; harbor porpoises in Puget Sound; and Steller sea lions throughout the shared waters; are at risk. In addition, many species of intertidal invertebrates, seaweeds and fish that have not traditionally fallen under the purview of fisheries and wildlife agencies are being harvested in increasing numbers.

With growing awareness worldwide for the need to manage for sustainable fisheries, fisheries and wildlife agencies in British Columbia and Washington, aided by their federal counterparts, must move toward a regime of protecting the fisheries and wildlife resources rather than managing for optimal harvests.

The panel recommends that fisheries and wildlife agencies act to severely curtail the harvest of every species for which a significant decline in population has been noted. In addition, these agencies should adopt a precautionary approach toward managing those fish and wildlife species for which they have insufficient population information. Similarly, species harvested in non-traditional fisheries should be managed conservatively, with a goal of maintaining optimum population levels.

Prevent Large Fresh Water Diversions

The major river diversion projects that have been undertaken in the region have had immense and far-reaching impacts on the marine environment and living resources of the region. The damming of the Columbia River is implicated in major declines of salmon runs in Washington and is suspected of having altered the coastal oceanography and ecology (Ebbesmeyer and Tangborn, 1992). Examples of the negative impacts of fresh water diversion from further afield (e.g., San Francisco Bay) are even more dramatic.

The panel recommends that no further large fresh water diversion projects be permitted until the potential impacts on estuarine circulation, nearshore and subtidal habitats, and marine plant and animal populations are more fully understood. We doubt that major river diversions ever can be made without significant adverse estuarine effects.

Minimize Introduction of Exotic Species

The shared waters are beginning to suffer serious impacts from the intentional and accidental introduction of exotic species. Furthermore, warnings from other regions, such as San Francisco Bay and the Black Sea, clearly do not bode well for the survival of many native species. The panel urges that serious efforts be made to prevent the introduction of exotic species into the shared and adjacent waters. Introductions can be prevented by the establishment and enforcement of strict ballast-water regulations in British Columbia and Washington; through hatchery and aquaculture enhancement activities that will foster flexible harvest regulations and allow native marine plants and animals to outcompete their introduced competitors; and by an aggressive public education program to reduce the intentional and inadvertent importation of exotics. In addition, the panel urges the governments of British Columbia and Washington to consider the code of practice developed by the ICES working group to reduce the risks of adverse effects arising from introductions and transfers of marine species (Wallentinus, 1994).

Control Toxic Wastes

There is evidence that toxic chemicals discharged into the marine environment accumulate in many types of marine organisms, where some may cause harm in certain organisms. In order to avoid deleterious effects to marine plants and animals, and to ensure that the supply of seafood from the shared waters is safe for human consumption, it is important that the concentrations of toxic chemicals in marine organisms not reach harmful levels. The risk to marine life from small accumulations

of toxic chemicals cannot justify the prohibitive cost of eliminating all toxic discharges into the marine environment. However, we believe that an acceptable level of contamination (one that protects marine life and human health) can be reached by careful controls on toxic sources.

Point sources of toxic chemcials are being brought under control in both Washington and British Columbia. Nonpoint sources, including storm water discharges, continue to contribute significantly to contaminated "hotspots" in urban and industrial areas. Agricultural chemicals including fertilizer and pesticides contribute toxic chemicals from farming activities, from home gardening and from golf course maintenance. Combustion products from motor vehicles reach marine water through runoff and via atmospheric deposition. Small amounts of radioactivity may be contributed to the marine environment from radioactive storage facilities or active discharges.

The panel recommends that efforts to bring all point sources of toxic chemicals under control continue while additional emphasis be placed on controlling nonpoint sources of pollution, especially surface water runoff from urban and industrial areas. Effective research and monitoring are needed to obtain quantitative estimates of toxic chemical loading to the shared waters. Optimum control measures cannot be put in place without these estimates.

Prevent Large Oil Spills

It has been clearly demonstrated that our ability to remedy the impacts of both large oil spills and chronic petroleum inputs to the shared waters is poor. It is also clear that society will continue to consume petroleum products at a high rate. The focus in protecting the marine environment from oil therefore must be on conservation and spill prevention.

The environmental harm caused by a large oil spill in the shared waters could be great in the short term, although most components of the ecosystem would be expected to recover in the long term. Nevertheless, the prospect of long-term recovery does not negate the imperative to take simple and cost-effective measures that could prevent unnecessary biological and economic impacts. The panel urges an accelerated implementation schedule for recommendations from the British Columbia/States Task Force on Oil Spill Prevention, focusing on those measures that have been proved most cost effective.

Recommendations for More Effective Environmental Management

Strategic Planning

The overlapping nature of the marine resources of British Columbia and Washington and the profusion of government entities with responsibility for aspects of marine environmental protection in the region point toward the need for joint strategic planning for the region's resources. The panel recommends that this planning involve agencies and institutions on both sides of the border, with clear guidelines as to which entities have the responsibility and authority to speak for the provincial, state, federal and regional/local governments. This planning process should encompass all aspects of the marine environment, the surrounding watersheds and any other anthropogenic activities that have an impact on the aquatic resources (i.e., land use, transportation, air emissions, etc.). While creating no new bureaucracies, the joint strategic planning effort must report equally to both the provincial and state governments.

Comprehensive Program Review of the Shared Waters

Despite a large financial investment, many years of effort, numerous regulations, and the attention of natural resource managers and fisheries biologists, we have failed to protect and conserve stocks of salmon and other anadromous and marine fish in the shared waters. Runs of wild salmon in Washington coastal and inshore waters are sufficiently threatened that, in most areas, all commercial and recreational fishing has been restricted for 1994.

Our failure to protect these stocks may be the result of gaps in scientific knowledge that prevent fisheries managers from adequately predicting and averting adverse impacts. Alternately, this failure may be the result of the fragmented authority and overlapping responsibility of federal, state/provincial and regional agencies for marine resource protection. Government agencies on both sides of the border are constrained by legislative mandates and compartmentalized jurisdictions, as outlined by federal (and to some extent, state and provincial) laws.

Environmental protection programs that look at water quality, waste discharges, fish and wildlife habitat, and seafood safety have a history of similar puzzling failures and inconsistencies. The evidence gathered by the panel clearly points to the need for a systematic examination of the programs and policies that govern our handling of the marine environment and its resources.

The dynamic nature of the natural world ensures that the implementation of

most natural resource policies is experimental. We must be prepared to learn from our successes and failures in a rational and systematic fashion, allowing for revisions and updates to policies as the state of our scientific understanding changes.

The panel recommends that the Environmental Cooperation Council contract with an independent body to audit the goals and accomplishments of, and resource allocations to, programs and management activities that influence the shared waters and resources. This body would look at both the amount of resources devoted to these programs and the ways in which the resources have been expended. Through this audit, we can gain an understanding of which environmental policies and programs are effective and which should be changed. This body would conduct an audit and report to the legislative bodies and the people of the British Columbia and Washington state on a periodic basis.

The panel acknowledges that there may be several viable models for choosing the body (to be called the Reviewers) to carry out the environmental audit. The Reviewers must have the necessary scientific and management expertise and conduct an open, public process, independent of the agencies or institutions whose actions it is examining . They must be free of political control or influence, and cannot be in a position to benefit from the outcome of the program review. The Reviewers must be willing to proceed carefully and to learn from the overlapping intricacies and complexities of environmental management, science and policy. Models upon which the Reviewers might be based include the U.S. National Academy of Science, Canada's Office of the Auditor General; or the U.S. General Accounting Office.

Monitoring and Research Framework

To support strategic planning, there is a need for a binational coordinated monitoring and research effort for the transboundary waters, sediment and biota. Monitoring programs, if carefully designed, can answer research questions. In many instances, monitoring programs are the only way to obtain long-term data sets to answer ecological questions.

The panel recommends that this effort focus on habitat preservation and waste disposal, as well as on the assessment and conservation of joint stocks of fish, invertebrates, birds and marine mammals. Strong emphasis must be placed both on collection and on timely interpretation and release of data. The goals of the monitoring, and the most economical ways of meeting these aims, should be clearly defined. Protocols for consistent and reliable sample collection and analysis of marine water, sediment and biota, including taxonomic identification of biota by non-experts, should be developed and uniformly used on both sides of the border. The protocols should be

performance-based and accessible to a variety of agency, university and private laboratories. The panel further recommends that the data collected by monitoring and research programs become the major factor in determining environmental management policies. In order to maintain the quality, applicability and credibility of these programs, an external, independent peer review of all monitoring programs must be scheduled every five years. Monitoring data collected by dischargers should be held to the same stringent standards as other monitoring programs and should be encouraged to add to the overall databases and information for the shared waters.

Increased Communication

There is a clear need to manage and preserve the habitat and resources remaining in the region effectively and efficiently, using the limited resources available in British Columbia and Washington. To achieve this goal, it is imperative that there be strong collaboration between and among U.S. and Canadian scientists and managers, and vigilance by an informed public.

The panel recommends that the collaboration between British Columbia and Washington scientists and managers take the form of joint planning, monitoring activities and research studies, and the development of compatible environmental regulations on both sides of the border. The governments of British Columbia and Washington, working with their respective federal governments and the universities, must establish an atmosphere that encourages and rewards collaboration between their scientists and managers. Furthermore, the British Columbia and Washington governments must supply or seek funding to carry out joint studies and programs and must create opportunities for joint conferences, workshops and public forums.

The panel further recognizes the importance of providing accurate, accessible and effective information to the public concerning the state of the marine resources and our level of scientific understanding of the shared waters. The public must further be invited to become equal partners with government and industry in determining the fate of those resources and be armed with factual information with which to make these crucial decisions. The panel recommends vigorous education programs be supported in British Columbia and Washington, both in the schools (formal education) and through non-profit and governmental groups (informal education).

Freedom of Scientific Discussion

Proper interpretation of scientific information, be it derived from monitoring, experimentation or modelling, requires open (i.e., public) discourse in the scientific community. This discourse is particularly important, perhaps critically so, in the

multidisciplinary field of environmental management. The panel is disturbed to see that, where the subject of inquiry may be controversial, open dissemination of hypotheses, data and ideas sometimes is not encouraged among researchers in government institutions. Rather, a "designated spokesperson" is frequently assigned the task of meting out information.

This situation is anathema to scientific progress because it misleads the community at large. The public needs to see that scientists often disagree, that uncertainty is almost always present, and indeed, that science is not perfect. Citizens cannot develop such a perspective when interpretation and data are "managed" by senior officials rather than by the scientists who collect the information, weigh it, assess its imperfections and draw conclusions. Silencing scientific researchers only exacerbates the erosion of trust in government that is being witnessed on a broad scale in North America. Hence, the panel recommends that the British Columbia and Washington governments adopt a spirit of openness within government departments that are conducting environmental research, and that the province and state encourage scientists to discuss their findings with their colleagues on both sides of the border.

Appendix A

Contributors to the Symposium on the BC/WA Marine Environment held in Vancouver, B.C., January 13 & 14, 1994

Bourne, N.F. and K.K. Chew, The Present and Future for Molluscan Shellfish Resources in the Strait of Georgia-Puget Sound-Juan de Fuca Strait Areas.

Brinkhurst, R.O., Casillas, E. and J.Q. Word, Marine Benthos of British Columbia/Washington State Boundary Waters.

Calambodikis, J. and R.W. Baird, Status of Marine Mammals in the Strait of Georgia, Puget Sound and Juan de Fuca Strait, and Potential Human Impacts.

Harrison, P.J., D.L. Mackas, B.W. Frost, R.W. Macdonald and E.A. Crecelius, 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.

Johnson, L.L., M.S. Myers, D. Goyette and R.F. Addison, Toxic Chemicals and Fish Health in Puget Sound and the Strait of Georgia.

Kalman, D.A., G. Patrick, S. Peck and M. Samadpour, Marine Pollution and Human Health: Current Status and Future Prospects.

Levings, C.D. and R.M. Thom, Habitat Changes in Georgia Basin: Implications for Resource Management and Restoration.

Macdonald, R.W. and E.A. Crecelius, Marine Sediments in the Strait of Georgia, Juan de Fuca Strait and Puget Sound: What Can They Tell Us About Contamination?

Mahaffy, M.S., D.R. Nysewander, K. Vermeer, T.R. Wahl, and P.E. Whitehead, Status, Trends and Potential Threats Related to Birds in the Strait of Georgia, Puget Sound and Juan de Fuca Strait.

Schmitt, C., J. Schweigert and T.P. Quinn, Anthropogenic Influences on Fish Populations of the Georgia Basin: I. Salmonids. II. Marine Fishes.

Taylor, F.J.R. and R.A. Horner, Red Tides and Other Problems With Harmful Algal Blooms in Pacific Northwest Coastal Waters.

Thomson, R.E., Physical Oceanography of the Strait of Georgia-Puget Sound-Juan de Fuca Strait System.

West, P., T.M. Fyles, B. King and D.C. Peeler, The Effects of Human Activity on the Marine Environment of the Georgia Basin: Present Waste Loadings and Future Trends.

Appendix B

Contributors of Written and/or Oral Briefs
oral briefings held in Vancouver, Seattle and Victoria, January and February 1994

Atkins, Rowland J., Hay and Company Consultants, Inc., Vancouver, B.C. Contaminant Transport Mechanisms: A Process Review.

Broten, Delores, Reach for Unbleached!, Cortez Island, B.C.

Burrows, Mae, T. Buck Suzuki Foundation, Vancouver, B.C.

Cokelet, Edward D., National Oceanic and Atmospheric Administration, Pacific Marine Environmental Laboratories, Seattle, WA. Puget Sound Effluent Concentrations Due to Vancouver, Victoria and Seattle Sewage Discharges.

Dzinbal, Kenneth A., Washington State Department of Ecology, Ambient Monitoring Section, Olympia, WA. General Observations and Summary of Ambient Water Column and Sediment Data Collected by the Washington Department of Ecology.

Ellis, Derek, Biology Department, University of Victoria, Victoria, B.C. Brief on Tributyltin and Dump Sites.

Friesen, Michele, T. Buck Suzuki Foundation, Vancouver, B.C.

Hannah, Linda, State of the Environment Reporting, Province of British Columbia, B.C. State of the Environment Reporting for a Marine System.

Heidorn, Keith, Skies Above Foundation, Saanichton, B.C.

Hodgins, D.O., Seaconsult Marine Research Ltd., Vancouver, B.C. Integrated Modelling and Remote Sensing Systems for Environmental Management: Status and Future Trends.

Levy, D., Hatfield Consultants, Vancouver, B.C. Proposal to Review Technical Information Pertaining to Fisheries and Water Quality in the Puget Sound and Georgia Basin.

Malcolm, Don, Reach for Unbleached!, Cortez Island, B.C.

Marliave, Jeffrey B., Vancouver Aquarium, Vancouver, B.C. Larval Drift Dispersal and Recruitment: Transboundary Implications.

McBride, Laurie, Save Georgia Strait Alliance, Gabriola Island, B.C.

Mearns, Alan, National Oceanic and Atmospheric Administration, HAZMAT, Seattle, WA. Background on the NRC 1993 report on Managing Wastewater in Coastal Urban Areas, and Resource and Pollutant Trends in Puget Sound.

Neel, Jon, Washington Department of Ecology, Olympia, WA and Jean Cameron, Oregon Department of Environmental Quality, Portland, OR. Briefing on Activities of States/BC Oil Spill Task Force.

Paisley, Richard Kyle, University of British Columbia, Vancouver and Elin Kelsey, Vancouver Aquarium, Vancouver, B.C. Marine Protected Areas, Environmental Partnerships and the Utilization of Scientific Information in Environmental Decision Making—the Whytecliffe Project.

Rash, Jeffrey A., Marine Animal Resource Center, Seattle, WA. Brief on Marine Mammals.

Reimer, K.J., Environmental Sciences Group, Marine Monitoring Advisory Group, Victoria, B.C. Scientific Consensus on the State of the Receiving Environment Around the Clover and Macaulay Point Sewage Outfalls: Knowledge and Concerns.

Spence, John A., SPARK Oceans Committee, B.C. Brief on the Requirement for Sustainable Management and Use of the Marine Environment.

Stronach, James, Seaconsult Marine Research Ltd., Vancouver, B.C. Modern Oceanographic Tools for Monitoring and Research into Transborder Pollution Problems.

Thomson , R.B. and Wayne Belzer, Ecosystem Science Division, Environmental Science Branch, Environment Canada, Vancouver, B.C. Brief on the Atmospheric Pathway of Toxics to the Marine Environment.

Torrie, Bruce, Skies Above Foundation, Saanichton, B.C.

Warheit, Kenneth I., Washington Department of Wildlife, Habitat Management Division, Olympia, WA. Brief on Washington State Departments of Wildlife and Fisheries.

Williams, M.C., Capital Regional District, Victoria, B.C. Brief on the Capital Regional District.

Wolferstan, William H., BC Environment, Lands and Parks, Victoria, B.C. Marine Oil Spill Risk as a Factor in Potential Transboundary Pollution.

References

Alvarez, M.M. and D.V. Ellis. 1990. Widespread Neogastropod Imposex in the Northeast Pacific: Implications for TBT Contamination Surveys. *Mar. Poll. Bull.* 21(5):244-247.

Atwater, B.F. 1987. Evidence for Great Holocene Earthquakes along the Outer Coast of Washington State. *Science* 236: 942–944.

BC Ministry of Environment. 1993. State of the Environment Report for British Columbia. Ministry of Environment, Lands and Parks; Environment Canada. Ottawa. 127 pp.

Barnes, C.A., A.C. Duxbury, and B.A. Morse. 1972. Circulation and Selected Properties of the Columbia River Effluent at Sea. In: *The Columbia River Estuary and Adjacent Ocean Waters,* University of Washington Press, 868 pp.

Bisson, P.A., T.P. Quinn, G.H. Reeves, and S.V. Gregory. 1992. Best Management Practices, Cumulative Effects, and Long-Term Trends in Fish Abundance in Pacific Northwest River Systems. In: *Watershed Management: Balancing Sustainability and Environmental Change.* Ed. R.J. Naiman. Springer-Verlag, New York, NY. 542pp.

Bolton, M., W. Rapatz and S. Hugget. 1983. Current Atlas, Juan de Fuca Strait, Canadian Hydrographic Service, Institute of Ocean Sciences, 212 pp.

Bourne, N.F. and K.K. Chew. 1994. The Present and Future for Molluscan Shellfish Resources in the Strait of Georgia-Puget Sound-Juan de Fuca Strait Areas. Proceedings of the BC/WA Symposium on the Marine Environment, January 13 & 14, 1994.

Brinkhurst, R.O., E. Casillas and J.Q. Wood. 1994. Marine Benthos of British Columbia/Washington State Boundary Waters. Proceedings of the BC/WA Symposium on the Marine Environment, January 13 & 14, 1994.

Bucknam, R.C., E. Hemphill-Haley, and E.B. Leopold. 1992. Abrupt Uplift within the Past 1700 Years at Southern Puget Sound, Washington. *Science* 258: 1611–1614.

Calambokidis J. and R.W. Baird. 1994. Status of Marine Mammals in the Strait of Georgia, Puget Sound and Juan de Fuca Strait, and Potential Human Impacts. Proceedings of the BC/WA Symposium on the Marine Environment, January 13 & 14, 1994.

Cokelet, E.D. and R.J. Stewart. 1985. The Exchange of Water in Fjords: the Efflux/Reflux Theory of Advective Reaches Separated by Mixing Zones. *Journal of Geophysical Research,* 90, 7287-7306.

Cokelet, E.D., R.J. Stewart, and C.C. Ebbesmeyer. 1990. The Annual Mean Transport in Puget Sound. NOAA Tech. Memo. ERL PMEL-92, 59pp.

Cokelet, E.D., R.J. Stewart, and C.C. Ebbesmeyer. 1991. Concentrations and Ages of Conservative Pollutants in Puget Sound. Puget Sound Research '91 Proceedings, Vol. 1, 99-108, Puget Sound Water Quality Authority, Olympia, Washington.

Cokelet, E.D. 1994. Puget Sound Effluent Concentrations Due to Vancouver, Victoria and Seattle Sewage Discharges, a Brief Submitted to the BC/WA Symposium on the Marine Environment, 30 December 1994, 8 pp.

Crean, P.B., T.S. Murty and J.A. Stronach. 1988. Mathematical Modelling of Tides and Estuarine Circulation, the Coastal Seas of Southern British Columbia and Washington State. Lecture notes on Coastal and Estuarine Studies, Springer-Verlag, 471 pp.

Cummins, E.B., and M. Kyte. 1990. Management of Nongame Marine Invertebrates. pp. 48–55. In: J.W. Armstrong and A.E. Copping (Eds.), *Status and Management of Puget Sound's Biological Resources.* Proceedings of a Workshop, Seattle, WA, September 11–12, 1989. U.S. Environmental Protection Agency EPA 910/9–90–001, 190 pp.

Ebbesmeyer, C.C., J.M. Cox, J.M. Helseth, L.R. Hinchey, and D.W. Thompson. 1979. Dynamics of Port Angeles Harbor and Approaches, Washington, U.S. Environmental Protection Agency, Interagency Energy/Environment R&D Report no. EPA-600/7-79-252, 107 pp.

Ebbesmeyer, C.C., C.A. Coomes, G.A. Cannon, and D.E. Bretschneider. 1989. Linkage of ocean and fjord dynamics at decadal period. In: *Aspects of Climate Variability in the Pacific and Western Americas,* D.H. Peterson editor, American Geophysical Union, Geophysical Monograph 55, 399-417.

Ebbesmeyer, C.C., D.R. Cayon, D.R. McLain, F.H. Nichols, D.H. Peterson and K.T. Redmond. 1991. 1976 Step in the Pacific Climate: Forty Environmental Changes Between 1968-1975 and 1977-1984. pps. 115-126. In: J.L. Betancourt and V.L. Tharp (eds.) *Proceedings of the Seventh Annual Pacific Climate (AACUM) Workshop, April 1990.* California Department of Water Resources. Interagency Ecological Studies Program Technical Report 26.

Ebbesmeyer, C. and W. Tangborn. 1992. Linkage of Reservoir, Coast, and Strait Dynamics, 1936-1990: Columbia River Basin, Washington Coast, and Juan de Fuca Strait. pps 288-299. In: *Interdisciplinary Approaches in Hydrology and Hydrogeology.* Jone, M. and A. Laenan (eds.)

Ebbesmeyer, C.C. and C.A. Coomes. 1994. Historical Shoreline Recoveries of Drifting Objects: an Aid for Future Shoreline Utilization, Oceans '93 Proceedings, Vol. III. 159-164.

Garton, D.W. and W.R. Haag. 1992. Seasonal Reproductive Cycle and Settlement Patterns of *Dreissena polymorpha* in Western Lake Erie. Reprinted from *Zebra Mussels: Biology, Impacts and Control.* Ohio Sea Grant College Program, Ohio State University, Columbus, OH. 17 pp.

GESAMP (IMO/FAO/Unesco/WMO/IAEA/UNEP Joint Group of Experts on the Scientific Aspects of Marine Environmental Protection) Report of the Twenty-Third Session, London, 19-23 April, 1993. GESAMP Reports and Studies GESAMP No. 51. 41 pp.

Hardy, J.T., and C.E. Cowan. 1986. Model and Assessment of the Contribution of Dredged Material Disposal to Sea-Surface Contamination in Puget Sound. Prepared for the U.S. Army Corps of Engineers, Seattle District, by Pacific Northwest Laboratory, Richland, Washington. Published in Puget Sound Dredged Disposal Analysis PSDDA

Reports, by Washington State Department of Natural Resources, Washington State Department of Ecology, EPA Region 10.

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. Proceedings of the BC/WA Symposium on the Marine Environment, January 13 & 14, 1994, pp. 390.

Holtly, L.B. and J. C. Scrivener. 1989. Observed and Simulated Effects of Climatic Variability, Clear-Cut Logging and Fishing on the Numbers of Chum Salmon (Oncorhynchus keta) and Coho Salmon (O. kisutch) Returning to Carnation Creek, British Columbia. *Canadian Special Publications on Fishery and Aquatic Sciences,* 105:62-81.

Houghton, J.T., G.J. Jenkins, and J.J. Ephraums (Eds.). 1990. Climate Change: the Intergovernmental Panel on Climate Change Scientific Assessment. Cambridge & New York: Cambridge University Press.

International Atomic Energy Agency (IAEA). 1993. Risk Comparisons Relevant to Sea Disposal of Low Level Radioactive Waste. IAEA–Tecdoc–725. Vienna, Austria.

Johnson, L.L., M.S. Myers, D. Goyette and R.F. Addison. 1994. Toxic Chemicals and Fish Health in Puget Sound and the Strait of Georgia. Proceedings of the BC/WA Symposium on the Marine Environment, January 13 & 14, 1994.

Kaiser, G.W. 1993. Seabird Wreck in Boundary Bay. Unpublished manuscript, Canadian Wildlife Service. 5 pp.

Kalman, D.A., G. Patrick, S. Peck and M. Samadpour. 1994. Marine Pollution and Human Health: Current Status and Future Prospects. Proceedings of the BC/WA Symposium on the Marine Environment, January 13 & 14, 1994.

Kuris, A.M. and K.D. Lafferty. 1994. Green Crab Alert. In: *The Crab Newsletter.* 1(1):4-5.

Levings, Colin. 1994. Personal communication.

Levings, C.D. and R.M. Thom. 1994. Habitat Changes in Georgia Basin: Implications for Resource Management and Restoration. Proceedings of the BC/WA Symposium on the Marine Environment, January 13 & 14, 1994.

Macdonald, R.W. and E.A. Crecelius. 1994. Marine Sediments in the Strait of Georgia, Juan de Fuca Strait and Puget Sound: What Can They Tell Us About Contamination? Proceedings of the BC/WA Symposium on the Marine Environment, January 13 & 14, 1994.

Mahaffy, M.S., D.R. Nysewander, K. Vermeer, T.R. Wahl and P.E. Whitehead. 1994. Status, Trends and Potential Threats Related to Birds in the Strait of Georgia, Puget Sound and Juan de Fuca Strait. Proceedings of the BC/WA Symposium on the Marine Environment, January 13 & 14, 1994.

Mumford, T.F., Jr., P. Peyton, J.R. Sayce, and S. Harbell. 1991. Spartina Workshop Record. Proceedings of a Workshop, Seattle, WA, November 14–15, 1990. Washington Sea Grant, Seattle, WA. 73 pp.

Munkittrick, K.R., C.B. Portt, G.J. Van der Kraak, I.R. Smith, and D.A. Rokosh. 1991. Impact of Bleached Kraft Mill Effluent on Population Characteristics, Liver MFO Activity, and Serum Steroid Levels of a Lake Superior White Sucker (Catostomus commersoni) Population. *Can J. Fish Aquat. Sci.* 48:1371-1380.

National Research Council (NRC). 1985. Oil in the Sea—Inputs, Fates and Effects. National Academy Press, Washington, D.C.

National Research Council (NRC). 1993. Managing Wastewater in Coastal Urban Areas. National Academy of Science, Washington, D.C.

Nichols, F., J. Cloun, S. Luoma and D. Peterson. 1986. The Modification of an Estuary *Science* 231:567-573.

Nishitani, L., G. Erickson, and K.K. Chew. 1988. PSP Research: Implications for Puget Sound. pp. 392–399. In: *Proceedings First Annual Meeting on Puget Sound Research.* Seattle, WA, March 18–19, 1988. Puget Sound Water Quality Authority, Seattle, WA. 789 pp.

Paulson, A.J., E.D. Cokelet, R.A. Feely, R.J. Stewart, and H.J. Curl, Jr. 1993. Modeling the decrease in dissolved copper in Puget Sound during the early 1980s, *Environmental Science and Technology.* December, 1993, 2685-2691.

Pearcy, W.G. 1992. Ocean Ecology of North Pacific Salmonids. Washington Sea Grant, Seattle, WA. 179 pp.

Peltier, W.R., and A. M. Tushingham. 1989. Global Sea Level Rise and the Greenhouse Effect: Might They be Connected? *Science* 244: 806-810.

Puget Sound Water Quality Authority. 1990. Puget Sound Update: First Annual Report of the Puget Sound Ambient Monitoring Program. Puget Sound Water Quality Authority, Olympia, WA. 89 pp.

Puget Sound Water Quality Authority. 1991. Puget Sound Update: Second Annual Report of the Puget Sound Ambient Monitoring Program. Puget Sound Water Quality Authority, Olympia, WA. 99 pp.

Puget Sound Water Quality Authority. 1992. Puget Sound Update: Third Annual Report of the Puget Sound Ambient Monitoring Program. Puget Sound Water Quality Authority, Olympia, WA. 69 pp.

Puget Sound Water Quality Authority. 1993. Puget Sound Update: Fourth Annual Report of the Puget Sound Ambient Monitoring Program. Puget Sound Water Quality Authority, Olympia, WA. 89 pp.

Schmitt, C. 1990. Marine Fish Users and Managers: How Are We Doing? pp. 118-141. In: J.W. Armstrong and A.E. Copping (eds.), *Status and Management of Puget Sound's Marine Resources.* EPA 910/9-90-001, U.S. Environmental Protection Agency, Seattle, WA.

Schmitt, C., J. Schweigert and T.P. Quinn. 1994. Anthropogenic Influences on Fish Populations of the Georgia Basin: I. Salmonids. II. Marine Fishes. Proceedings of the BC/WA Symposium on the Marine Environment, January 13 & 14, 1994.

Schoener, A., and D.F. Tufts. 1987. Changes in Oyster Condition Index with El Niño–Southern Oscillation Events at 46°N in an Eastern Pacific Bay. *J. Geophys. Res.* 92: 14,429–14,435.

Stronach, J.A., J.O. Backhaus, and T.S. Murty. 1993a. An Update on the Numerical Simulation of Oceanographic Processes in the Waters between Vancouver Island and the Mainland: the GFS Model, Oceanogr. Mar. Biol. Annu. Rev., 1993, 31, 1-86.

Stronach, J.A., A.J. Webb, T.S. Murty, and W.J. Cretney. 1993b. A Three-Dimensional Numerical Model of Suspended Sediment Transport in Howe Sound, British Columbia, *Atmosphere-Ocean*, 1993, 31(1), 73-97.

Taylor, Laura. 1994. Personal communication.

Taylor, F.J.R. and R.A. Horner. 1994. Red Tides and Other Problems With Harmful Algal Blooms in Pacific Northwest Coastal Waters. Proceedings of the BC/WA Symposium on the Marine Environment, January 13 & 14, 1994.

Thomson, R.E. 1994. Physical Oceanography of the Strait of Georgia - Puget Sound - Juan de Fuca Strait System. Proceedings of the BC/WA Symposium on the Marine Environment, January 13 & 14, 1994.

Troutman, B.L., S.A. Jeffries, T.A. Young. 1991. Identification of Areas for Potentials Seabird Mortality in the Commercial Salmon Gill Net and Purse Seine Fisheries of the Strait of Juan de Fuca and Northern Puget Sound. Final Report to the U.S. Fish and Wildlife Service, Portland, OR. 26 pp.

Vagners, J. and P. Mar. 1972. Oil on Puget Sound, an Interdisciplinary Study in Systems Engineering, University of Washington Press, 629 pp.

Varanasi, U., E. Casillas, M.R. Arkoosh, T. Hom, D.A. Misitano, D.W. Brown, S.Chan, T. Collier, B.B. McCain, and J.E. Stein. 1993. Contaminant Exposure and Associated Biological Effects in Juvenile Chinook Salmon (*Oncorhynchus tshawytscha*) from Urban and Nonurban Estuaries of Puget Sound. U.S. Dept. of Commerce. NOAA Tech. Memo. NMFS-NWFSC-8. 112 pp.

Waldichuk, M. 1958. Drift Bottle Observations in the Strait of Georgia, Journal Fisheries Research Board of Canada, 1065-1102.

Wallentinus, I. 1994. Concerns and Activities of the ICES Working Group on Introductions and Transfers of Marine Organisms. In: *Introduced Species in European Coastal Waters*. Boudouresque, C.F., F. Briand and C. Nolan (eds.). Luxembourg.

Washington Department of Fisheries, Washington Department of Wildlife and Western Washington Treaty Indian Tribes, 1993. 1992 Washington State Salmon and Steelhead Stock Inventory. Olympia, WA. 211 pp.

West, P., T.M. Fyles, B. King and D.C. Peeler. 1994. The Effects of Human Activity on the Marine Environment of the Georgia Basin: Present Waste Loadings and Future Trends. Proceedings of the BC/WA Symposium on the Marine Environment, January 13 & 14, 1994.

Wilson, R.C.H., R.J. Beamish, F. Aitkins and J. Bell (eds.). 1994. Proceedings of the BC/WA Symposium on the Marine Environment, January 13 & 14, 1994, pp. 390.

Wilson, Uhlrich. 1994. Personal communication.

Wolverstan W. 1994. Marine Oil Spill Risk as a Factor in Potential Transboundary Pollution. Briefing to BC/WA Marine Science Panel, January 13 & 14, 1994. 74 pp.

Wooster, W.S., and D.L. Fluharty. (Eds.). 1985. El Niño North. Washington Sea Grant, Seattle, WA. 312 pp.

Word, J.Q., C.D. Boatman, C.C. Ebbesmeyer, R.E. Finger, S. Fischnaller, and Q.S. Stober. 1990. Vertical Transport of Effluent Material to the Surface of Marine Waters. In: Oceanic Processes

in Marine Pollution, Vol. 6, Physical and Chemical Processes: Transport and Transformation, ed. D.J. Baumgartner and I.W. Duedall. Krieger Publishing Co. pp. 133-149.

6. Ecosystem Sensitivity and Future Scope of Anthropogenic Impacts

QUESTION—What components of the transboundary marine ecosystem appear to be the most sensitive to harm from human activities?

Sensitive Ecosystem Components

Our judgments of the components of the shared waters most sensitive to harm from human activities are presented below. The components are discussed in order of decreasing sensitivity, with the most sensitive component (fish and wildlife habitat) presented first, and the least sensitive (human health effects from the marine environment) presented last.

Fish and Wildlife Habitat

When pristine habitat is abundant, it is resilient and can tolerate considerable localized disturbance. Today, however, certain types of natural habitat are scarce, and disturbances are ubiquitous in the shared waters. The remaining fish and wildlife habitat can be harmed by physical alteration, resource overuse and disturbance. The habitats most vulnerable to disturbance, and those that have suffered the most harm, are those in closest contact with human activities. Scientists believe that these are also the habitats in the basin that are the most critical for the survival of threatened fish and wildlife populations. Ironically, we have very poor inventories of nearshore habitats in British Columbia and Washington; further research and monitoring are needed.

Nearshore estuarine habitat has been most severely affected, primarily in urban areas, and secondarily in suburban and rural areas. Upland wetlands are being irreversibly filled and degraded in the basin. Subtidal habitats in general are less at risk mainly because they are further removed from human activities. There is a general correlation between the distance from major population and development centers and the condition of the habitat, although poor forest practices and freshwater diversions have radically altered habitat in many remote areas.

Fish, Shellfish, Birds, Mammals and Marine Plants

Loss of critical habitat, fishing pressure (including unintentional bycatch of many species including birds and mammals), human disturbance (especially of bird nesting grounds) and other inadvertent human impacts take the greatest toll on the basin's living marine resources.

The most vulnerable species are those whose populations would not rebound quickly if environmental stresses were reduced. The maximum possible protection should be extended to species considered threatened or in danger of extinction, regionally or globally. In the shared waters, these include several Puget Sound runs of salmon and steelhead, the marbled murrelet, and the Steller sea lion.

The next level of protection should be afforded to those populations that are depressed or depleted. This list would include several salmon stocks in Puget Sound and chinook salmon in the Strait of Georgia, marine fish such as lingcod and rockfish on both sides of the border, Pacific hake in Puget Sound, harbor porpoise, harlequin ducks and raptors such as osprey.

The third priority for protection should extend to species that provide important linkages in the marine food web and whose absence could cause wide spread die-offs of other species. These species also may pass contamination up the food chain from their own body burden of chemicals. This group would include baitfish such as herring and smelt, intertidal and shallow subtidal invertebrates, and plankton.

Sediments and Benthic Organisms

Contaminants bound to sediment particles sink to the bottom close to their points of origin except where they are spread by dredging and dredge spoil disposal. Accordingly, the areas of greatest contamination and impacts by dredging and dredge material disposal are in close proximity to the urban areas of the basin. Shallow subtidal estuarine habitat areas are observed to support the greatest diversity and abundance of organisms. Many of these very productive and diverse habitats are close to sources of contamination in and around the urban bays. The threat to bottom

dwellers from toxic contamination decreases with distance from each source. Animals living in, on or close to bottom sediments, generally small invertebrates and fish, are at greatest risk from contamination. Animals that are near the top of the food chain may be vulnerable to accumulating contaminants as well.

Marine Water Column

Most of the shared waters are strongly tidally mixed and flushed. They generally are not at risk for the accumulation of chemical contaminants or excess nutrients. However, these materials may build up in localized areas within poorly circulating bays and close to strong contaminant sources. Because most chemical contaminants bind to particles, the principal toxic chemicals of concern in the water column are those few that remain dissolved in seawater, such as dioxins, furans and associated compounds. Recent studies have suggested that some contaminants may accumulate at the sea surface, dissolved in oils and greases (Word et al., 1990). Further investigations in this area are needed.

Unlike most of the major developed estuaries of the world, the shared waters do not exhibit limited phytoplankton growth as a result of dissolved nutrients. Therefore, discharges of nitrogen and phosphorus do not contribute to additional algal growth, eutrophication or fish kills on a basin-wide scale (Harrison et al., 1994). However, some caution is needed in controlling nutrient inputs to poorly flushed embayments, because marine phytoplankton in these areas are "starved" for nutrients during parts of the summer and may begin to grow rapidly with the addition of nutrients, later dying and robbing the water of oxygen.

Pathogenic organisms are generally believed to be rapidly diluted and killed in sea water, with buildups occurring only in poorly circulating areas. However, little is known about many human pathogens, particularly viruses and protozoans, so there is a need to keep untreated human fecal material out of poorly circulated swimming and shellfish areas until additional research can verify that risks are low from potentially virulent pathogens.

Human Health

Because the most chemically contaminated sediments, water and organisms tend to occur in urbanized and/or industrialized areas, these areas provoke the greatest concern for human health effects of seafood contamination. Fecal contamination is most prevalent in shellfish collected from areas with little or no sewage treatment, in the vicinity of failing septic fields, and in waters receiving agricultural or stormwater runoff. These areas often are rural, although waters off towns and cities without adequate sewage treatment also may be contaminated.

Despite the geographic spread and more frequent observation of toxic algal blooms in the shared waters over the last decade, there is little evidence that local blooms result from human activities. Some types of these blooms are more frequent or more intense in certain areas; these areas are the focus of increased monitoring by public health officials in British Columbia and Washington. Additional research on toxic algae also is needed.

> ***QUESTION—Given forecasts of human population increases for the lands that drain to the Strait of Georgia, Puget Sound and the Strait of Juan de Fuca, and assuming little or no change to the current level of pollution control, harvest management and land use management activities, will the amount or severity of harm from transboundary pollution to the habitats, aquatic biota, human health or public health be greater, less or the same in 20 years?***

> ***QUESTION—Are the transboundary populations of biological resources associated with the Strait of Georgia, Puget Sound and the Strait of Juan de Fuca anticipated to increase, decrease or stay the same in 20 years?***

The Shared Waters in 2014—A Projection of Current Trends

The condition of the shared waters in 20 years will depend on a number of natural and human factors. The primary natural factor is the recovery of each component of the ecosystem from each type of contamination or resource use. Ideally, the system can respond to these stresses and can recover from any harm done. Within limits set by circulation, for example, contaminants can be safely diluted and flushed out of the system or buried in sediments. Likewise, if losses from exploitation and contamination do not exceed reproductive capacity, plants and animals can sustain their populations.

There are a few situations, however, in which no use occurs without some harm, recovery is very slow or impossible, and harm therefore becomes essentially permanent. For example, once altered or destroyed, fish and wildlife habitat recovers to its original state so slowly that the harm is essentially irreversible. Likewise, fish, bird or mammal populations that are depleted below a certain critical level may not recover for decades, if ever.

The primary human factors that will determine the condition of the shared waters in 20 years are the total human population of the region, the average level of fresh water and other resource use and the amount of waste disposal. Recent years have seen significant efforts on both sides of the border to reduce the amount of contaminants entering the system and to manage living resources more carefully. However, as the human population expands, greater efforts will be needed—not only to relieve existing problems of contamination and resource depletion, but also to prevent those problems from actually growing worse.

Relative Risks, Cumulative Impacts, and Uncertainty

If present management practices are not improved, marine resources in the shared waters will suffer significant additional harm over the next two decades. Some of this harm, while apparently serious, would be remedied quickly once the causes were removed. More serious harm is done by gradual, incremental changes that are essentially irreversible and deprive future generations of options. Loss of habitat is the most pervasive change of this kind, although irreversible changes to the shared waters also could arise from introductions of exotic species or from major river diversion projects. Threats that are unknown today—such as harm caused by new forms of chemical contaminants—also may arise. Monitoring and basic research must be maintained to provide the earliest possible warning if such problems arise.

We have listed numerous types of harm individually. We also must point out that no one of these exists in isolation from the others. If we consider types of harm individually, rather than looking at how they affect an ecosystem collectively, we paint an over-optimistic picture. In reality, the effects of multiple environmental stresses are *cumulative* and in some cases may cause effects that are more than additive. The ability of the ecosystem to recover from a single source of harm is diminished if the system is suffering additional stress from other sources—which, given the wide spectrum of harm outlined above, is often the case. In addition, the complexity of the ecological linkages is poorly understood in the shared waters. This fact makes assessment of cumulative effects very difficult.

TABLE 6.1

Current and projected status of components of shared waters: "Business as usual" scenario[1]

	PRESENT STATUS		STATUS CHANGE 1994 to 2014	
COMPONENT	WA	BC	WA	BC
AQUATIC HABITATS				
Vegetated shores	very poor	good	slightly worse	much worse
Unvegetated shores	acceptable	good	much worse	slightly worse
Rivers upstream	poor	acceptable-good	slightly worse	slightly worse
Subtidal	good	good	unchanged	unchanged
Sediments in urban bays	very poor	poor	unchanged	unchanged
Water column	very good	very good	unchanged	unchanged
LIVING RESOURCES				
Salmonids	very poor	acceptable-good	slightly worse	slightly worse
Marine fish	very poor	good[2]	slightly worse	slightly worse
Bottomfish in urban bays	poor	good[3]	unchanged	unchanged
Commercial/recreational invertebrates	good	good	slightly worse	slightly worse
Birds	mixed	mixed	slightly worse	slightly worse
Marine mammals	mixed	mixed	slightly worse	slightly worse
HUMAN HEALTH				
Safety from direct contaminant and pathogen exposure	very good	very good	slightly worse	slightly worse
Safety from contaminated seafood	good	good	slightly worse	slightly worse
Safety from toxic algae	good	good	slightly worse	slightly worse

[1] Assumes (1) existing management programs continue unchanged; (2) no change in current per capita contaminant discharge, resource consumption and land use; and (3) population grows at current rates.

[2] Except lingcod

[3] Except portions of Vancouver Harbor

Furthermore, it is relatively easy to evaluate the time scale for resource recovery following (for example) elimination of contaminant discharge or harvesting pressure. It often can be very expensive or logistically difficult, however, to implement and enforce these remedial measures. Outside the realm of scientific evaluation, these realities complicate the task of forecasting marine environmental quality conditions two decades from now.

Status of Shared Waters

The existing levels of harm visible in components of the shared waters have been reviewed in previous chapters. Table 6.1 presents a synopsis of conditions of these components on both sides of the border at the present time. The conditions range from very good to very poor, depending on the component and the location.

Alongside the present condition column in Table 6.1 is the panel's judgment about how this condition will have changed in 20 years. This "business as usual" scenario assumes that existing management programs continue unchanged. In some cases the harm caused by contaminant discharge or resource use is maintained acceptably low as a result of these existing programs. This scenario also assumes that there will be little or no change in the current *per capita* levels of contaminant discharge, resource consumption and land use. Current upward trends in population growth are assumed to continue.

The judgments in this scenario are qualitative, without detailed calculations of population, contamination, or resource use trends. Furthermore, the judgments are not *predictions* of what the actual state of the system will be in 2014; they are *projections* of existing trends into the future, recognizing that if any of those trends change in the interim, the outcome may differ.

It is immediately evident that no condition is projected to improve. This pessimistic scenario results despite the current trend toward lower per capita discharges of many contaminants and uses of many resources. For example, sediments and bottomfish in urbanized areas are becoming less contaminated as cleaner sediments are being deposited. The panel fears, however, that this decline in most cases would be outweighed by the effects of the projected rate of population increase. Current pollution and resource management practices would appear—at best—only to compensate for the resource contamination and depletion resulting from projected increases in population around the shared waters.

In some cases current pollution and resource management practices do not appear adequate to prevent significant ongoing environmental harm under today's conditions. Wild salmonid and marine fish populations in Puget Sound, for example,

are in severe decline for reasons that are not understood, and there is little prospect of restoration under current management. Their condition is projected to become "slightly" rather than "much" worse by 2014 only because their condition cannot get much worse than it already is unless the stocks become extinct.

Conditions in British Columbia are generally better than in Washington state and probably will be for the foreseeable future because the Canadian portion of the shared waters has a larger surface area, longer shoreline and smaller human population. Localized habitats in British Columbia are as heavily affected as those in Washington, however, and some biological populations are suffering stresses similar to those in Puget Sound. British Columbia has the opportunity to learn from Washington's experience and prevent the conditions in its waters from deteriorating to a comparable extent.

Aquatic Habitats

Shoreline and riverine habitats in the shared waters area have suffered variable degrees of harm from human activities, with a serious degree of harm done to vegetated estuarine wetlands and rivers in the Puget Sound basin. Although the rate at which harm continues to be done to these habitats is decreasing, the harm is cumulative and essentially irreversible. Continued proposals for large shoreline developments, freshwater diversions and dams, poor forestry practices in the watersheds, and building of shoreline homes, septic tanks and seawalls all will take their toll on natural habitats. Therefore, if present trends continue, losses of these types of habitat will become more serious over the next 20 years. So much vegetated estuarine wetland and riverine habitat around Puget Sound already has been lost or degraded that even continued destruction of the remainder at the present rate would make the situation only slightly worse.

Subtidal habitats away from urban areas show low levels of contamination and probably will not be affected much by changes over the next 20 years. Chronic sediment contamination problems do exist in many urban embayments on both sides of the border (MacDonald and Crecelius, 1994). These problems generally are responding to reduced discharges from point sources, as cleaner sediments are deposited, and there is a downward trend in surface sediment contamination. These gains may diminish or reverse over the next 20 years, however, as nonpoint source inputs increase with population growth.

At present, the water column habitat on a basin-wide scale appears to suffer negligible harm from waterborne contaminants, loadings of which (West et al., 1994) appear to be well within the self-cleansing capacity of the shared waters system,

coupled with management programs that treat sewage, maintain septic tanks, and otherwise decrease waste streams. Transboundary harm to the water column habitat caused by these contaminants is likely to remain minimal in 20 years, despite incremental increases above present discharge levels, barring serious spills of oil or other harmful chemicals. Some localized harm now occurs to the water column in confined basins, but if response measures already under way are continued, these problems should be controlled. There is the possibility that extensive freshwater diversions could affect salinity and circulation in the water in unforeseen ways.

One transboundary problem that is statistically probable in the next 20 years under current practices is the occurrence of one or more large oil spills of more than 1,600 cubic meters (10,000 barrels; 420,000 U.S. gallons) (Wolverstan, 1994, and original sources quoted therein). A large spill would certainly cause significant immediate harm to the shoreline habitats with which it came into contact, as well as to many other valued aspects of the marine environment. The probability of such spills can be greatly reduced by various measures, including many recommended by the BC/States Task Force on Oil Spills (Wolverstan,1994). However, there are times when the wind is strong enough to drive an inwards surface flow of ocean water onto the southern shore of the Strait of Juan de Fuca, carrying with it any oil spilled in the outer Strait or off the coast of Washington. The deep estuarine inflow could also transport submerged oil back into the inland shared waters. Even if oil transshipment into the Straits and Puget Sound were discontinued, there would still be some risk of a fuel oil spill from the large marine vessels plying the inland shared waters. If such a spill were to occur today, and not again, most habitats would have recovered by 2014, although oil residues might remain in some sheltered, muddy shores.

Furthermore, persistent, chronic discharges of oil products from sources such as surface runoff, atmospheric transport and boat motors, also may cause widespread and lasting low-level contamination. The amount of harm that may be caused by such diffuse sources of petroleum hydrocarbons is not well studied.

Fish

As reviewed in Chapters 4 and 5, many fish populations in the shared waters are reduced or threatened, at least partially because of overharvesting. If present practices continue, depleted fish stocks are unlikely to recover, and many fish populations that are now robust will decline.

Salmon populations have declined because of harm caused by habitat degradation and loss (from poor upland land use practices, freshwater diversion and destruction of estuarine habitat), by overfishing, by possible interactions between wild and

hatchery-produced salmon, and by natural fluctuations in oceanic conditions. The losses have been much greater on the U.S. side of the border. Depleted salmon populations appear unlikely to recover in the next 20 years, given the difficulty of restricting harvest and of restoring lost habitat and genetic resources.

Salmon populations in the region also undergo significant natural fluctuations due to interannual changes in freshwater discharge and in marine conditions that affect food availability and predation (Schmitt et al., 1994). In recent years, salmon population declines have been attributed partly to reductions in river flow and coastal upwelling, but it is difficult to project how these climate-related conditions will change in 20 years.

Part of the difficulty in managing salmon harvest has arisen because of conflicts over harvest of fish originating in one nation by fishers of another nation. Years of negotiation between Canada and the United States have failed to produce a satisfactory agreement as critical wild stocks have continued to decline. The panel takes no position on the relative merits of the positions of the parties to these negotiations and prescribes no cure for the ongoing difficulties. If the conflicts are not adequately resolved in a short time, however, all the parties—and especially the resource—will be losers.

Other fish species do not cross the boundary to the same extent as salmonids. Most commercial and recreational fish stocks in U.S. waters are significantly depleted (Schmitt et al., 1994) and likely to remain that way unless current practices change. Rockfish and lingcod stocks are depleted in the Strait of Georgia as well.

Invertebrates

As reviewed in Chapters 4 and 5, most commercially and recreationally valuable invertebrate populations in the shared waters are healthy but face some threats. Many populations of non-game marine invertebrates may decline sharply if management measures are not instituted. If present practices continue, depleted stocks are unlikely to recover, many populations that are now healthy will decline, and contamination from nonpoint sources is likely to be more widespread.

Despite the potential exchange of planktonic larval stages, many invertebrate stocks in Puget Sound and the Strait of Georgia appear to be distinct, separated by the waters of the Strait of Juan de Fuca (Bourne and Chew, 1994; Brinkhurst et al., 1994). There are, however, a number of common problems in the region associated with industrial, agricultural, and domestic pollution; overharvesting; and multiple use conflicts. These problems are expected to continue in the next 20 years, and they may intensify in the absence of appropriate management strategies.

Birds

Most marine bird populations are being sustained in the shared waters, despite a small number of populations that are declining in number, such as those of common murres and marbled murrelets, and other populations that are very sparse, such as harlequin ducks. The overall rating of "Mixed" reflects the differences in population health among bird species. Even though some species are in good condition, there is still a need to attend to problems that threaten other species. Human activities affecting birds include commercial fisheries (food competition and net entanglement), spills of oil and other hazardous materials, contaminant discharges from point and nonpoint sources, disturbance of bird colonies by humans (and their pets), and especially habitat loss (Mahaffy et al., 1994). All these sources of stress are likely to become more severe in the next 20 years as the human population increases. The statistical likelihood of a major oil spill in the future also could threaten stressed populations of diving birds that nest and feed along tanker routes and shipping lanes.

Bird populations fluctuate greatly in response to natural changes in climate and food abundance and availability, and these changes are not very predictable. Migratory bird stocks also are affected by natural and anthropogenic changes in distant places. These distant influences need to be taken into account in any management strategy.

Mammals

Most marine mammal populations are being sustained in the shared waters, although numbers of some species, such as Steller sea lions, are low. Harbor porpoises have disappeared from Puget Sound for reasons that are uncertain but probably related to human disturbance, which also appears to have affected Steller sea lions. Some of the mammals in the shared waters are affected by bioaccumulated contaminants, and others are affected by incidental mortality in various fisheries. How these factors are affecting mammal populations is uncertain (Calambokidis and Baird, 1994).

Marine mammals also are affected by poorly predictable natural variations in food availability, and in many instances they compete with man for food. It is thus difficult to predict what the population levels of marine mammals will be in 20 years' time, although it seems unlikely that harbor porpoises will return to Puget Sound. Recent increases in the populations of harbor seals and California sea lions throughout the region are likely to level off, if only due to limited food supplies. Human disturbance of marine mammals is likely to increase in the absence of increased regulation and public education, and it is unknown at what point this could reach

critically low population levels. The main human impacts on marine mammals probably will continue to arise from competition for foodfish. The poor status and continuing decline in marine fish populations bode poorly for the pinnipeds and small cetaceans that use marine fish, and the declining status of salmonids could have severe impacts on orca whales. In addition, the statistical likelihood of a major oil spill in the future could threaten mammal populations that are already suffering other stresses.

Human Uses and Public Health

Direct human exposure to waterborne and particle-bound contaminants and pathogens is generally slight, but the incidence of exposure will increase as human populations expand. Despite considerable incidence of contaminants and algal toxins in seafood, present management efforts are generally sufficient to keep human exposures low. The problems have the potential to become incrementally more difficult to manage if present trends of human population growth and contamination continue.

Potential Future Problems

Large-Scale Environmental Change

Additional harm to marine resources in the shared waters, beyond the types and magnitude now occurring, also may result from environmental changes that could occur in the next 20 years. Although most of these are beyond human control, an awareness of, and preparedness for, these changes can mitigate the harm they cause to marine resources.

Regional climate change, whether caused by natural variability or by possible human alteration of the global climate, also could lead to widespread harm to the marine environment within the next 20 years. Changes in water temperature would affect the abundance of some temperature-sensitive species, would alter the distribution of migratory marine organisms and might increase the incidence of the outbreak of toxic algal blooms (Nishitani et al., 1988). Any changes in prey abundance or availability could affect higher animals and disrupt the food chain. The effects of climate change, including those from sea level rise and reductions in freshwater discharge, would be likely to trigger or magnify a number of the other marine impacts listed above.

These potential climatic impacts are, by and large, unavoidable through actions taken within the region. However, the harm would be greatly aggravated if marine resources were already suffering stresses that reduced the resilience of the system, and if management activities to protect these resources do not relieve some those stresses.

A major earthquake is expected in this region at any time in the next few hundred years. Such a quake could cause shoreline flooding and erosion from a tsunami and might involve up to several meters of rapid shoreline uplift or submergence, causing the collapse of coastal bluffs and artificial structures. Fossil evidence shows that large earthquakes have occurred and are likely again both off the outer coast, with most impacts sustained along the coast, and along a fault crossing Puget Sound, with significant impacts seen along inland shorelines (Atwater, 1987; Bucknam et al., 1992).

These natural effects of seismic activity are unavoidable. However, damage to buildings and other facilities in the nearshore zone is, in theory, preventable with appropriate precautions. Such damage could cause harm to the marine environment if contaminants are discharged from such sources as ruptured pipelines and damaged storage facilities on land.

Emerging Problems

The panel recognizes the strong possibility that further research and monitoring may reveal problems that are currently only suspected or completely unforeseen. Among the former, a number of anthropogenic chemicals are found to disrupt endocrine function in marine organisms and humans, causing impacts as serious as, or more serious than, those of cancer induction.

The anti-fouling agent tributyl tin (TBT) is one example of a chemical known to be capable of disrupting reproductive functions and development in marine snails (Alvarez and Ellis, 1990). TBT use is presently banned for boats of less than 25 meters in length in Canada and the United States. Evidence of further impacts may dictate more stringent restrictions. Surfactant compounds, widely used in industrial and domestic detergents and discharged to the marine environment, also are prompting concern because they mimic natural reproductive and developmental hormones (MacDonald and Crecelius, 1994). These chemicals may prove a significant problem for marine biota in 20 years unless their discharge is controlled.

A number of contaminants may be entering the ecosystem and concentrating in the sea surface microlayer, the upper millimeters of the water column. Contaminants in this layer may harm the floating eggs and larvae of many marine animals.

Such contaminants might affect adult organisms as the layer traverses the intertidal zone on an ebb tide, or as breaking waves and bubbles create potential "toxic pills" that could be ingested. Part of the input of contaminants to this layer is thought to originate from airborne emissions such as automobile exhaust, wood smoke and industrial emissions. If this is verified to be a significant environmental problem, remedial actions could require reduction of discharges to the atmosphere by human transportation systems, industry and even wood stoves.

A major continuing external threat to shared waters arises from the introduction of new marine organisms from other parts of the world. The ballast water often discharged by merchant ships approaching ports in the region appears to be the major source of these exotic species. Other exotic species are introduced intentionally or unintentionally in packaging and live marine animals exhibits and experiments. If present practices do not change over the next 20 years, it is possible that the region will see the introduction of one or more exotic species that could produce substantial alterations in the local food chain structure.

7. Degree of Harm and Management Priorities

QUESTION—What types of harm appear to be most serious and should be the focus of monitoring, research and management activities over the next 10 years?

In our criteria for identifying priorities for management action (Chapter 1), we stressed the primary importance of recovery time. This is the time it would take for the ecosystem to respond to reductions in human activities causing harm and for any accumulated harm to be eliminated or reduced to acceptable levels. The recovery may take place by entirely natural processes, or where practicable it may be accelerated by restoration activities. We categorize recovery times as follows:

SHORT: recovery time less than about three years

MEDIUM: recovery time about three to 30 years

LONG: recovery time greater than 30 years

IRREVERSIBLE: recovery time extremely long (centuries or more) with or without remediation

A second criterion for identifying priorities for management action is the amount of harm caused by a human activity. We assign harm a secondary role and recovery time the primary role because recovery time includes an estimation of the environmental "harm commitment"—the total future harm, as well as the immediate effect—entailed by some present action. An action that causes a small but persistent harm may entail a greater environmental harm commitment than one that does more harm in the short term but from which the environment recovers quickly.

In addition to recovery time and harm, we used two more criteria—preventability and cost—to assign priorities for management action. These criteria relate more to

the magnitude and technical feasibility of management actions than to the natural responses of the ecosystem. Priority is given to actions that may be taken easily to prevent or to mitigate harm, and to types of harm that would necessitate a high cost and a long time to clean up or restore.

Seriousness of Harm and Management Needs

The panel's ranking of various marine environmental issues, using the four criteria above, is shown in Table 7.1, in order of descending priority for management response. The details of these issues and their rankings are discussed in the sections that follow. Research, monitoring and management activities over the next 10 years should focus on those ecosystem components that are most vulnerable and should be chosen to meet the four criteria described above.

Human activities that damage the ecosystem in ways where recovery times are potentially very long or harm is irreversible, and where remediation is prohibitively expensive, are assigned high priority and demand immediate corrective action. Activities from which the environment recovers quickly, once the insult ceases, are assigned medium to low priority for management action. In these instances, decisions can be postponed to ensure that the best scientific information has been obtained before action is taken.

Recovery time refers only to the response of the natural environment. We do not account for the time required for decisions to be made and implemented in society. In the real world, both of these time intervals must be considered when calculating how long it will take to improve the marine environment from its present condition to a desired condition. However, it is not our goal to produce a timetable for environmental cleanup. Our goal instead is to set an agenda for management attention by giving high priority to the harm that is longest-lasting and giving low priority to harm that will disappear quickly, whether remedial action is taken immediately or delayed for many years.

Destruction, Alteration or Degradation of Habitat

Prevention of habitat destruction is accorded the highest priority because its impacts are irreversible, the potential harm to the environment is great, and habitat losses are highly preventable while the cost and effort needed to restore the amount of functional habitat are very high.

TABLE 7.1

Criteria for setting priorities in the shared waters

ISSUE	RECOVERY TIME[1]	HARM TO ENVIRONMENT	EASY TO PREVENT?[2]	CORRECTION OR MITIGATION COST	OVERALL PRIORITY
Habitat loss	irreversible	high	yes	very high	very high
Fish & shellfish populations	medium[3]	high	yes	high	high
Exotic species	long/irreversible	low/high	no/yes[6]	high	high
Freshwater diversions	long/irreversible	high	yes	very high	high
Toxics in living resources	short/medium	medium	yes/no[4]	medium/high	medium
Toxics in sediments	medium	medium	yes/no[4]	medium/high	medium
Oil spills	medium (long for some populations)	medium	no/yes[6]	high	medium
Toxic algae	irreversible (short for some populations)	low[5]	no	low	medium
Fecal contamination	short	low	yes	medium	medium
Water column contamination	short	very low	yes	medium	low

1 Accounts only for ecological recovery after action is taken, not time required to choose and implement recovery actions.

2 Accounts only for technical feasibility of prevention, not difficulties in political decision-making or enforcement.

3 Certain stocks may never recover and may be replaced with other stocks.

4 Point source toxic releases can be prevented; nonpoint source control of toxics is considerably more difficult.

5 Except for human health.

6 Total prevention is impracticable, but simple measures can greatly reduce risks.

Quite conservative habitat management practices are necessary. Surprisingly little is known about the quantity and quality of all major habitat types, and there is a need for additional research and monitoring as soon as possible to facilitate habitat protection. Management should concentrate on preserving remaining nearshore estuarine habitat, restoring and enhancing marginally degraded habitat, preventing additional freshwater diversions, controlling exotic (non-indigenous) species and protecting contiguous terrestrial wetlands. Research should focus on nearshore habitat functions and values, food chain linkages, investigations into the impacts and spread of exotic species on nearshore habitat, and the effects of chronic contamination on nearshore and terrestrial habitats. Monitoring efforts should provide accurate inventories of nearshore and adjacent terrestrial wetlands and should track changes in quantity and quality of those areas.

Declines in Fish and Shellfish Populations

Halting further losses of fish and shellfish populations is assigned a high priority because these resources require at least a medium time frame for recovery from impacts, which in some cases may be irreversible, and the high likelihood of harm to the food web. These losses can be prevented with relative ease, and the cost and effort required to rebuild or replace stocks is high.

Very conservative management practices are necessary for many depleted or threatened stocks, while further research and monitoring should continue at an accelerated pace. Management practices should focus on fisheries regulations and practices that minimize impacts on depleted stocks. Research is needed on the basic biology of many marine fish species, fisheries-oceanography interactions, food chain dynamics, interactions among hatchery and wild stocks of anadromous fish, and impacts of escape of Atlantic salmon and other farmed fish on wild stocks. Monitoring should be extended to include better stock assessments of non-commercial marine fish species and non-game marine invertebrates.

Introduction of Exotic Species

Preventing the introduction of exotic species is assigned a high priority because changes from such introductions can be persistent or irreversible, and the range of effects from introduced species can be immense. We have the ability to prevent the introduction of certain exotics, while others may prove more elusive; however, the cost to correct or mitigate invasions of exotic species is extremely high.

Sometimes species are introduced deliberately for beneficial uses, although little attention may be paid at the outset to biological side effects of such introduc-

tions. Some species introduced locally, such as the Pacific oyster, have proved to be highly beneficial, while others, such as the oyster drill and the smooth cordgrass *Spartina*, cause or might cause significant harm. Atlantic salmon, introduced for net-pen aquaculture, have been caught in the fisheries in the Strait of Georgia. No evidence of harm from this escape has yet been established. Elsewhere in the world, there are examples of extreme alteration of aquatic ecosystems by exotic species such as the freshwater zebra mussel, which is fouling water intakes in the central United States (Garton and Haag, 1992), and a ctenophore that has preyed on fish eggs and larvae and devastated fisheries in the Black Sea (GESAMP, 1993).

Monitoring and research must be stepped up to understand the extent and life cycle of exotic species that are already present in our marine waters and along shorelines, and monitoring and management for the early detection and exclusion of new species must be increased. Exchanges of information with adjacent areas and among the world-wide research community are crucial to providing early warning of new threats. A recent example is the information from California researchers that a European green crab is undergoing a population explosion and displacing native subtidal benthos, including harvestable invertebrates (Kuris and Lafferty, 1994).

Freshwater Diversions and Alteration

Minimizing diversions and alterations of fresh water supply is assigned a high priority because their impacts are very persistent or irreversible and the impact on the environment is high. The time span required for recovery of salmonid populations following partial or complete restoration of natural river flow patterns is unknown. Evidence of the severity of impacts in our region is provided by the example of the damming of the Columbia River (Ebbesmeyer and Tangborn, 1992) and, even more drastically, the impending loss of estuarine circulation in San Francisco Bay caused by losses of fresh water (Nichols et al., 1986). We have the ability to avoid large freshwater diversions, and the costs to correct or mitigate the effects of large diversions of fresh water from estuarine and coastal areas are very high.

Large and small rivers and streams must be monitored so that the water flow can be maintained for fish passage and for normal estuarine circulation and salinity. Research is needed to determine the sensitivity of estuarine systems to disruptions of fresh water supply. For example, the proposed diversion of the Nechako River, which joins the Fraser in central British Columbia, could potentially affect the salinity distribution at the distant mouth of the Fraser, causing harm to the estuarine habitat. Management activities that encourage and educate the public about water and energy conservation are needed in order to continue to supply adequate fresh water and hydroelectric power for the needs of the growing human population.

Toxic Contamination of Living Resources

Preventing toxic contamination of living resources is assigned a medium priority because recovery occurs over a medium time frame, although the impact on the environment may be reasonably strong. The ability to prevent toxic contamination of resources is high, and cost and time required to turn off contaminant sources and allow for natural recovery are medium to high.

Management activities should concentrate on controlling contaminant sources and spills. Considerable research is needed to define better the pathways through which contaminants enter organisms and the effects that those contaminants have on individual organisms, populations and marine community interactions. Monitoring activities should delineate the extent and severity of resource contamination and should follow the course of recovery.

Toxic Contamination of Sediments

This issue is considered to be of medium priority because recovery occurs over a medium time frame and because there is a fairly substantial impact to the environment, including the potential for human health problems caused by passage of contaminants through the food chain. Prevention of sediment contamination from point sources is well within our ability, and the cost of source control to allow for natural recovery is moderate, although contamination from nonpoint sources is a problem that is more difficult and expensive to remedy. Recovery time could be shortened through capping, sediment removal and other remediation techniques, although the cost would be considerably higher than that for natural recovery.

Management activities, like those for cleaning up living resources, should focus on source control and the prevention of spills. Additional research is needed on the bioavailability and relative toxicity of chemical contaminants in sediments, the development of robust assays to determine harm to organisms from sediment contaminants, and the chemical alterations that occur when freshwater contaminants reach salt water. Monitoring activities should delineate the extent and severity of sediment contamination and follow the recovery.

Oil Spills

Management of oil spill risks is assigned a medium priority, but we segregate this issue into two separate parts. Recovery from oil spills occurs over a moderate time frame. The overall harm to the environment can be acute in the short term but is considered moderate over the longer term. Certain bird and mammal populations may require a long recovery time to return to historic levels if key habitats are oiled or

if these species are suffering cumulative impacts of other stresses. Preventing oil spills is not completely possible as long as oil is transported, yet preventive measures that are available are much less expensive and more effective than cleanup. Cost-effectiveness of most oil recovery and cleanup efforts after a spill is considered to be low, based on information gathered following cleanup activities after the 1989 *Exxon Valdez* oil spill in Alaska and other spills in the British Columbia-Washington region.

Management activities must focus on oil spill prevention and oil conservation. Although some oil spill response and cleanup activities are warranted, such as skimming and booming to protect vital areas, most large-scale oil spill cleanup is ineffective and may cause additional harm. Management activities that provide for the safe transportation of petroleum products will prevent most major spills, while chronic small spills and discharges, as well as the atmospheric-borne wastes from cars, are best handled by increased technical assistance to the marine industry, boaters and the public. Monitoring and research activities that directly support management of spill prevention and conservation are needed.

Toxic Algae

Response to toxic algal blooms is assigned medium priority because the potential threat to the environment (with the exception of human health risks) is low. Recovery time from a single incidence of toxic algal contamination is short, while the effects of introducing toxic algae to a new area appear to be very persistent or irreversible. Toxic algal blooms are the single chronic problem in the shared waters in which human activities are not conclusively implicated, and as a result our ability to prevent toxic blooms is very low. It is possible that human activities could foster the spread of toxic algal organisms by inadvertent introduction of exotic algal species via ballast water or other mechanisms, although to date there is no evidence that this has happened. Costs for dealing with toxic blooms are low and are largely directed at monitoring and management activities to protect public health.

Management efforts that prevent human and other animal contact with toxic marine products, and which inform the public of the risks, should continue. Research efforts should be increased greatly to determine the source of domoic acid and outbreaks of other toxins that are likely to arrive in our waters and to search for correlations between blooms producing saxitoxins, domoic acid and other toxins, and oceanographic or climatic conditions. Monitoring of marine waters, shellfish and other organisms should continue with an increased emphasis on targeting organisms consumed in non-traditional harvesting.

Fecal Contamination of Seafood

Contamination of water and seafood is assigned a medium priority. The recovery time is short after fecal sources are controlled, and the risk of harm to the environment is low, although there is some human health risk from pathogens in seafood. Our technical ability to prevent fecal contamination is high, although placing limits on nonpoint sources may be expensive, difficult and time-consuming to implement. Sewage treatment plants also are extremely expensive and politically difficult to construct and upgrade.

Management activities should continue to focus on reducing sources of fecal material, including both upgrading some urban sewage and surface runoff treatment systems and controlling non-urban sources such as agriculture and domestic drainage systems in the watersheds. The application of a risk-based approach, as we recommend, may lessen the need for construction or extensive improvement of sewage treatment plants. Research is needed on methods for distinguishing between fecal coliform bacteria of human versus animal origin and for isolating and identifying other bacteria, viruses and protozoans from marine waters and organisms. In addition, research is needed to determine the lengths of time that these pathogens remain virulent once they enter salt water. Monitoring of fecal contamination in marine water and shellfish should continue.

Contamination of the Water Column

Water column contamination is accorded low priority because over most of the shared waters, chemical contaminants, including inorganic nutrients, oil and toxins are dispersed and flushed from the system over a short time frame. Also, the environmental damage from water column contamination is very low, and our ability to prevent such spills is fairly high. Although large sums have been spent to keep human contaminants from the water column, future costs should be low.

Management activities should focus on the prevention of spills and chronic inputs of oil and chemicals. Research on food chain interactions, basic oceanographic processes, and the sea-surface microlayer are needed to better understand the distribution and fate of contaminants and their effects on planktonic larvae, eggs and prey organisms. Monitoring activities should be used to support research efforts and to maintain a watch on poorly circulating embayments where future water column problems will first appear.

Unknowns

There always will be threats to the marine environment and its resources that are not foreseen, and the effects of such threats could range from slight perturbations to system-wide collapses. While we cannot evaluate the priority of these unknown threats, it is vital that some focus and resources always be available for their detection and management.

Some uncertain threats are more familiar to us than others. The potential for earthquakes, tsunamis, and global and regional-scale changes in climatic or oceanographic conditions are real and likely threats to the shared waters, yet we cannot predict or prevent them. Planning for these occurrences can provide us with rapid response abilities to deal with these uncertainties. Research and monitoring activities that scan for and better understand these natural phenomena can provide important clues for managers preparing response plans.

Other unknowns belong in the realm of educated speculation. In the future, we might see new synthetic chemicals posing threats to our resources; a new and virulent exotic species taking over large tracts of marine habitats and outcompeting native species; or any of a host of other possible threats. We cannot guarantee against such threats. We can, however, take reasonable precautions in activities that may contribute to such threats, such as in discharges of new chemicals and of ballast water. We also can mount vigilant monitoring programs and broad-based research programs in hopes of recognizing unknown and emerging threats to the marine environment at an early stage. With foreknowledge, managers can move quickly to respond and minimize impacts of the new threats.

The Shared Waters in 2014—Optimum Future Scenario

Table 7.2 presents an idealized scenario for the optimal state of the shared waters in 20 years as an alternative to the "business as usual" scenario outlined in Chapter 6. This "best-case" scenario supposes that appropriate management measures are taken **immediately** to reduce contaminant input and resource depletion significantly and to allow the natural or assisted recovery of the system. The degree of improvement possible under such a scenario depends upon the relative rates at which resources in the shared waters recover from the harm discussed in previous chapters.

This scenario does not account for the time that elapses in the normal process of decision-making, nor for the time needed to build or improve facilities that enhance water quality. These activities can span time intervals of the same order as

those required for the recovery of the natural system once action is taken—i.e., decades. As such, we clearly present an idealized, optimistic, "best-case" scenario.

The judgments in this scenario are qualitative, without detailed calculations of population, contamination or resource use trends. Furthermore, the judgments are not predictions of what the actual state of the system will be in 2014; they are projections of existing trends into the future, recognizing that if any of those trends change in the interim, the outcome may differ.

Aquatic Habitats

The condition of vegetated shore, unvegetated shore, and upstream river habitats will change little or not at all in 20 years even if afforded the most enlightened management. Natural recovery is extremely slow or irreversible, and experiments in restoration of natural habitat and artificial creation of new habitat have not yet developed methods that can reliably mitigate destruction of natural habitat. Thus even a radical reduction in the rate of development and degradation of these habitats can do no more than preserve the status quo.

The present downward trend in surface sediment contamination largely results from reduced discharges from point sources (PSWQA, 1993). Given further reductions in contaminant inputs, mainly from nonpoint sources, the system should respond quickly, and the downward trend could be continued despite increases in human populations. Cleaner sediments could cover the seafloor and thus continue to improve the quality of subtidal habitats, especially in urban areas.

Prevention of the building of major new dams would assure the protection of riverine flows and habitats and would maintain the supply of clean sediments to the estuaries. It also would maintain the natural supply of fresh water and natural salinity and circulation in the water column. Water column habitats for the most part are in very good condition and could not be improved much by better management. If further monitoring or research were to reveal an unforeseen problem, the system would recover quickly after appropriate controls were applied.

Water column and shoreline habitats also can be maintained in their present condition over the next 20 years if a major oil spill can be prevented. Even in an optimal scenario, however, an accident is possible and could harm transboundary habitats. If a major spill occurred today, and no more occurred for 20 years, water column and rocky shore habitats would completely recover, and sandy, gravelly and muddy shore habitats would mostly recover within 20 years. The harm caused by persistent small spills is uncertain but potentially involves greater harm commitment over 20 years. If this source of contamination could be reduced, habitats could recover substantially within 20 years.

TABLE 7.2

Current and projected status of components in the shared waters: Optimal future scenario*

	PRESENT STATUS		RECOVERY TIME	STATUS CHANGE 1994 to 2014	
COMPONENT	WA	BC		WA	BC
AQUATIC HABITATS					
Vegetated shores	very poor	good	irreversible	unchanged	unchanged
Unvegetated shores	acceptable	good	irreversible	unchanged	unchanged
Rivers upstream	poor	acceptable-good	irreversible	unchanged	unchanged
Subtidal	good	good	medium	slightly better	slightly better
Urban sediments	very poor	poor	medium	slightly better	slightly better
Water column	very good	very good	short	unchanged	unchanged
LIVING RESOURCES					
Salmonids	very poor	acceptable-good	medium-long	slightly better	slightly better
Marine fish	very poor	good	medium-long	slightly better	slightly better
Bottomfish in urban bays	poor	good	medium	slightly better	slightly better
Commercial/recreational invertebrates	good	good	medium	slightly better	slightly better
Birds	mixed	mixed	medium-long	slightly better	slightly better
Marine mammals	mixed	mixed	medium-long	slightly better	slightly better
HUMAN HEALTH					
Safety from direct contaminant and pathogen exposure	very good	very good	short	unchanged	unchanged
Safety from contaminated seafood	good	good	short-medium	slightly better	slightly better
Safety from toxic algae	good	good	irreversible	slightly worse	slightly worse

*This ideal scenario assumes that management measures to reduce contamination and resource depletion are instituted and enforced immediately.

Fish and Invertebrates

The serious decline in many Puget Sound wild salmon stocks is blamed on habitat degradation and loss (from poor upland land use practices, freshwater diversion and destruction of estuarine habitat), overfishing, possible interactions between wild and hatchery-produced salmon, and natural fluctuations in oceanic conditions. While stocks could generally recover from overfishing alone within 20 years, the irreversible loss of habitat and genetic resources dims the prospect for fully restoring depleted Puget Sound wild salmon populations by 2014. Any hope for recovery also requires that the quantity or timing of freshwater discharge from the Fraser and other rivers not be significantly regulated or altered. Restrictions on catch and habitat loss hold the prospect of sustaining Strait of Georgia salmon stocks at their present levels or better.

Most marine fish in Puget Sound, and some invertebrate populations in the shared waters, are reduced or threatened, at least partially because of overharvesting. Reduction or elimination of catch could lead to recovery for most species within 20 years, although the species composition following recovery might differ from the original. Stocks of some long-lived rockfish species are very low on both sides of the border and could take longer to recover. Contamination problems suffered by bottomfish and invertebrates in the shared waters could be significantly reduced in the next 20 years by rigorous controls, especially on nonpoint sources.

Fish and invertebrate populations also can be maintained in their present condition and allowed to improve over the next 20 years if a major oil spill can be prevented. Even in an optimal scenario, however, an accident is possible that would cause significant ecological harm in the transboundary area. If a major spill occurred today, and no more occurred for 20 years, population levels of some fish and invertebrate species could be affected in the short term, but most would recover to their current levels within 20 years. Greater harm to commercial and recreational uses probably would result from contamination by oil residues, which could still be present at low levels in 20 years in organisms inhabiting sheltered muddy shore habitats.

Recovery of most fish and invertebrate species would require that natural oceanographic and climatic conditions remain favorable, a condition that may not be met even today. All recovery efforts could be less effective if the carrying capacity of the shared waters declines because of externally driven environmental changes.

Marine Birds and Mammals

Marine birds and mammals are affected by commercial fisheries (through food competition and net entanglement), spills of oil and other hazardous materials,

contaminant discharges from point and nonpoint sources, human disturbance of feeding and breeding areas, and habitat loss. If the latter two sources of stress, especially, can be reduced even as human populations grow over the next 20 years, bird and mammal populations can be sustained, and the depleted bird species will have some opportunity to recover. It seems unlikely, even if considerable effort were made to limit human disturbances, that harbor porpoises will return to Puget Sound. Recent increases in the populations of harbor seals and California sea lions throughout the region might be sustained somewhat longer if human competition for foodfish is reduced, but fish stocks already are so low that this effect would probably be minimal. The continued well-being of resident orca whale populations will depend on arresting the decline in salmon stocks.

If a major oil spill can be prevented over the next 20 years, bird populations have a chance of maintaining their current populations. Even in an optimal scenario, however, an accident is possible and could harm transboundary bird stocks. Harbor seals also would be vulnerable to a spill. If a major spill occurred today, and no more occurred for 20 years, harbor seals and most bird populations could completely recover, along with their habitats, as long as they were spared serious stresses from other sources. Particularly sensitive populations of diving birds, such as common murres, marbled murrelets and harlequin ducks, which are now at low levels, probably could not recover from a major oil spill within 20 years.

Human Uses and Public Health

There currently are only limited and isolated threats to public health posed by marine resources. Of these, furthermore, the naturally occurring toxic algae blooms are as significant a threat as those caused by contaminants. Reduced waste discharge and increased treatment of waste that is discharged (including well maintained and better designed septic systems) could prevent the contaminant-caused risk to human health from worsening as populations increase. Also, more vigorous education and monitoring programs could reduce the risks posed by whatever level of contamination is present, including risk from toxic algae.

QUESTION—What indicators are recommended for future state of the environment reporting for the transboundary marine ecosystem?

Ecosystem Indicators

The panel recommends that a full set of environmental indicators be used in future state of the environment reporting. The use of a more limited set of indicators may miss important changes in resources of concern and/or miss the emergence of new threats or changes to the marine environment. Indicators should be chosen that meet the following criteria: 1) They must be scientifically-based and replicable; 2) parameters can be easily and cheaply measured; and 3) indicators are tightly tied to the resources and ecosystem components of greatest concern.

Present monitoring programs in British Columbia and Washington collect many types of information ranging from fisheries stock assessments to population counts of birds and marine mammals, water column and sediment chemistry, and measurements of biological and chemical contaminants in biota. The panel recommends that the Puget Sound/Strait of Georgia Working Group undertake a rigorous assessment of the parameters currently measured, choose those parameters that meet the panel's criteria and seek to institutionalize the collection of those environmental parameters in monitoring programs in British Columbia and Washington.

The panel further recommends that the Working Group consider augmenting monitoring data collection with key measures of ecosystem components that are generally lacking in current British Columbia and Washington monitoring programs, including the monitoring of water column phytoplankton and zooplankton species and benthic community structure; the extent and functional value of subtidal seagrass beds; and the health and numbers of sensitive species of fish, invertebrates, birds and mammals that are not of commercial interest. The Working Group also should look closely at indicators for which a sufficient research base exists to interpret changes in resource populations, habitat functions and contaminant levels. The Working Group should encourage the funding of research to elucidate pathways and relationships among the physical and biological environment that are poorly understood.

8. Recommendations

QUESTION—Which types of human activities (for example, discharges or spills of toxic compounds, nutrients, pathogens, physical land modification) need the most management attention?

The panel has formulated 12 specific management recommendations that address the priority issues outlined in Chapters 6 and 7. These recommendations are summarized in Table 8.1. Seven are specific recommendations on dealing with a particular source of harm, and five are recommendations for increasing management effectiveness and enhancing scientific understanding. These recommendations are to be implemented using two important principles outlined below.

Principles for Sound Ecosystem Management

There are two principles, discussed in detail in Chapter 1, that the panel recommends be used to guide future research, management and monitoring activities in the shared waters.

Risk-based Management System

Management decisions that affect the future health of habitats and resources in the shared waters must be based on an integrated scientific risk-based management system. Risks must be evaluated quantitatively, by analyzing the probability that harm will occur and the amount and seriousness of harm that may result. The duration of risks also must be considered to determine the magnitude of harm to which the environment becomes committed. Frequently, risks must be evaluated using incomplete or inadequate information, because society must act and cannot afford to wait or to pay for more complete information. Under these circumstances, scientific inferences are made, typically presuming, without proof, that properties or condi-

TABLE 8.1

Recommendations for actions and effective management to protect the shared waters (ranked in order of priority)

PRIORITY	ACTIONS
Highest	Minimize estuarine wetland habitat losses
	Establish marine protected areas
	Protect marine animals and plants
	Minimize large fresh water diversions
	Minimize introduction of exotic species
	Control toxic wastes
	Prevent large oil spills

PRIORITY	EFFECTIVE ENVIRONMENTAL MANAGEMENT
Highest	Strategic planning
	Comprehensive program review
	Monitoring/research/ management framework
	Increased public and scientific communication
	Freedom of scientific communication

tions observed at one site can be applied at another. Where risk cannot be adequately evaluated because insufficient information is available, a precautionary approach in tandem with appropriate scientific inquiry is warranted. Strategic planning for ecosystem stewardship must consider uncertainties and unknowns; flexibility will be a key to good policy.

Precautionary Approach

Based on our scientific understanding, we recommend three courses of action, based principally on the potential of various activities to create irreversible harm to the marine environment.

1) **Prevent irreversible harm.** Despite incomplete information, there is persuasive evidence that certain human activities produce irreversible effects on the marine environment. Therefore, we must take a cautious approach and minimize all further harm until we can better understand the vulnerability of these resources. Examples include the protection of remaining nearshore habitat, the protection of runs of British Columbia coho salmon and the protection of several species of marine fish that are at critically low levels.

2) **Proceed with caution.** Gaps remain in our knowledge of processes such as the potential impact of pathogens on humans and marine biota and the importance of the sea-surface microlayer as a source of contamination to marine and intertidal biota. Other gaps surround new potential problems, such as the introduction of new chemicals, exotic species and other stressors in the marine environment. Still others come from our lack of understanding of cumulative impacts on the environment and resources from several types of assaults, such as physical alterations of habitats and chronic chemical contamination.

We cannot yet adequately judge the severity of these kinds of threats without further research. In the meantime, we must proceed very conservatively when allowing degradation or contamination of these resources, although more leeway might be allowed in cases where the environment would recover quickly from potential harm. Additional exploratory research and monitoring in these areas are essential.

3) **Take cost-effective action.** Some sources of contamination cause only minor harm to the environment and/or are beyond our capabilities to remedy. Significant expenditures of public funds are not justified in such situations. Examples of actions that are not justified include most measures for cleaning up large oil spills, which have tremendous costs for very little demonstrated benefit. They also include removal of nutrients and BOD from sewage effluent. In the latter case, the treatment required is very costly, and the contaminants do little harm to the environment of the shared waters except in local cases. (Some toxic contaminants may be associated with particles that generate BOD. However, it is better to reduce such toxic inputs sources than to try to reduce them indirectly by removing BOD.) We need not place great emphasis on monitoring and research in these areas nor commit significant resources to their management.

Special Transboundary Issues

The recommendations below reflect special attention given to issues that are particularly transboundary in nature—that is, issues that cannot be adequately managed by separate and uncoordinated actions on each side of the international boundary. Such issues fall into two categories.

1) Contaminants, exotic species or nonliving resources (such as fresh water) that are transported across the boundary.

2) Living resource populations whose migrations or critical habitat requirements straddle and do not recognize the boundary.

Recommendations

In both sections below, the most important recommendations are listed first. The panel feels there is no time to be lost in implementing the key recommendations of this report, and we challenge the provincial and state governments to act quickly. In general, we assign priorities to these recommendations based on reversibility of harm.

Prevent Estuarine Habitat Losses

The extent of natural nearshore habitats along all of the developed and many of the rural shorelines of the region has reached critically low levels, and no further losses can be sustained. Existing mitigation and restoration measures clearly are not adequate to replace these habitats. The beneficial use of the nearshore estuarine areas is an issue of intense public concern; the public must decide how much of this habitat it wants to preserve in order to maintain viable stocks of marine biota.

The panel recommends that a public process be undertaken in British Columbia and Washington at the community level to determine the extent of losses that are acceptable to society. To participate in this process, the public must be armed with the best scientific information available, presented in an accessible and understandable format.

As a guideline until such a process can be undertaken, the panel recommends that any further loss of nearshore estuarine habitat be prohibited in embayments that already have lost more than 30 percent of their historic habitat area. In the absence of scientific guidelines on possible threshold levels of habitat loss that cause biological harm, the 30 percent figure is chosen arbitrarily as a level of destruction at which losses may become significant. The panel further recommends that along shorelines that have not yet been as severely degraded, no net loss of nearshore estuarine habitat be permitted, and that monitored habitat enhancement and restoration be required to compensate for losses due to nearshore development, dredging and other anthropogenic activities. The panel urges that estuarine habitat be the subject of additional research and monitoring efforts. So little is known about these vital areas that wise conservation and management decisions currently are very difficult to make.

Establish Marine Protected Areas

In order to protect both habitat and resource populations, a portion of each major type of marine and nearshore habitat in the shared waters should be desig-

nated as marine protected areas and be set aside from most or all human activities. These protected areas will most effectively protect against further human encroachment, permit recovery of depleted fish stocks, and provide refuge areas for marine mammals and birds. Many fish stocks in particular have reached such a critical status in Puget Sound that limits on catches and seasons are inadequate for safeguarding the resource. Although most fish stocks (except rockfish and lingcod) remain much more abundant in British Columbia, they ultimately will face the same pressures and potentially the same fate unless strong preventive measures are implemented.

Whole embayments or stretches of coastline could be strictly set aside as marine protected areas, or mixed uses could be allowed for portions of an area. To protect lingcod habitat, for example, the seabed and deep waters might be declared off-limits to human activity, while recreational fishing might be allowed in the overlying water column.

Protect Marine Animals and Plants

The vast majority of fish, invertebrate, bird and mammal species in the shared waters are still found in abundant numbers. However, the population sizes of many stocks that are harvested for commercial or recreational purposes, as well as those whose habitats have been severely altered, are alarmingly low. Many of these species no longer can sustain the harvest levels that have been enjoyed by fishers and hunters in British Columbia and Washington. In particular, stocks of salmonids and marine fish species in Puget Sound; lingcod and rockfish in British Columbia; marbeled murrelet, common murre and tufted puffin populations in the Straits; harbor porpoises in Puget Sound; and Steller sea lions throughout the shared waters; are at risk. In addition, many species of intertidal invertebrates, seaweeds and fish that have not traditionally fallen under the purview of fisheries and wildlife agencies are being harvested in increasing numbers.

With growing awareness worldwide for the need to manage for sustainable fisheries, fisheries and wildlife agencies in British Columbia and Washington, aided by their federal counterparts, must move toward a regime of protecting the fisheries and wildlife resources rather than managing for optimal harvests.

The panel recommends that fisheries and wildlife agencies act to severely curtail the harvest of every species for which a significant decline in population has been noted. In addition, these agencies should adopt a precautionary approach toward managing those fish and wildlife species for which they have insufficient population information. Similarly, species harvested in non-traditional fisheries should be managed conservatively, with a goal of maintaining optimum population levels.

Prevent Large Fresh Water Diversions

The major river diversion projects that have been undertaken in the region have had immense and far-reaching impacts on the marine environment and living resources of the region. The damming of the Columbia River is implicated in major declines of salmon runs in Washington and is suspected of having altered the coastal oceanography and ecology (Ebbesmeyer and Tangborn, 1992). Examples of the negative impacts of fresh water diversion from further afield (e.g., San Francisco Bay) are even more dramatic.

The panel recommends that no further large fresh water diversion projects be permitted until the potential impacts on estuarine circulation, nearshore and subtidal habitats, and marine plant and animal populations are more fully understood. We doubt that major river diversions ever can be made without significant adverse estuarine effects.

Minimize Introduction of Exotic Species

The shared waters are beginning to suffer serious impacts from the intentional and accidental introduction of exotic species. Furthermore, warnings from other regions, such as San Francisco Bay and the Black Sea, clearly do not bode well for the survival of many native species. The panel urges that serious efforts be made to prevent the introduction of exotic species into the shared and adjacent waters. Introductions can be prevented by the establishment and enforcement of strict ballast-water regulations in British Columbia and Washington; through hatchery and aquaculture enhancement activities that will foster flexible harvest regulations and allow native marine plants and animals to outcompete their introduced competitors; and by an aggressive public education program to reduce the intentional and inadvertent importation of exotics. In addition, the panel urges the governments of British Columbia and Washington to consider the code of practice developed by the ICES working group to reduce the risks of adverse effects arising from introductions and transfers of marine species (Wallentinus, 1994).

Control Toxic Wastes

There is evidence that toxic chemicals discharged into the marine environment accumulate in many types of marine organisms, where some may cause harm in certain organisms. In order to avoid deleterious effects to marine plants and animals, and to ensure that the supply of seafood from the shared waters is safe for human consumption, it is important that the concentrations of toxic chemicals in marine organisms not reach harmful levels. The risk to marine life from small accumulations

of toxic chemicals cannot justify the prohibitive cost of eliminating all toxic discharges into the marine environment. However, we believe that an acceptable level of contamination (one that protects marine life and human health) can be reached by careful controls on toxic sources.

Point sources of toxic chemcials are being brought under control in both Washington and British Columbia. Nonpoint sources, including storm water discharges, continue to contribute significantly to contaminated "hotspots" in urban and industrial areas. Agricultural chemicals including fertilizer and pesticides contribute toxic chemicals from farming activities, from home gardening and from golf course maintenance. Combustion products from motor vehicles reach marine water through runoff and via atmospheric deposition. Small amounts of radioactivity may be contributed to the marine environment from radioactive storage facilities or active discharges.

The panel recommends that efforts to bring all point sources of toxic chemicals under control continue while additional emphasis be placed on controlling nonpoint sources of pollution, especially surface water runoff from urban and industrial areas. Effective research and monitoring are needed to obtain quantitative estimates of toxic chemical loading to the shared waters. Optimum control measures cannot be put in place without these estimates.

Prevent Large Oil Spills

It has been clearly demonstrated that our ability to remedy the impacts of both large oil spills and chronic petroleum inputs to the shared waters is poor. It is also clear that society will continue to consume petroleum products at a high rate. The focus in protecting the marine environment from oil therefore must be on conservation and spill prevention.

The environmental harm caused by a large oil spill in the shared waters could be great in the short term, although most components of the ecosystem would be expected to recover in the long term. Nevertheless, the prospect of long-term recovery does not negate the imperative to take simple and cost-effective measures that could prevent unnecessary biological and economic impacts. The panel urges an accelerated implementation schedule for recommendations from the British Columbia/States Task Force on Oil Spill Prevention, focusing on those measures that have been proved most cost effective.

Recommendations for More Effective Environmental Management

Strategic Planning

The overlapping nature of the marine resources of British Columbia and Washington and the profusion of government entities with responsibility for aspects of marine environmental protection in the region point toward the need for joint strategic planning for the region's resources. The panel recommends that this planning involve agencies and institutions on both sides of the border, with clear guidelines as to which entities have the responsibility and authority to speak for the provincial, state, federal and regional/local governments. This planning process should encompass all aspects of the marine environment, the surrounding watersheds and any other anthropogenic activities that have an impact on the aquatic resources (i.e., land use, transportation, air emissions, etc.). While creating no new bureaucracies, the joint strategic planning effort must report equally to both the provincial and state governments.

Comprehensive Program Review of the Shared Waters

Despite a large financial investment, many years of effort, numerous regulations, and the attention of natural resource managers and fisheries biologists, we have failed to protect and conserve stocks of salmon and other anadromous and marine fish in the shared waters. Runs of wild salmon in Washington coastal and inshore waters are sufficiently threatened that, in most areas, all commercial and recreational fishing has been restricted for 1994.

Our failure to protect these stocks may be the result of gaps in scientific knowledge that prevent fisheries managers from adequately predicting and averting adverse impacts. Alternately, this failure may be the result of the fragmented authority and overlapping responsibility of federal, state/provincial and regional agencies for marine resource protection. Government agencies on both sides of the border are constrained by legislative mandates and compartmentalized jurisdictions, as outlined by federal (and to some extent, state and provincial) laws.

Environmental protection programs that look at water quality, waste discharges, fish and wildlife habitat, and seafood safety have a history of similar puzzling failures and inconsistencies. The evidence gathered by the panel clearly points to the need for a systematic examination of the programs and policies that govern our handling of the marine environment and its resources.

The dynamic nature of the natural world ensures that the implementation of

most natural resource policies is experimental. We must be prepared to learn from our successes and failures in a rational and systematic fashion, allowing for revisions and updates to policies as the state of our scientific understanding changes.

The panel recommends that the Environmental Cooperation Council contract with an independent body to audit the goals and accomplishments of, and resource allocations to, programs and management activities that influence the shared waters and resources. This body would look at both the amount of resources devoted to these programs and the ways in which the resources have been expended. Through this audit, we can gain an understanding of which environmental policies and programs are effective and which should be changed. This body would conduct an audit and report to the legislative bodies and the people of the British Columbia and Washington state on a periodic basis.

The panel acknowledges that there may be several viable models for choosing the body (to be called the Reviewers) to carry out the environmental audit. The Reviewers must have the necessary scientific and management expertise and conduct an open, public process, independent of the agencies or institutions whose actions it is examining . They must be free of political control or influence, and cannot be in a position to benefit from the outcome of the program review. The Reviewers must be willing to proceed carefully and to learn from the overlapping intricacies and complexities of environmental management, science and policy. Models upon which the Reviewers might be based include the U.S. National Academy of Science, Canada's Office of the Auditor General; or the U.S. General Accounting Office.

Monitoring and Research Framework

To support strategic planning, there is a need for a binational coordinated monitoring and research effort for the transboundary waters, sediment and biota. Monitoring programs, if carefully designed, can answer research questions. In many instances, monitoring programs are the only way to obtain long-term data sets to answer ecological questions.

The panel recommends that this effort focus on habitat preservation and waste disposal, as well as on the assessment and conservation of joint stocks of fish, invertebrates, birds and marine mammals. Strong emphasis must be placed both on collection and on timely interpretation and release of data. The goals of the monitoring, and the most economical ways of meeting these aims, should be clearly defined. Protocols for consistent and reliable sample collection and analysis of marine water, sediment and biota, including taxonomic identification of biota by non-experts, should be developed and uniformly used on both sides of the border. The protocols should be

performance-based and accessible to a variety of agency, university and private laboratories. The panel further recommends that the data collected by monitoring and research programs become the major factor in determining environmental management policies. In order to maintain the quality, applicability and credibility of these programs, an external, independent peer review of all monitoring programs must be scheduled every five years. Monitoring data collected by dischargers should be held to the same stringent standards as other monitoring programs and should be encouraged to add to the overall databases and information for the shared waters.

Increased Communication

There is a clear need to manage and preserve the habitat and resources remaining in the region effectively and efficiently, using the limited resources available in British Columbia and Washington. To achieve this goal, it is imperative that there be strong collaboration between and among U.S. and Canadian scientists and managers, and vigilance by an informed public.

The panel recommends that the collaboration between British Columbia and Washington scientists and managers take the form of joint planning, monitoring activities and research studies, and the development of compatible environmental regulations on both sides of the border. The governments of British Columbia and Washington, working with their respective federal governments and the universities, must establish an atmosphere that encourages and rewards collaboration between their scientists and managers. Furthermore, the British Columbia and Washington governments must supply or seek funding to carry out joint studies and programs and must create opportunities for joint conferences, workshops and public forums.

The panel further recognizes the importance of providing accurate, accessible and effective information to the public concerning the state of the marine resources and our level of scientific understanding of the shared waters. The public must further be invited to become equal partners with government and industry in determining the fate of those resources and be armed with factual information with which to make these crucial decisions. The panel recommends vigorous education programs be supported in British Columbia and Washington, both in the schools (formal education) and through non-profit and governmental groups (informal education).

Freedom of Scientific Discussion

Proper interpretation of scientific information, be it derived from monitoring, experimentation or modelling, requires open (i.e., public) discourse in the scientific community. This discourse is particularly important, perhaps critically so, in the

multidisciplinary field of environmental management. The panel is disturbed to see that, where the subject of inquiry may be controversial, open dissemination of hypotheses, data and ideas sometimes is not encouraged among researchers in government institutions. Rather, a "designated spokesperson" is frequently assigned the task of meting out information.

This situation is anathema to scientific progress because it misleads the community at large. The public needs to see that scientists often disagree, that uncertainty is almost always present, and indeed, that science is not perfect. Citizens cannot develop such a perspective when interpretation and data are "managed" by senior officials rather than by the scientists who collect the information, weigh it, assess its imperfections and draw conclusions. Silencing scientific researchers only exacerbates the erosion of trust in government that is being witnessed on a broad scale in North America. Hence, the panel recommends that the British Columbia and Washington governments adopt a spirit of openness within government departments that are conducting environmental research, and that the province and state encourage scientists to discuss their findings with their colleagues on both sides of the border.

Appendix A

Contributors to the Symposium on the BC/WA Marine Environment held in Vancouver, B.C., January 13 & 14, 1994

Bourne, N.F. and K.K. Chew, The Present and Future for Molluscan Shellfish Resources in the Strait of Georgia-Puget Sound-Juan de Fuca Strait Areas.

Brinkhurst, R.O., Casillas, E. and J.Q. Word, Marine Benthos of British Columbia/Washington State Boundary Waters.

Calambodikis, J. and R.W. Baird, Status of Marine Mammals in the Strait of Georgia, Puget Sound and Juan de Fuca Strait, and Potential Human Impacts.

Harrison, P.J., D.L. Mackas, B.W. Frost, R.W. Macdonald and E.A. Crecelius, 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.

Johnson, L.L., M.S. Myers, D. Goyette and R.F. Addison, Toxic Chemicals and Fish Health in Puget Sound and the Strait of Georgia.

Kalman, D.A., G. Patrick, S. Peck and M. Samadpour, Marine Pollution and Human Health: Current Status and Future Prospects.

Levings, C.D. and R.M. Thom, Habitat Changes in Georgia Basin: Implications for Resource Management and Restoration.

Macdonald, R.W. and E.A. Crecelius, Marine Sediments in the Strait of Georgia, Juan de Fuca Strait and Puget Sound: What Can They Tell Us About Contamination?

Mahaffy, M.S., D.R. Nysewander, K. Vermeer, T.R. Wahl, and P.E. Whitehead, Status, Trends and Potential Threats Related to Birds in the Strait of Georgia, Puget Sound and Juan de Fuca Strait.

Schmitt, C., J. Schweigert and T.P. Quinn, Anthropogenic Influences on Fish Populations of the Georgia Basin: I. Salmonids. II. Marine Fishes.

Taylor, F.J.R. and R.A. Horner, Red Tides and Other Problems With Harmful Algal Blooms in Pacific Northwest Coastal Waters.

Thomson, R.E., Physical Oceanography of the Strait of Georgia-Puget Sound-Juan de Fuca Strait System.

West, P., T.M. Fyles, B. King and D.C. Peeler, The Effects of Human Activity on the Marine Environment of the Georgia Basin: Present Waste Loadings and Future Trends.

Appendix B

Contributors of Written and/or Oral Briefs
oral briefings held in Vancouver, Seattle and Victoria, January and February 1994

Atkins, Rowland J., Hay and Company Consultants, Inc., Vancouver, B.C. Contaminant Transport Mechanisms: A Process Review.

Broten, Delores, Reach for Unbleached!, Cortez Island, B.C.

Burrows, Mae, T. Buck Suzuki Foundation, Vancouver, B.C.

Cokelet, Edward D., National Oceanic and Atmospheric Administration, Pacific Marine Environmental Laboratories, Seattle, WA. Puget Sound Effluent Concentrations Due to Vancouver, Victoria and Seattle Sewage Discharges.

Dzinbal, Kenneth A., Washington State Department of Ecology, Ambient Monitoring Section, Olympia, WA. General Observations and Summary of Ambient Water Column and Sediment Data Collected by the Washington Department of Ecology.

Ellis, Derek, Biology Department, University of Victoria, Victoria, B.C. Brief on Tributyltin and Dump Sites.

Friesen, Michele, T. Buck Suzuki Foundation, Vancouver, B.C.

Hannah, Linda, State of the Environment Reporting, Province of British Columbia, B.C. State of the Environment Reporting for a Marine System.

Heidorn, Keith, Skies Above Foundation, Saanichton, B.C.

Hodgins, D.O., Seaconsult Marine Research Ltd., Vancouver, B.C. Integrated Modelling and Remote Sensing Systems for Environmental Management: Status and Future Trends.

Levy, D., Hatfield Consultants, Vancouver, B.C. Proposal to Review Technical Information Pertaining to Fisheries and Water Quality in the Puget Sound and Georgia Basin.

Malcolm, Don, Reach for Unbleached!, Cortez Island, B.C.

Marliave, Jeffrey B., Vancouver Aquarium, Vancouver, B.C. Larval Drift Dispersal and Recruitment: Transboundary Implications.

McBride, Laurie, Save Georgia Strait Alliance, Gabriola Island, B.C.

Mearns, Alan, National Oceanic and Atmospheric Administration, HAZMAT, Seattle, WA. Background on the NRC 1993 report on Managing Wastewater in Coastal Urban Areas, and Resource and Pollutant Trends in Puget Sound.

Neel, Jon, Washington Department of Ecology, Olympia, WA and Jean Cameron, Oregon Department of Environmental Quality, Portland, OR. Briefing on Activities of States/BC Oil Spill Task Force.

Paisley, Richard Kyle, University of British Columbia, Vancouver and Elin Kelsey, Vancouver Aquarium, Vancouver, B.C. Marine Protected Areas, Environmental Partnerships and the Utilization of Scientific Information in Environmental Decision Making—the Whytecliffe Project.

Rash, Jeffrey A., Marine Animal Resource Center, Seattle, WA. Brief on Marine Mammals.

Reimer, K.J., Environmental Sciences Group, Marine Monitoring Advisory Group, Victoria, B.C. Scientific Consensus on the State of the Receiving Environment Around the Clover and Macaulay Point Sewage Outfalls: Knowledge and Concerns.

Spence, John A., SPARK Oceans Committee, B.C. Brief on the Requirement for Sustainable Management and Use of the Marine Environment.

Stronach, James, Seaconsult Marine Research Ltd., Vancouver, B.C. Modern Oceanographic Tools for Monitoring and Research into Transborder Pollution Problems.

Thomson , R.B. and Wayne Belzer, Ecosystem Science Division, Environmental Science Branch, Environment Canada, Vancouver, B.C. Brief on the Atmospheric Pathway of Toxics to the Marine Environment.

Torrie, Bruce, Skies Above Foundation, Saanichton, B.C.

Warheit, Kenneth I., Washington Department of Wildlife, Habitat Management Division, Olympia, WA. Brief on Washington State Departments of Wildlife and Fisheries.

Williams, M.C., Capital Regional District, Victoria, B.C. Brief on the Capital Regional District.

Wolferstan, William H., BC Environment, Lands and Parks, Victoria, B.C. Marine Oil Spill Risk as a Factor in Potential Transboundary Pollution.

References

Alvarez, M.M. and D.V. Ellis. 1990. Widespread Neogastropod Imposex in the Northeast Pacific: Implications for TBT Contamination Surveys. *Mar. Poll. Bull.* 21(5):244-247.

Atwater, B.F. 1987. Evidence for Great Holocene Earthquakes along the Outer Coast of Washington State. *Science* 236: 942–944.

BC Ministry of Environment. 1993. State of the Environment Report for British Columbia. Ministry of Environment, Lands and Parks; Environment Canada. Ottawa. 127 pp.

Barnes, C.A., A.C. Duxbury, and B.A. Morse. 1972. Circulation and Selected Properties of the Columbia River Effluent at Sea. In: *The Columbia River Estuary and Adjacent Ocean Waters,* University of Washington Press, 868 pp.

Bisson, P.A., T.P. Quinn, G.H. Reeves, and S.V. Gregory. 1992. Best Management Practices, Cumulative Effects, and Long-Term Trends in Fish Abundance in Pacific Northwest River Systems. In: *Watershed Management: Balancing Sustainability and Environmental Change.* Ed. R.J. Naiman. Springer-Verlag, New York, NY. 542pp.

Bolton, M., W. Rapatz and S. Hugget. 1983. Current Atlas, Juan de Fuca Strait, Canadian Hydrographic Service, Institute of Ocean Sciences, 212 pp.

Bourne, N.F. and K.K. Chew. 1994. The Present and Future for Molluscan Shellfish Resources in the Strait of Georgia-Puget Sound-Juan de Fuca Strait Areas. Proceedings of the BC/WA Symposium on the Marine Environment, January 13 & 14, 1994.

Brinkhurst, R.O., E. Casillas and J.Q. Wood. 1994. Marine Benthos of British Columbia/ Washington State Boundary Waters. Proceedings of the BC/WA Symposium on the Marine Environment, January 13 & 14, 1994.

Bucknam, R.C., E. Hemphill-Haley, and E.B. Leopold. 1992. Abrupt Uplift within the Past 1700 Years at Southern Puget Sound, Washington. *Science* 258: 1611–1614.

Calambokidis J. and R.W. Baird. 1994. Status of Marine Mammals in the Strait of Georgia, Puget Sound and Juan de Fuca Strait, and Potential Human Impacts. Proceedings of the BC/ WA Symposium on the Marine Environment, January 13 & 14, 1994.

Cokelet, E.D. and R.J. Stewart. 1985. The Exchange of Water in Fjords: the Efflux/Reflux Theory of Advective Reaches Separated by Mixing Zones. *Journal of Geophysical Research,* 90, 7287-7306.

Cokelet, E.D., R.J. Stewart, and C.C. Ebbesmeyer. 1990. The Annual Mean Transport in Puget Sound. NOAA Tech. Memo. ERL PMEL-92, 59pp.

Cokelet, E.D., R.J. Stewart, and C.C. Ebbesmeyer. 1991. Concentrations and Ages of Conservative Pollutants in Puget Sound. Puget Sound Research '91 Proceedings, Vol. 1, 99-108, Puget Sound Water Quality Authority, Olympia, Washington.

Cokelet, E.D. 1994. Puget Sound Effluent Concentrations Due to Vancouver, Victoria and Seattle Sewage Discharges, a Brief Submitted to the BC/WA Symposium on the Marine Environment, 30 December 1994, 8 pp.

Crean, P.B., T.S. Murty and J.A. Stronach. 1988. Mathematical Modelling of Tides and Estuarine Circulation, the Coastal Seas of Southern British Columbia and Washington State. Lecture notes on Coastal and Estuarine Studies, Springer-Verlag, 471 pp.

Cummins, E.B., and M. Kyte. 1990. Management of Nongame Marine Invertebrates. pp. 48–55. In: J.W. Armstrong and A.E. Copping (Eds.), *Status and Management of Puget Sound's Biological Resources.* Proceedings of a Workshop, Seattle, WA, September 11–12, 1989. U.S. Environmental Protection Agency EPA 910/9–90–001, 190 pp.

Ebbesmeyer, C.C., J.M. Cox, J.M. Helseth, L.R. Hinchey, and D.W. Thompson. 1979. Dynamics of Port Angeles Harbor and Approaches, Washington, U.S. Environmental Protection Agency, Interagency Energy/Environment R&D Report no. EPA-600/7-79-252, 107 pp.

Ebbesmeyer, C.C., C.A. Coomes, G.A. Cannon, and D.E. Bretschneider. 1989. Linkage of ocean and fjord dynamics at decadal period. In: *Aspects of Climate Variability in the Pacific and Western Americas,* D.H. Peterson editor, American Geophysical Union, Geophysical Monograph 55, 399-417.

Ebbesmeyer, C.C., D.R. Cayon, D.R. McLain, F.H. Nichols, D.H. Peterson and K.T. Redmond. 1991. 1976 Step in the Pacific Climate: Forty Environmental Changes Between 1968-1975 and 1977-1984. pps. 115-126. In: J.L. Betancourt and V.L. Tharp (eds.) *Proceedings of the Seventh Annual Pacific Climate (AACUM) Workshop, April 1990.* California Department of Water Resources. Interagency Ecological Studies Program Technical Report 26.

Ebbesmeyer, C. and W. Tangborn. 1992. Linkage of Reservoir, Coast, and Strait Dynamics, 1936-1990: Columbia River Basin, Washington Coast, and Juan de Fuca Strait. pps 288-299. In: *Interdisciplinary Approaches in Hydrology and Hydrogeology.* Jone, M. and A. Laenan (eds.)

Ebbesmeyer, C.C. and C.A. Coomes. 1994. Historical Shoreline Recoveries of Drifting Objects: an Aid for Future Shoreline Utilization, Oceans '93 Proceedings, Vol. III. 159-164.

Garton, D.W. and W.R. Haag. 1992. Seasonal Reproductive Cycle and Settlement Patterns of *Dreissena polymorpha* in Western Lake Erie. Reprinted from *Zebra Mussels: Biology, Impacts and Control.* Ohio Sea Grant College Program, Ohio State University, Columbus, OH. 17 pp.

GESAMP (IMO/FAO/Unesco/WMO/IAEA/UNEP Joint Group of Experts on the Scientific Aspects of Marine Environmental Protection) Report of the Twenty-Third Session, London, 19-23 April, 1993. GESAMP Reports and Studies GESAMP No. 51. 41 pp.

Hardy, J.T., and C.E. Cowan. 1986. Model and Assessment of the Contribution of Dredged Material Disposal to Sea-Surface Contamination in Puget Sound. Prepared for the U.S. Army Corps of Engineers, Seattle District, by Pacific Northwest Laboratory, Richland, Washington. Published in Puget Sound Dredged Disposal Analysis PSDDA

Reports, by Washington State Department of Natural Resources, Washington State Department of Ecology, EPA Region 10.

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. Proceedings of the BC/WA Symposium on the Marine Environment, January 13 & 14, 1994, pp. 390.

Holtly, L.B. and J. C. Scrivener. 1989. Observed and Simulated Effects of Climatic Variability, Clear-Cut Logging and Fishing on the Numbers of Chum Salmon (Oncorhynchus keta) and Coho Salmon (O. kisutch) Returning to Carnation Creek, British Columbia. *Canadian Special Publications on Fishery and Aquatic Sciences,* 105:62-81.

Houghton, J.T., G.J. Jenkins, and J.J. Ephraums (Eds.). 1990. Climate Change: the Intergovernmental Panel on Climate Change Scientific Assessment. Cambridge & New York: Cambridge University Press.

International Atomic Energy Agency (IAEA). 1993. Risk Comparisons Relevant to Sea Disposal of Low Level Radioactive Waste. IAEA–Tecdoc–725. Vienna, Austria.

Johnson, L.L., M.S. Myers, D. Goyette and R.F. Addison. 1994. Toxic Chemicals and Fish Health in Puget Sound and the Strait of Georgia. Proceedings of the BC/WA Symposium on the Marine Environment, January 13 & 14, 1994.

Kaiser, G.W. 1993. Seabird Wreck in Boundary Bay. Unpublished manuscript, Canadian Wildlife Service. 5 pp.

Kalman, D.A., G. Patrick, S. Peck and M. Samadpour. 1994. Marine Pollution and Human Health: Current Status and Future Prospects. Proceedings of the BC/WA Symposium on the Marine Environment, January 13 & 14, 1994.

Kuris, A.M. and K.D. Lafferty. 1994. Green Crab Alert. In: *The Crab Newsletter.* 1(1):4-5.

Levings, Colin. 1994. Personal communication.

Levings, C.D. and R.M. Thom. 1994. Habitat Changes in Georgia Basin: Implications for Resource Management and Restoration. Proceedings of the BC/WA Symposium on the Marine Environment, January 13 & 14, 1994.

Macdonald, R.W. and E.A. Crecelius. 1994. Marine Sediments in the Strait of Georgia, Juan de Fuca Strait and Puget Sound: What Can They Tell Us About Contamination? Proceedings of the BC/WA Symposium on the Marine Environment, January 13 & 14, 1994.

Mahaffy, M.S., D.R. Nysewander, K. Vermeer, T.R. Wahl and P.E. Whitehead. 1994. Status, Trends and Potential Threats Related to Birds in the Strait of Georgia, Puget Sound and Juan de Fuca Strait. Proceedings of the BC/WA Symposium on the Marine Environment, January 13 & 14, 1994.

Mumford, T.F., Jr., P. Peyton, J.R. Sayce, and S. Harbell. 1991. Spartina Workshop Record. Proceedings of a Workshop, Seattle, WA, November 14–15, 1990. Washington Sea Grant, Seattle, WA. 73 pp.

Munkittrick, K.R., C.B. Portt, G.J. Van der Kraak, I.R. Smith, and D.A. Rokosh. 1991. Impact of Bleached Kraft Mill Effluent on Population Characteristics, Liver MFO Activity, and Serum Steroid Levels of a Lake Superior White Sucker (Catostomus commersoni) Population. *Can J. Fish Aquat. Sci.* 48:1371-1380.

National Research Council (NRC). 1985. Oil in the Sea—Inputs, Fates and Effects. National Academy Press, Washington, D.C.

National Research Council (NRC). 1993. Managing Wastewater in Coastal Urban Areas. National Academy of Science, Washington, D.C.

Nichols, F., J. Cloun, S. Luoma and D. Peterson. 1986. The Modification of an Estuary *Science* 231:567-573.

Nishitani, L., G. Erickson, and K.K. Chew. 1988. PSP Research: Implications for Puget Sound. pp. 392–399. In: *Proceedings First Annual Meeting on Puget Sound Research,* Seattle, WA, March 18–19, 1988. Puget Sound Water Quality Authority, Seattle, WA. 789 pp.

Paulson, A.J., E.D. Cokelet, R.A. Feely, R.J. Stewart, and H.J. Curl, Jr. 1993. Modeling the decrease in dissolved copper in Puget Sound during the early 1980s, *Environmental Science and Technology,* December, 1993, 2685-2691.

Pearcy, W.G. 1992. Ocean Ecology of North Pacific Salmonids. Washington Sea Grant, Seattle, WA. 179 pp.

Peltier, W.R., and A. M. Tushingham. 1989. Global Sea Level Rise and the Greenhouse Effect: Might They be Connected? *Science* 244: 806-810.

Puget Sound Water Quality Authority. 1990. Puget Sound Update: First Annual Report of the Puget Sound Ambient Monitoring Program. Puget Sound Water Quality Authority, Olympia, WA. 89 pp.

Puget Sound Water Quality Authority. 1991. Puget Sound Update: Second Annual Report of the Puget Sound Ambient Monitoring Program. Puget Sound Water Quality Authority, Olympia, WA. 99 pp.

Puget Sound Water Quality Authority. 1992. Puget Sound Update: Third Annual Report of the Puget Sound Ambient Monitoring Program. Puget Sound Water Quality Authority, Olympia, WA. 69 pp.

Puget Sound Water Quality Authority. 1993. Puget Sound Update: Fourth Annual Report of the Puget Sound Ambient Monitoring Program. Puget Sound Water Quality Authority, Olympia, WA. 89 pp.

Schmitt, C. 1990. Marine Fish Users and Managers: How Are We Doing? pp. 118-141. In: J.W. Armstrong and A.E. Copping (eds.), *Status and Management of Puget Sound's Marine Resources.* EPA 910/9-90-001, U.S. Environmental Protection Agency, Seattle, WA.

Schmitt, C., J. Schweigert and T.P. Quinn. 1994. Anthropogenic Influences on Fish Populations of the Georgia Basin: I. Salmonids. II. Marine Fishes. Proceedings of the BC/WA Symposium on the Marine Environment, January 13 & 14, 1994.

Schoener, A., and D.F. Tufts. 1987. Changes in Oyster Condition Index with El Niño–Southern Oscillation Events at 46°N in an Eastern Pacific Bay. *J. Geophys. Res.* 92: 14,429–14,435.

Stronach, J.A., J.O. Backhaus, and T.S. Murty. 1993a. An Update on the Numerical Simulation of Oceanographic Processes in the Waters between Vancouver Island and the Mainland: the GFS Model, Oceanogr. Mar. Biol. Annu. Rev., 1993, 31, 1-86.

Stronach, J.A., A.J. Webb, T.S. Murty, and W.J. Cretney. 1993b. A Three-Dimensional Numerical Model of Suspended Sediment Transport in Howe Sound, British Columbia, *Atmosphere-Ocean*, 1993, 31(1), 73-97.

Taylor, Laura. 1994. Personal communication.

Taylor, F.J.R. and R.A. Horner. 1994. Red Tides and Other Problems With Harmful Algal Blooms in Pacific Northwest Coastal Waters. Proceedings of the BC/WA Symposium on the Marine Environment, January 13 & 14, 1994.

Thomson, R.E. 1994. Physical Oceanography of the Strait of Georgia - Puget Sound - Juan de Fuca Strait System. Proceedings of the BC/WA Symposium on the Marine Environment, January 13 & 14, 1994.

Troutman, B.L., S.A. Jeffries, T.A. Young. 1991. Identification of Areas for Potentials Seabird Mortality in the Commercial Salmon Gill Net and Purse Seine Fisheries of the Strait of Juan de Fuca and Northern Puget Sound. Final Report to the U.S. Fish and Wildlife Service, Portland, OR. 26 pp.

Vagners, J. and P. Mar. 1972. Oil on Puget Sound, an Interdisciplinary Study in Systems Engineering, University of Washington Press, 629 pp.

Varanasi, U., E. Casillas, M.R. Arkoosh, T. Hom, D.A. Misitano, D.W. Brown, S.Chan, T. Collier, B.B. McCain, and J.E. Stein. 1993. Contaminant Exposure and Associated Biological Effects in Juvenile Chinook Salmon (*Oncorhynchus tshawytscha*) from Urban and Nonurban Estuaries of Puget Sound. U.S. Dept. of Commerce. NOAA Tech. Memo. NMFS-NWFSC-8. 112 pp.

Waldichuk, M. 1958. Drift Bottle Observations in the Strait of Georgia, Journal Fisheries Research Board of Canada, 1065-1102.

Wallentinus, I. 1994. Concerns and Activities of the ICES Working Group on Introductions and Transfers of Marine Organisms. In: *Introduced Species in European Coastal Waters.* Boudouresque, C.F., F. Briand and C. Nolan (eds.). Luxembourg.

Washington Department of Fisheries, Washington Department of Wildlife and Western Washington Treaty Indian Tribes, 1993. 1992 Washington State Salmon and Steelhead Stock Inventory. Olympia, WA. 211 pp.

West, P., T.M. Fyles, B. King and D.C. Peeler. 1994. The Effects of Human Activity on the Marine Environment of the Georgia Basin: Present Waste Loadings and Future Trends. Proceedings of the BC/WA Symposium on the Marine Environment, January 13 & 14, 1994.

Wilson, R.C.H., R.J. Beamish, F. Aitkins and J. Bell (eds.). 1994. Proceedings of the BC/WA Symposium on the Marine Environment, January 13 & 14, 1994, pp. 390.

Wilson, Uhlrich. 1994. Personal communication.

Wolverstan W. 1994. Marine Oil Spill Risk as a Factor in Potential Transboundary Pollution. Briefing to BC/WA Marine Science Panel, January 13 & 14, 1994. 74 pp.

Wooster, W.S., and D.L. Fluharty. (Eds.). 1985. El Niño North. Washington Sea Grant, Seattle, WA. 312 pp.

Word, J.Q., C.D. Boatman, C.C. Ebbesmeyer, R.E. Finger, S. Fischnaller, and Q.S. Stober. 1990. Vertical Transport of Effluent Material to the Surface of Marine Waters. In: Oceanic Processes

in Marine Pollution, Vol. 6, Physical and Chemical Processes: Transport and Transformation, ed. D.J. Baumgartner and I.W. Duedall. Krieger Publishing Co. pp. 133-149.