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REVIEW OF THE MARINE ENVIRONMENT AND BIOTA OF STRAIT OF GEORGIA, PUGET SOUND AND JUAN DE FUCA STRAIT

Proceedings of the BC/ Washington Symposium on the Marine Environment, January 13 & 14, 1994

Edited by
R.C.H. Wilson, R.J. Beamish, Fran Aitkens and J. Bell

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R.C.H. Wilson[1], R.J. Beamish[2], Fran Aitkens[3] and J. Bell[1]

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ABSTRACT

Wilson, R.C.H., R.J. Beamish, Fran Aitkens and J. Bell [eds.]. 1994. Review of the marine environment and biota of Strait of Georgia, Puget Sound and Juan de Fuca Strait: Proceedings of the BC/Washington Symposium on the Marine Environment, January 13 & 14, 1994. Can. Tech. Rep. Fish. Aquat. Sci. 1948: 398 p.

This report includes the text and discussion highlights of presentations at the British Columbia/Washington Symposium on the Marine Environment, held in Vancouver, BC on January 13 and 14, 1994. The symposium was organized by the BC/Washington Environmental Cooperation Council to help the BC/Washington Marine Science Panel prepare a report for the Council on marine environmental quality in the boundary region. The Panel's report to Council is published separately.

The symposium brought together key presentations on status, quality and trends in the physical and chemical environment and biota of the coastal marine ecosystem shared by Canada and the USA. Geographic areas included are Puget Sound, the Strait of Georgia, and Juan de Fuca Strait. Topics included in this report are: loading of pollutants from industrial, municipal and non-point sources; estuarine circulation, hydography, currents and ocean model results; contaminant concentrations in sediments, shellfish and fish; sublethal effects of contaminants on fish; potential human health implications of consuming contaminated fish from boundaiy areas; nutrients and eutrophication; algal toxins and the problems due to toxic algal blooms; the status of marine and intertidal benthos and the use of benthos to indicate ecosystem health; the influence of fisheries, changes in the physical environment, and pollution on abundance and disrribution of commercially harvested species of invertebrates, shellfish and fish; the status and ecology of seabird and marine mammal populations; and the loss of marsh and other types of shore-zone habitat. Also included is the text of a presentation by the BC Minister of Environment, Lands and Parks about priorities for government action, particularly on oil spills.

The symposium was focused around six questions related to the sustainability of development around the shared waters of the Georgia Depression, and the projected impact of population growth. Further information about the symposium is contained in the introduction of this report.

KEYWORDS:

algae, benthos, bird, bloom, British Columbia, contaminant, effect, fish, groundfish, habitat, herring, human health, Juan de Fuca Strait, marine, marine mammal, nutrient, oceanography, plankton, pollution, Puget Sound, salmon, seabird, sediment, shellfish, Strait of Georgia, sustainable development, toxic, Washington, wetland.

RÉSUMÉ

Wilson, R.C.H., R.J. Beamish, Fran Aitkens and J. Bell [eds.]. 1994. Review of the marine environment and biota of Strait of Georgia, Puget Sound and Juan de Fuca Strait: Proceedings of the BC/Washington Symposium on the Marine Environment, January 13 & 14, 1994. Can. Tech. Rep. Fish. Aquat. Sci. 1948: 398 p.

Ce rapport rend compte du symposium sur le milieu marin que l'État de Washington et la province de la Colombie-Britannique ont donné à Vancouver (C.-B.) les 13 et 14 janvier 1994; on y présente le texte des exposés et un résumé des débats qui ont suivi. Le symposium fut organisé par le Conseil de coopération environnementale BC/Washington afin d'aider le Comité de science marine BC/Washington à préparer un rapport pour le Conseil sur la qualité environnementale marine dans la région frontière. Le rapport du Comité est publié à part.

Le symposium a permis d'entendre des exposés de grand intérêt sur l'état, la qualité et l'évolution probable des facteurs physiques et chimiques et du biote de l'écosystème côtier que se partagent le Canada et les États-Unis. Entre autres régions, on a considéré le détroit de Puget, le détroit de Géorgie et le détroit Juan de Fuca. Au nombre des questions traitées dans le rapport, signalons la pollution d'origine industrielle et urbaine et la pollution diffuse; la modélisation de la circulation estuarienne, de l'hydrographie, des courants et de l'océan; les concentrations de contaminants dans les sédiments et dans les tissus des coquillages, des crustacés et des poissons; les effets sublétaux des contaminants chez les poissons; les conséquences possibles que peut avoir chez l'humain la consommation de poissons contaminés provenant des zones limitrophes; les nutriments et l'eutrophisation; les phycotoxines et les problèmes dus aux efflorescences toxiques, l'état du benthos marin et intertidal et l'intérêt du benthos comme indicateur de l'état de l'écosystème; l'influence des pêches, des changements des caractères physiques du milieu et de la pollution sur l'abondance sur la distribution des espèces d'invertébrés, de coquillages et de poissons d'intérêt commercial; l'état et l'écologie des populations d'oiseaux et de mammifères marins; la disparition des marais et d'autres types d'habitats littoraux. On donne également le texte de l'exposé du ministre de l'Environnement, des Terres et des Parcs de la Colombie-Britannique expliquant l'ordre de priorité des interventions gouvernementales, plus particulièrement en ce qui touche les déversements de pétrole.

Le symposium portait sur six thèmes liés à la durabilité du développement à proximité des eaux de la dépression de Géorgie, que se partagent les deux pays, et ayant trait aux incidences probables de la croissance démographique. L'introduction du rapport contient d'autres détails sur le symposium.

Mots-Clés:

algues, benthos, coquillages, Colombie-Britannique, contaminant, crustacés, détroit de Géorgie, détroit de Puget, détroit Juan de Fuca, développement durable, effet, efflorescence, habitat, hareng, mammifère marin, marais, marin, nutriment, océanographie, oiseau, oiseau marin, plancton, poisson, poisson de fond, pollution, santé publique, saumon, sédiments, toxique, Washington.

FOREWORD

Overview of the Symposium

In May 1992, the Premier of British Columbia and the Governor of Washington State signed an Environmental Cooperation Agreement. A joint **British Columbia/Washington Environmental Cooperation Council** was established to ensure coordinated action and information sharing on environmental issues of mutual concern. The Council is composed of the B.C. Deputy Minister of Environment, Lands and Parks, and the Director of Washington's Department of Ecology. Regional Directors of the two federal environmental agencies, the U.S. Environmental Protection Agency and Environment Canada, are formal observers.

Marine water quality in the Strait of Georgia, Puget Sound and Juan de Fuca Strait is one of the priority issues addressed by the Council. In July 1993, the **Marine Science Panel**, a panel of Canadian and American scientists, was established to provide an independent scientific assessment of current conditions and trends in the shared waters, and to report the results to the Council.

To assist the Panel, the Council organized a **Symposium on the Marine Environment**, held at Robson Square Conference Centre, Vancouver, on January 13 and 14, 1994, and attended by approximately 200 people. These proceedings are a record of the presentations and subsequent discussions that took place at the symposium.

Acknowledgments

The symposium and this publication would not have been possible without the effort and help of a great many organizations and individuals. While the contribution of most is reflected only in the experience of the symposium and the quality of these proceedings, the editors wish to acknowledge by name the following for their role:

Financial Contributors

- B.C. Ministry of Environment Lands and Parks
- Environment Canada
- Fisheries and Oceans Canada
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- United States Environmental Protection Agency
- Washington State Department of Ecology

Symposium Organizers:

- John Azar, B.C. Ministry of Environment, Lands and Parks
- Lynn Bailey, B.C. Ministry of Environment, Lands and Parks
- John Dohrmann, Puget Sound Water Quality Authority
- Wendelin Fraser, Simon Fraser University
- Brendan Holden, B.C. Ministry of Environment, Lands and Parks
- Carol Jolly, Washington State Department of Ecology
- Ben Kangasniemi, B.C. Ministry of Environment, Lands and Parks

The papers presented at the symposium were submitted in written form for the proceedings, and have been edited only for consistency and clarity. Standard spelling lies somewhere between Canadian and American usage. The discussions following each paper are based on taped transcripts. The most relevant topics were extracted and edited for interest and brevity while still maintaining the 'voice' of the speaker.

Bob Wilson
Dick Beamish
Fran Aitkens
Jill Bell

April 1994

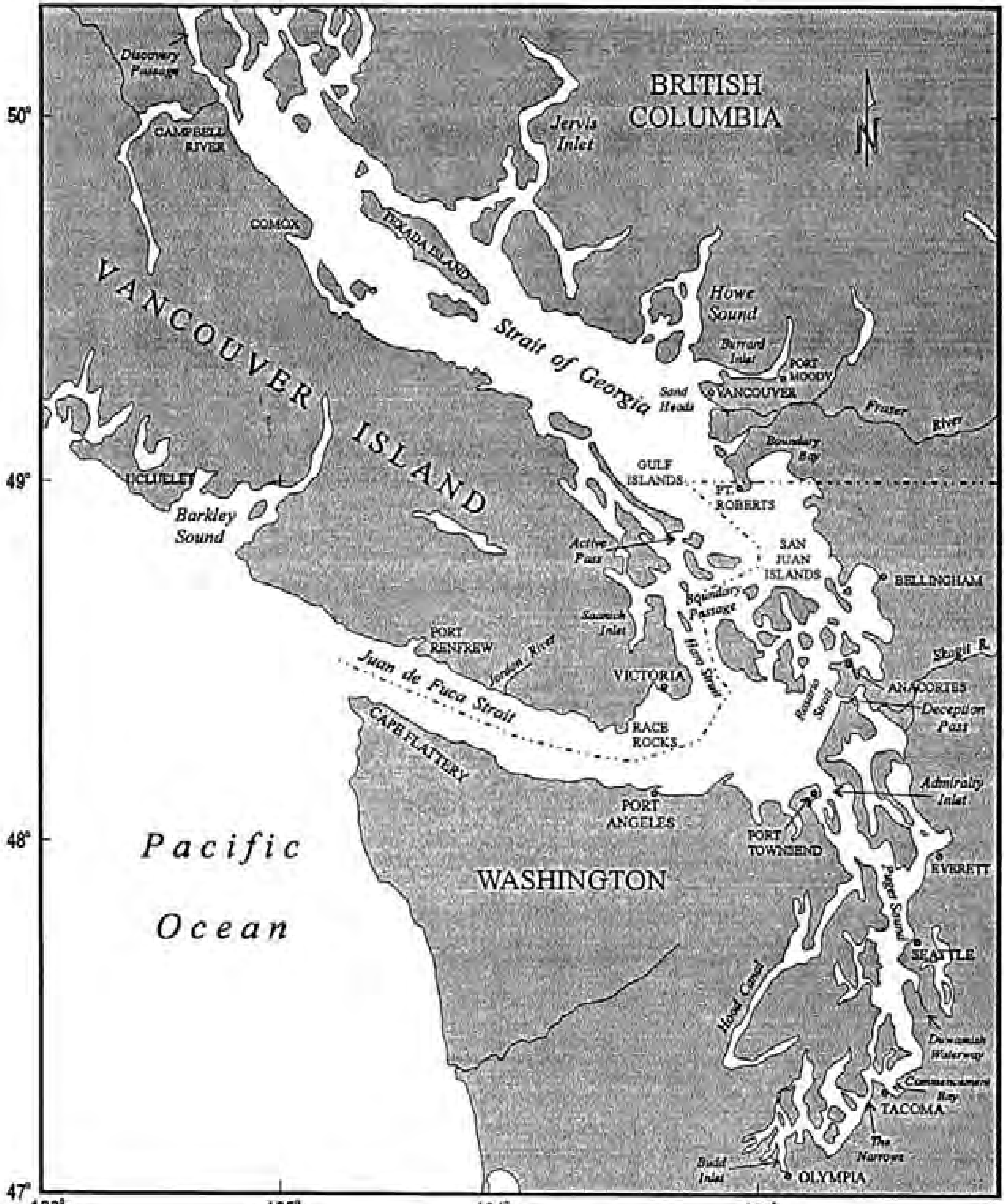

Figure 1. The Strait of Georgia-Puget Sound-Juan de Fuca Strait system

The six 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?

2.
   - 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.)

3.
   - What do we know about the status of transboundary populations of invertebrates, finfish, birds, and marine mammals of the Strait of Georgia, Puget Sound and Juan de Fuca Strait?
   - Are there long-term trends in the populations, and if so, what are the likely causes?

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 Juan de Fuca Strait?
   - As compared to five or ten years ago, is the amount or severity of harm greater, less, or the same?

5.
   - Given forecasts of human population increases for the lands that drain to the Strait of Georgia, Puget Sound and Juan de Fuca Strait, 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 uses, or public health be greater, less, or the same in 20 years?
   - Are the transboundary populations of invertebrates, finfish, birds, and marine mammals associated with the Strait of Georgia, Puget Sound, and Juan de Fuca Strait anticipated to increase, decrease, or stay the same in 20 years?

6.
   - What components of the transboundary marine ecosystem appear to be most sensitive to harm from human activities?
   - What types of harm appear to be most serious and should be the focus of monitoring, research and management activities over the next ten years?
   - Which types of human activities (for example, discharges or spills of toxic compounds, nutrients, pathogens / pathogen indicators, physical land modification) need the most management attention?
   - What indicators are recommended for future state-of-the-environment reporting for the transboundary marine ecosystem?

Figure 2. Issues to be addressed by this symposium, and by the Marine Science Panel.

Planning for Sustainable Development

Mary Riveland

Director
Washington Department of Ecology

ESTABLISHMENT OF THE ENVIRONMENTAL COOPERATION COUNCIL

Good morning. I am delighted to welcome all of you here today to the opening of this two-day symposium on the marine environment. It is gratifying to see that the international border creates no barrier to this type of meeting, where American and Canadian scientists with expertise on numerous issues can exchange information, assess and debate new developments, and attempt to resolve unanswered questions. I want to take a few minutes to offer some background on the establishment of the BC/Washington Environmental Cooperation Council, the group that began the cross-border work that led to this event.

Many of you will recall just over five years ago when oil spilled from the barge *Nestucca* off our coast and polluted beaches in both Washington and Vancouver Island. That event led the state and province to establish a task force charged with investigating ways to prevent oil spills, developing improved response procedures and creating mechanisms for handling compensation claims. Following the *Exxon Valdez* disaster, the group expanded to include Alaska, Oregon and California. The success of that task force in developing joint recommendations, in formulating successful legislative proposals, and in preparing agency personnel in Washington and British Columbia to respond more effectively to spill situations, helped pave the way for further collaboration across the international border.

In May of 1992, then-governor Booth Gardner and Premier Mike Harcourt met and signed an environmental cooperation agreement. During their meeting, Premier Harcourt said, "We're not here to point fingers. Let's work together. We're part of a megalopolis between southwest British Columbia and northwest Washington. Let's roll up our sleeves and get on with this job as friends and neighbours."

The agreement they signed acknowledged that environmental impacts respect neither physical nor political boundaries and that inter-jurisdictional impacts require joint action. The agreement pledged the two governments to "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 agreement created an Environmental Cooperation Council. Tom Gunton — the Deputy Minister of Environment, Lands and Parks — and I serve on this council. And we have been gratified from the outset to have, as formal observers, the regional directors of the American and Canadian federal environmental agencies — The US Environmental Protection Agency and Environment Canada. The original agreement identified five issues as high priorities for action by the British Columbia and Washington governments. The first of these was Puget Sound/Georgia Basin water quality.

Those of you who are here from Washington are well aware of the level of effort our state has invested in protecting and managing Puget Sound. Since 1985, when the Puget Sound Water Quality Authority was established, we have spent millions of state, federal and local dollars on assessing problems, identifying solutions, and putting new approaches into place. We have created or expanded programs for shellfish protection, sediment management, monitoring and non-point source pollution control, to name just a few.

I know that the Canadian and British Columbia governments are strongly committed to protecting this shared waterbody. Under Canada's Green Plan, the Fraser Basin Management Program is bringing together all levels of government and diverse interest groups to tackle water quality, sediment and biological problems in the Fraser River.

Similarly, the intent behind the provincial government's Georgia Basin Initiative is to create a sustainable environment and economy in the region. Its focus is effective management of the region's growth, and its workplan is to consider such issues as urbanization, economic development and the quality of life.

Both the state and province see the value of close coordination and integration of these activities. Soon after the signing of the 1992 agreement, the Environmental Cooperation Council created a Puget Sound/ Georgia Basin Work Group to recommend and conduct joint efforts on information sharing, monitoring and research for transboundary waters. That group — which includes federal agencies from both nations and a representative of the Fraser Basin Initiative — has already begun exchanging detailed information on existing monitoring and research programs, with the goal of identifying gaps that need to be filled. The members have also begun organizing to gather comprehensive information on sources currently discharging wastes in the basin.

REAFFIRMING WASHINGTON'S COMMITMENT

We all know that changes in political leadership can bring changes in emphasis or focus. Since May of 1992, Washington has had a new governor, but given the significance of these cross-border environmental issues and the recognition that they are likely to continue to increase, within a few months of his inauguration, my new boss — Governor Mike Lowry — met with Premier Harcourt and reaffirmed Washington's commitment to the Environmental Cooperation Agreement. Last April the two leaders issued a joint statement in which they: "recognized the need to ensure that the side-effects of the region's success not be allowed to diminish its attractiveness as a destination for investment and as a place to live."

At that same meeting, the Governor and the Premier directed the Environmental Cooperation Council to establish a scientific panel to examine water quality issues in our shared marine waters. You'll be hearing more about the panel from Tom Gunton.

PLANNING FOR THE FUTURE

Those of us who live here know that we are fortunate to have such a high quality of life, such incredible environmental resources and beauty. But we also know how easily these conditions can change as we continue to grow. There are now just over five million people in the Georgia Basin — about three million in Washington and two million in southwest British Columbia. Under current estimates, in the next two decades that number could double to 10 million. The Department of Ecology and the Ministry of Environment, Lands and Parks realize that we must plan for the future we want. We can't do that planning without a firm understanding of where we are, a valid assessment of current conditions and trends. Those of us in the world of policy know that our decisions are more sound and more defensible when they are based on good science. We rely on information, guidance and recommendations from you and your peers in selecting the best course of action.

CONCLUSION

The papers presented during the next two days will cover a wealth of information on the health of our shared waters and the impacts of our actions on the animals and plants with which we share them. I'd like to extend my hope that they are productive sessions with active, enthusiastic exchanges and intense, constructive debates. That will allow the Environmental Cooperation Council to receive the best possible report on the waters we treasure and how they are faring, so that we can make the best decisions on how to protect them for generations to come.

Work of the Marine Science Panel

Thomas Gunton

Deputy Minister
B.C. Ministry of Environment, Lands and Parks

I am pleased to join Mary Riveland in welcoming you to this symposium. I encourage each of you to take this opportunity to participate in the important work of the British Columbia/Washington Marine Science Panel.

Mary Riveland has provided you with background information on the Environmental Cooperation Council. I will discuss the formation and purpose of the Marine Science Panel and tell how you can contribute to the success of this two-day event, and I will close by introducing you to the Panel members.

British Columbia and Washington State, in conjunction with their respective federal governments, share responsibility for maintaining high standards of marine water quality in the Georgia Basin and Puget Sound. When Premier Harcourt and Governor Lowry met in April 1993, they agreed to establish a joint panel of United States and Canadian scientists to examine this shared marine environment under the direction of the Environmental Cooperation Council.

The six-member Marine Science Panel was appointed in July 1993. The Environmental Cooperation Council asked the Panel to answer six questions relating to defining and assessing the transboundary marine environment (Figure 2).

The marine ecosystem of the Strait of Georgia, Puget Sound and Juan de Fuca Strait is so complex that it seems to defy broad scientific analysis. Nevertheless, public policy decisions with potential to affect this ecosystem are continually being made. The pressures of population and industrial growth predicted for this region will increase the magnitude of environmental stresses affecting it.

The resources available to government to study, monitor, prevent and remediate the impacts of human activities on the marine environment are limited and must compete with other societal demands. Therefore, available resources must be used efficiently. We must exercise caution in how the marine environment is used and we must focus our attention on the most significant problems.

One of the ways of improving our efficiency is to ensure that scientists and other stakeholders from both sides of the border have opportunities to share their knowledge. This symposium provides such an opportunity. It is one of the mechanisms being used by the Marine Science Panel to obtain information, together with briefings and the scientific literature.

Later this spring the Panel will submit a report to the Environmental Cooperation Council addressing the six questions. This report will assist the Council in setting priorities for future joint activities, such as information sharing, monitoring and research. It will also serve as a scientific foundation for the development of public policies aimed at ensuring that the health and integrity of this important, shared ecosystem are maintained.

The questions posed to the Panel are very general. However, providing answers to them requires thoughtful synthesis of what is known about the present state of the Strait of Georgia, Puget Sound and Juan de Fuca Strait marine ecosystem. Developing this synthesis of information on the status of our shared marine environment and expected trends is the challenge presented to the Marine Science Panel, and to you as symposium participants.

The symposium contributors have been asked to address six questions in their topic areas. After each presentation, 15 to 25 minutes have been set aside for all participants to question the authors and to contribute their thoughts and expertise on the topic. In addition, a 45-minute period has been set aside at the end of the two days for addressing the questions. This discussion will be moderated by the Marine Science Panel.

Your participation after each presentation and during the discussion period is vital. In addition to providing valuable information for the panel's deliberations, your input will become part of the symposium proceedings

published by the Canadian Department of Fisheries and Oceans.

It is now my pleasure to introduce you to the members of the British Columbia/Washington Marine Science Panel.

Dr. Richard Beamish is a senior scientist at the Department of Fisheries and Ocean's Pacific Biological Station in Nanaimo, British Columbia, where he was Director from 1980 to 1993. Among Dr. Beamish's research interests are factors affecting the carrying capacity of the Strait of Georgia for salmon and other commercially important species, and the association between long-term climate trends and long-term changes in fish abundance in the northern North Pacific Ocean.

Dr. Andrea Copping is Senior Marine Scientist for the Washington Sea Grant Program, and the Office of Marine Environmental and Resource Programs in Seattle. She facilitates and administers the research response to management needs and questions in the marine environment in Washington State, in the region, and nationally. Dr. Copping's research interests and activities focus largely on the ecological health of Puget Sound and Washington coastal waters.

Dr. Curtis Ebbesmeyer is Senior Physical Oceanographer and partner with the consulting firm of Evans-Hamilton Incorporated in Seattle. He specializes in the analysis of coastal, estuarine, climate and large-scale oceanographic phenomena, with particular emphasis on understanding movements of water in the Pacific Northwest, particularly Puget Sound and Juan de Fuca Strait.

Dr. Chris Garrett is Lansdowne Professor of Ocean Physics at the University of Victoria where he teaches courses in Ocean Physics and Physical Oceanography. Dr. Garrett's research is mainly concerned with theories of oceanic processes such as mixing and air-sea interaction that affect the role of the oceans in climate. He has also contributed to practical issues including tidal power, iceberg trajectory prediction and the oceanic disposal of radioactive waste.

Dr. Bruce McCain is a supervisory Fishery Biologist at the National Oceanic and Atmospheric Administration's Northwest Fisheries Science Center in Seattle. Dr. McCain manages a team of 15 scientists who conduct field and laboratory investigations on the effects of pollution on marine fish and shellfish. These include determining the severity and geographical distribution of pathological conditions in fish and shellfish, and evaluating the consequences of these effects on populations.

Dr. Tom Pederson is Associate Professor of Marine Geochemistry in the Department of Oceanography, University of British Columbia. Dr. Pederson is internationally known for his research on the chemical behaviour of mine wastes deposited on the sea floor, on natural chemical processes that influence the chemistry of marine and lacustrine sediments, and on the history of oceanic circulation and influences on the accumulation of sedimentary organic matter in the sea.

The Environmental Cooperation Council is gratified that these six experts have accepted the challenge of investigating this complex, shared marine ecosystem. The Panel is devoting a substantial amount of time and effort to finding and reviewing information, preparing for this symposium, reviewing and discussing briefs, and preparing its report. The Council very much appreciates the Panel members' generosity in carrying out this work in addition to their existing responsibilities. We look forward to receiving the Panel's findings and recommendations.

On behalf of Mary Riveland and myself, I wish the Marine Science Panel and the participants a stimulating and informative symposium.

Address by the Minister of Environment, Lands and Parks

The Honourable Moe Sihota

Good morning, and thank you for inviting me to share in your proceedings. On behalf of Premier Harcourt and the Government of British Columbia, I'd also like to extend a cordial welcome to all the participants from south of the border. This meeting is a crucial step in a cooperative process. It's vitally important to our government as well as our colleagues in Washington State. Sharing information and scientific data is the first step toward shared solutions. It was clearly identified as a top priority in the Environmental Cooperation Agreement signed in May 1992, and in the joint statement from Premier Harcourt and Governor Lowry following their meeting last April. The creation of the Marine Science Panel is a result of those initiatives. In turn, the proceedings of this Symposium are going to provide essential input to the Panel for its report later this spring.

I'm not going to talk in detail about the content of the work being carried out here; I am not a scientist. But I do want to emphasize how invaluable it will be to the efforts of both jurisdictions to protect the environmental quality of Georgia and Juan de Fuca straits and Puget Sound. In a more general way, the application of good scientific data is intrinsic to almost everything my ministry does. It's the foundation of our environmental policies and legislative program. It's the backbone of our enforcement and management activities in the field. Our awareness of environmental trends and impacts has grown phenomenally in the past quarter-century, and it's vital that governments act on that knowledge.

Our responsibility is two-fold: first, to support those branches of science involved in gathering and interpreting environmental data, and secondly, to make good use of the results. As the makeup of this meeting shows, this is an inclusive process. Government, academia, environmental groups and industry, both the consulting industry and the resource industries, are all involved. We have to cooperate fully in sharing and applying the results of research, monitoring and analysis. It's also abundantly clear that we can't afford to take chances in those cases where the scientific evidence may be incomplete or inconclusive.

We'll never have 100 percent certainty about the nature and extent of all the current and potential impacts of human activity on the environment. This has severely hampered consensus on some of the most serious issues in this region, in particular, discharges of chlorine from pulp mills and raw sewage from municipal sewers. On both of these issues, our policy is to take a precautionary approach. We've brought in the toughest pulp mill effluent regulation in North America, supported by the best scientific data available concerning known impacts and potential risks. Based on the same precautionary principle, we're committed to, at a minimum, secondary treatment of all sewage discharges, including discharges to the ocean.

We believe this is good science. It's also common sense. You don't wait till you smell smoke, you don't shout 'Fire!', and you don't start a stampede, you use the best information you have, determine what precautionary measures are needed, and plan accordingly.

I believe the process you are participating in complements this approach, by building a common understanding of the issues and better integration of existing knowledge. It will provide continuing direction and benchmarks for cooperative action, on both sides of the border.

Within British Columbia, in May of last year the provincial and federal governments jointly released our province's first-ever state of the environment report. It's given us an environmental base-line, a common understanding of what's really happening, of the progress we've made, and the challenges that confront us. We look forward to similar results from the activities of this Panel.

But I also want to emphasize that there are some areas where the hazard to the environment is all too clear — where we already know the options — and the potentially horrific results if we fail to take action. Right now, this region faces the threat of a catastrophic spill from oil tankers or barges plying our coastal waters. Everyone living on the west coast knows intuitively what the

exposure is, what damage can be done, and how vulnerable our fragile environment is to an oil spill. The potential damage to our beaches, wildlife, fish, seals, and other habitat is frightening. We have a responsibility to safeguard our shores from that risk. To minimize, if not eliminate the risk caused by the two tankers each day that travel down our coast. When the damage occurs, we wonder why more was not done to prevent such a catastrophe. We can't afford to wait for an incident. We must act now.

We have the basis upon which to act. Many studies have been completed — Brander-Smith's study, Anderson's study — which defined how the risk can be reduced from one incident every 20 years, to one incident every 50 years, and indeed as to how we can even eliminate the risk altogether. Yet the average person believes that these studies are on a shelf collecting dust. As a government, we are not prepared to stand by and allow these recommendations to be ignored.

The Citizens' Advisory Committee on Spill Prevention and Response in 1992 appropriately stated — and I quote:

> "If in the future an accident were to occur, particularly in the Strait of Georgia or Gulf Island area where tidal currents would severely hamper the work of recovery crews, the Committee has no doubt that the failure to fully examine existing risks and possible alternative delivery systems at this time would be bitterly regretted."

Rather, we as a government want to give the public every confidence that those recommendations are not forgotten, that they're being acted upon.

I want to pledge today to British Columbians that we will be pursuing solutions to reduce the risk and eliminate the sense of vulnerability. As I said, the British Columbia and Canadian governments have commissioned or undertaken several major reports and initiatives by Brander-Smith, David Anderson, the States/B.C. Oil Spill Task Force, and the B.C. Citizens' Advisory Committee. As a province, we've implemented many of the recommendations dealing with preparedness and response to an oil spill. In the event of an oil spill, we have developed a well-coordinated system for handling cleanup and other response activities. In the event of an oil spill, we have legislation to recover costs incurred by the government. In the event of an oil spill, we have produced an excellent computer-based system that has identified shoreline resources that are particularly sensitive to oil pollution, and we've taken a number of other initiatives for dealing more effectively with a spill when it occurs, such as training of volunteer groups.

No matter what we do to improve spill preparedness and response capabilities, no matter what we do to ensure appropriate equipment is on hand and volunteer training programs are in place, no matter how sophisticated our response capability, spill prevention provides the best environmental protection. And prevention is by and large a federal responsibility, particularly in Canada.

It seems to me that a number of preventative steps can be taken by government now. Let me outline what those steps are. Each of the reports I've mentioned gave top priority to the best single thing we can do to prevent oil spills — the implementation of double-hulling for all oil vessels entering Canadian waters as soon as possible. The previous federal government did not appear to take these recommendations too seriously. The schedule they set for the gradual phase-in of double-hulling won't see its full implementation until well into the next century.

Today I am calling on our new government in Ottawa to fast-track the schedule for double-hulling, to achieve full implementation by the year 1998 at the very latest. Back in 1989, the Anderson report recommended that a four-year phase-in begin immediately. The time to get it moving is long overdue. In other words, this should have been done. Had it been done, the risk would have been reduced by 1993. Today we are saying that we want those recommendations fulfilled.

Secondly: an oil spill doesn't recognize borders. Tanker traffic in Puget Sound and Juan de Fuca Strait is very heavy. Five per cent of that traffic is Canadian, 95 percent of the traffic is destined to the US. I know that Washington, Oregon and California have actively lobbied their federal government for stronger prevention measures. But today I want to make it clear that we will lend support to those governments in their initiatives, and we are requesting that the government of Canada lend its support by working with the United States to seek joint action on issues such as the faster phase-in of double hulls.

Thirdly: a number of other preventative initiatives have been recommended by David Anderson and others, and

we will be urging the federal government to follow these up, in addition to double-hulling. They include increased funding for the Coast Guard to inspect vessels and their systems, more enforcement activities — and, not least, better training programs for tanker and terminal personnel, all of which were recommended by Mr. Anderson. In particular, Ottawa should introduce the requirement that a prevention plan be filed by each tanker entering or leaving our waters. This requirement has been introduced on the US side by Washington State, but requires federal action on this side of the border.

Fourth: it's going to cost money to finance these preventative measures. As a start, I'll be reminding my federal colleagues of the $200 million that has been sitting for nearly 20 years in the federal Ship-Source Oil Pollution Fund — and doing practically nothing. This fund was initiated in 1973 to collect levies on every ton of oil shipped in or out of Canada, and discontinued in 1976. It was intended to cover costs of oil spill cleanup where the polluter could not, or would not pay. We now have a better understanding today of what it takes to protect the environment than we did in the 1970s. For example, the *Exxon Valdez* spill cost $2 billion to clean up, and only 10 percent of that oil was released. In the 1990s, it makes good sense to use this money, not just as a last-resort insurance fund for cleanups, but as a source of user-pay funding that covers prevention as well. Government budgets are tight. The risk of oil spill is created by the industry, and the industry has to bear the burden of the prevention cost.

I am therefore proposing that the federal government reinstate the levy. Imagine what funds would be available for prevention if the fund had not been discontinued in 1976. I am further proposing that the federal government broaden the fund's mandate to cover prevention and preparedness. Government should follow through on the Brander-Smith recommendation to make the levy of $2 per tonne on all oil and oil products coming into Canada a reality. This is not a unique request. California, Washington and Alaska have equivalent levies.

We would also like to see some of this fund transferred to the province to cover its involvement in these activities. At the present time, British Columbia assumes many risks and costs, and by using the fund we would ensure the costs are borne to a greater degree by those posing the risks. For example, the fund could assist in response research or cost recovery of natural resources damage in the event of a spill. This fund could also be used to support pooling of resources across the border to achieve maximum cost-effectiveness in shared risk zones such as the Strait of Georgia and Juan de Fuca Strait. This fund would also help expedite replacement of Canada's flag fleet with double-hulled vessels, as recommended by Mr. Anderson. Not only would this make our straits safer, it would provide much-needed jobs, preferably in local shipyards. I can tell you that I'm looking forward to an enlightened approach from the new federal government on this critical issue. In particular, David Anderson has long been a strong advocate of many of these initiatives. Now, as a member of the federal cabinet, he is in a good position to champion his own recommendations. As well, I'll be approaching federal Environment Minister, Sheila Copps, to discuss these concerns as soon as possible.

So far I have focused on initiatives involving the federal government. Now I want to turn to our relationship with our good friends in Washington State, Oregon and California. I want to pursue a very critical option at the provincial/state level that I would like to take up with Washington State officials. We need a comprehensive, multi-agency analysis of the risks to our shared waters. Most of the studies up to this point have respected the border, and I believe the process you're participating in today under the auspices of the Marine Science Panel could serve as a model for the kind of cooperative effort that's needed. For truly effective risk analysis — analysis that points to prevention — we must dissolve the boundary. The fact is that even if the spill is in the United States, due to tidal and current factors, the spill would drift into British Columbia. British Columbia is the most vulnerable of all the jurisdictions on the west coast. The location of the terminal at Cherry Point, deep within Puget Sound, is one of the undeniable risks that needs to be given much closer examination, together with alternative options such as the removal of the terminal to Low Point, much closer to open water. On this side of the border, we should also examine the feasibility of phasing-out traffic in Burrard Inlet. I understand that there are environmental and other concerns with regard to the recommendation of Low Point, and at this point all I am suggesting is that we must engage in the multi-agency analysis of risk to ensure

that we arrive at a solution acceptable to all of us. In July 1992, British Columbia, Washington, California, Oregon and Alaska signed a memorandum of cooperation dealing with oil spills. I want to announce today that, as a government, we want to accelerate work under that agreement.

It is my intention to travel to Washington State to meet with officials and to ensure that work is expedited in four areas, namely:

1. A mutual aid plan — improved government-to-government communications and notification in the event of a spill;
2. Oil spill reporting systems — that is, public-to-government communications in the event of a spill;
3. Incident command system — to respond to spills;
4. Oil spill response system — a consistent approach to spill preparation, volunteer training, sharing of equipment, a uniform approach to spill response.

In summary, I'm proposing four key initiatives to achieve a major shift in emphasis from reaction to prevention:

1. Fast-track the phase-in of double-hulling for Canadian tanker traffic.
2. Work with the United States to accelerate this vital measure on both sides of the border.
3. Reinstate the federal levy and use the funds for improved prevention and preparedness programs at both the federal and provincial levels.
4. Review the risks, without reference to the international boundary.

This issue is not only one of the most urgent we face on both sides of the border, it's also central to the cooperative process in which you're taking part today. The bottom line is that a sustainable marine environment is vital to the ecological health of British Columbia and the Pacific Northwest, as well as our economic and social well-being. We're experiencing some of the most rapid growth of any region in North America. We can't just respond passively to the challenges that will inevitably result. Over the next few years, the conditions of our coastal waters — along with forests and air quality — will be the main measure of our ability to handle the pressures of urbanization and economic development, transportation issues, and the simple reality that we're going to have a lot more people in this region.

The policy of using the ocean to dilute our wastes; the persistence of 1950s technology for handling industrial toxics; the acceptance of spills as routine events — these represent the old way of doing things. They're simply not an option anymore. We have the opportunity to set a North American and World standard for sustainability in this region. For government, that means working and planning more cooperatively, making the best possible use of the resources available to us, and setting rules and standards we can enforce with confidence, supported by the most authoritative information available. This symposium, and the activities of the Marine Science Panel it supports, are fundamental to that process. I'd like to thank all of you again for contributing to its success.

The Effects of Human Activity on the Marine Environment of the Georgia Basin: Present Waste Loadings and Future Trends

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ABSTRACT

The Georgia Basin region, stretching from the northern end of the Strait of Georgia to the southern end of Puget Sound, is one of the most rapidly developing population centres in North America. Rapid urban development with accompanying industrial activity is occurring, not only in the major cities of Greater Vancouver and Seattle, but also on the east coast of Vancouver Island and in areas of Washington State adjacent to this coastal sea. Planning for the future of the region increasingly emphasizes the need to consider overall sustainability or sustainable development. Initiatives of the British Columbia Round Table and the work of the Sustainable Seattle Project are examples of addressing quality of life today while maintaining environmental integrity for future generations. The marine environment is a vital component of the larger ecosystem, and it is appropriate to consider the outcomes of this symposium in the context of regional sustainability.

Given current population and projected growth, the quantity and composition of waste loadings into Puget Sound, the Strait of Georgia and Juan de Fuca Strait will increasingly affect not only water quality, but also the status of the marine ecosystem. Two considerations will be of paramount importance in developing a strategy for monitoring and reducing loadings.

First, there is a need for a comprehensive international program to establish current (base) levels of loadings to the marine environment from domestic and industrial point and non-point sources. Such a program anticipates enhanced transboundary collaboration of agencies and municipal authorities in liquid waste management, and the development of standard protocols for estimating loadings. Data management using a 'meta-data' (data-about-data) approach will be essential. Such approaches emphasize methodology, data quality, and the spatial and temporal distribution of the collection of data. The program would parallel further development of information exchange on receiving environment measurements.

Second, there is a need to adopt common models and algorithms for estimating inputs from a range of non-point sources including urban population centres, agricultural activity and the forest industry. Specifically, models for loadings delivered to estuaries from watersheds are important in the Georgia Basin, particularly for the Fraser River which drains nearly 25% of British Columbia.

While effective monitoring and modeling of inputs will improve 'State of the Environment' reporting on loadings, achieving environmentally sound waste reduction involves additional considerations. Research is needed to fully estimate the environmental impact of reducing

loadings from industrial discharges through waste treatment and process changes (e.g. pulp and paper). Given the complexity of (synthetic) organic contaminants, changes in the detailed composition of the effluent may be more critical than the BOD (biochemical oxygen demand), COD (chemical oxygen demand) or TSS (total suspended sediment) values. Mixed industrial-domestic and stormwater waste management similarly requires not only source control and treatment strategies, but also more detailed monitoring of toxic and persistent toxic substances. Such programs are most effective when linked to long-term studies of ecosystem changes.

INTRODUCTION: THE SCOPE OF THE LOADING ISSUE

When viewed from a marine system perspective, the Georgia Basin might be considered to be that region stretching from the northern end of the Strait of Georgia to the southern end of Puget Sound, and including Juan de Fuca Strait. In estimating land-based impacts on these waters, the drainage both directly from shore areas and through river systems, must also be considered. The principal Canadian tributary is the Fraser River, which drains almost 25% of British Columbia. Puget Sound, estimated to contain 170 billion cubic metres of water, has an annual inflow of 48 billion cubic metres of fresh water, largely provided by ten river systems. Consequently, in their natural state, these coastal seas have always been significantly influenced by land-based nutrients, plant-derived organics, sediments and trace element loadings from tributaries.

In recent decades the Georgia Basin has become one of the most rapidly developing population areas in North America. Urban development with accompanying industrial, transportation and commercial activity is occurring throughout the region. Growth has spread from the major cities (Vancouver and Seattle) into adjacent suburban areas, both in the corridor between the two centres on the western borders of Puget Sound, and on the east coast of Vancouver Island. Much of this development is in unincorporated areas (without municipal or intensive regional management). Often provision of services and waste management is relatively unplanned. As Figure 1 shows, such development now tends to enclose the waters under consideration in a ring of human settlement with attendant land-based sources of pollution. Rapid increases in the Puget Sound and in the Greater Vancouver populations are projected in the period from 1990 to 2010 (Table 1). The magnitude and variety of contaminants entering the marine environment clearly have the potential to increase with population growth, an increase that may be mitigated only by vigorous management measures.

In approaching the loading issue, some reference to the historical pattern of marine pollution is appropriate. Wood preserving and processing, pulp and paper, metal working, shipyards, aluminum plants, and chloralkali operations on the Georgia Basin flourished long in advance of current regulations and monitoring capabilities, or indeed before the level of concern for the environment approached our present perception. Consequently there is a legacy or reservoir of contamination that represents loadings from past industrial and municipal waste disposal practices that is difficult to estimate. Largely bound in sediment, its bioavailability as a long-term background source is a matter of potential concern. However, the scope of the present study is confined to current loadings.

In 1993, public and private environmental management approaches might be assumed to have already addressed the monitoring and evaluation of loading to the marine waters of the Georgia Basin. As this paper will attempt to demonstrate, a number of impediments still exist that must be overcome before we reach that simple understanding. Self-evident factors include the differences between the ecosystem and the political boundaries. Two federal, a state, and a provincial jurisdiction are involved. Requirements for permitting and reporting of effluent discharge vary between the two levels of government in both countries, as well as across the border. Initiatives of the 'third level' (municipalities, counties and districts) are often not fully correlated with senior government activities, particularly with respect to the slate of trace toxic contaminants and effluent parameters that are routinely monitored and reported. The net effect is an uneven and fragmented data horizon, both in temporal and in spatial characteristics. Even more disconcerting is the problem of restricted information flow that has developed between

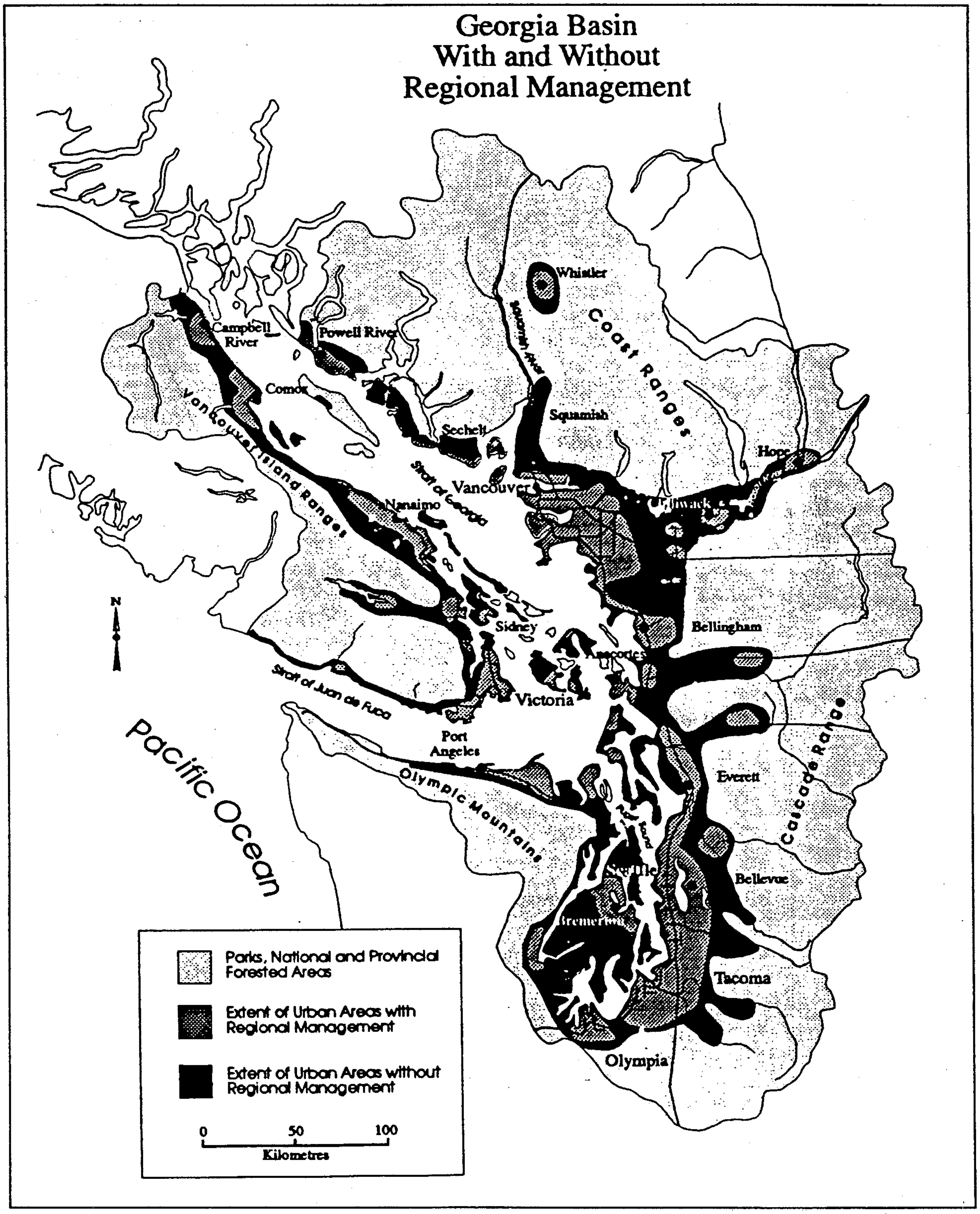

Figure 1. Georgia Basin with and without regional management. Reprinted by permission of the British Columbia Round Table on the Environment and the Economy.

the levels of government, between countries and between industry and government.

The same complex regulatory and political matrix also contributes to the apparent lack of models for inputs from all sources (point and non-point land sources, atmospheric, marine traffic, etc.). There are notable regional exceptions, including the work of the Greater Vancouver Regional District (GVRD), the Puget Sound Water Quality Authority (PSWQA) and localized studies by the senior environmental agencies. Some aspects, such as systematic modelling and subsequent verification of tributary (river and stream) inputs, stand out as requiring new initiatives.

In surveying human impacts on the marine environment of the Georgia Basin, two important themes emerge. The first is the need for an improved level of monitoring and data management to provide reliable indicators of loading to the marine ecosystem. Such data is essential to estimate the exposure of the ecosystem to stressors. Secondly, awareness of the total human impact informs strategic planning and management programs that deal with waste reduction through source control and pre-treatment programs. A lack of cooperation and overall coordination in data gathering and management can prevent a consensus being reached on priorities for action. Inputs from non-point sources and toxic contaminants will increase with explosive population growth, potentially challenging the assimilative capacity of the marine ecosystem.

This paper will survey the range of waste loadings in the Basin from human activity, address our current capacity to quantitatively estimate the point and non-point sources, and explore measures that will allow a more orderly tracking of the nature and extent of inputs in the future.

IDENTIFYING SOURCES OF MARINE POLLUTION

Using a general schematic approach, one can identify point and non-point sources, and mechanisms of entry to the system. Mechanisms involved in loading a marine environment ringed by human settlement like the Georgia Basin must include:

TABLE 1

Estimated population change in Puget Sound and Metro Vancouver by decade

Area	*Year*	*Population*	*Increase*	*Increase Percent*
Puget Sound[a]	1980	2,686,050	438,895 (from 1970)	20% (from 1970)
Puget Sound[a]	1990	3,302,649	616,599	23% (from 1980)
Puget Sound[a]	2000	3,881,179	578,530	18% (from 1990)
Puget Sound[a]	2010	4,348,938	467,759	32% (from 1990)
Vancouver Metro Total[b,c]	1986	1,380,729	—	—
Vancouver Metro Total[b,c]	2006	1,711,500	330,771	24%
Vancouver Metro Total[b,c]	2036	1,903,500	192,000	38% (from 1986)
City of Vancouver[c]	1986	435,997	—	—
City of Vancouver[c]	2006	432,000	−3,997	−1%
City of Vancouver[c]	2036	432,000	0	−1% (from 1986)
Total Georgia Strait[d]	1992/93	2,135,000		

[a] Puget Sound data derived from the Office of Financial Management 1992 (David Peeler pers. comm).
[b] Metro Vancouver includes: North Vancouver, West Vancouver, Burnaby, New Westminster, Coquitlam, Port Coquitlam, Port Moody, Richmond, Surrey, Delta, White Rock, Langley, Pitt Meadows, Maple Ridge and unincorporated areas in the GVRD.
[c] Totals from Greater Vancouver Regional District (1989).
[d] Statistics Canada 1992.

- Airborne input (suspended particulate) from the urban airsheds, including their imbedded point sources.
- Water-borne input from tributaries, from permitted liquid waste discharge (point sources) and from urban, agricultural, transportation, and forest industry runoff (non-point sources).
- Sources from direct use of the marine system for commerce and recreation, including harbours, marinas, ocean disposal of solids (dredge spoils and tailings), incidental (or deliberate) discharge from ship traffic, aquaculture and mariculture.
- Accidental and catastrophic spills.

Many of these general categories have complexities related to the mechanism of disposal. For example, liquid waste effluent involves both sanitary and stormwater components, further complicated by cross connection in heavy rainfall events. The range of inputs for the Canadian coastal marine environment has recently been reviewed by Wells and Rolston (1991). This study, by the Conservation and Protection Division of Environment Canada, identifies major source categories as: land runoff, dredging and ocean dumping, mining, municipal effluents, pulp and paper, spills and accidents, aquaculture, harbours and marinas.

Qualitative and Quantitative Estimation

While providing a valuable overview of the spectrum of sources, status reports or 'State of the Environment reports' (Wells and Rolston 1991; B.C. Ministry of Environment, Lands and Parks 1993), do not address the overall relative proportions of point and non-point sources, though some quantitative data for specific sources may be cited. For example, relative to other areas of the Canadian Pacific Coast, mining is less important in the Strait of Georgia. On the other hand, important effects of forestry, including bark deposition in coastal areas, sediment loading of tributaries (and direct coastal runoff) which do not involve chemical contaminants directly, may receive less attention. Those disturbances that change oxygen, turbidity or nutrient levels may be under-represented in State of the Environment survey reports, while the disturbances themselves may have dramatically elevated impacts on habitat or other ecosystem parameters. The industrial activity around Puget Sound, not addressed in these two Canadian surveys, also has important differences, notably the occurrence of aluminum refining and oil refineries.

Finally, there is a clear need to balance estimation of total loading with the study of the distribution and fate of contaminants. Stressor levels are important, and serious local pollution problems need to be addressed within the context of overall system loading.

Bulk Parameters

Many characteristics of effluent are deemed to be useful indicators of pollution of the marine environment, but contribute no persistent chemical contamination. Their effect may be in the immediate dilution zone (IMZ), for example pH, temperature and common contaminants (NH_3) at lethal concentrations; other characteristics like BOD (biochemical oxygen demand), COD (chemical oxygen demand), TSS (total suspended solids), organic debris, nutrients and bacterial concentrations, may broadly affect habitat or human health.

Specific Contaminants

Specific contaminants of concern are reviewed by Wells and Rolston (1991). As noted above, estimates of the total input of specific contaminants are not routinely provided. Instead, pollutants are identified in many cases by locating sites of greatest contamination (hot spots) often focused on long-term shipping and industrial activity. Heavy metals (cadmium, copper, mercury and lead) and other elements, such as arsenic, have been charted through sediment samples and sediment core analysis in harbours, in shoreline locations near industrial (pulp and paper) activity, and in the Strait of Georgia. Specific areas of concern on the Canadian side include Howe Sound, Burrard Inlet and False Creek in Vancouver, and the Victoria-Esquimalt Harbour. These studies are reported elsewhere in the proceedings. Other specific contaminants of concern include: PCB's (polychlorinated biphenyls) and chlorophenates (wood preservatives). Though being phased out, they still tend to enter the ecosystem by runoff from contaminated sites and former industrial operations. To some extent, polycyclic aromatic hydrocarbons, and chlorinated dioxins and furans will have the same declining point source and delayed non-point source entry profile over the next decade as their more

easily identified origins are curtailed. However, caution must be used in projecting overall trends in sources of toxic contaminants. Specifically, combustion-produced PAH, chlorinated PAH (PCB's) and chlorinated aromatic heterocycles (dioxins) will prove difficult to eliminate and will persist in non-point source runoff. Clearly, certain congeners of polychlorinated dibenzo-*p*-dioxins (e.g. 2,3,7,8-TCDD) and of polychlorinated dibenzofurans will be drastically curtailed by process changes that eliminate chlorine bleaching of Kraft pulp.

Contaminant Complexity

The slate of toxic contaminants, particularly trace organic compounds, can be composed of literally thousands of different compounds and isomers. Many of these are used or manufactured in urban areas and appear in runoff. If they are chemically or biologically resistant, they persist in the sludge or effluent from secondary sewage treatment plants. Some represent important threats to human health or the environment, as concluded by risk assessment studies. Both Canada and the United States identify priority pollutants. The US EPA selected 126 inorganic and organic chemicals (GVRD 1988) for special consideration in both monitoring and source control (limitations on discharge). There is now considerable emphasis on determining the danger of such toxic contaminants to the ecosystem. For example, chlorinated pulp mill effluent has been determined to be a toxic substance under the Canadian Environmental Protection Act not because of its danger to humans or human food but for potential harm to the aquatic and marine ecosystem (Environment Canada 1991). Similar conclusions have been reached in the U.S jurisdictions, and have resulted in a dramatic regulated curtailment of AOX discharge to Puget Sound.

New Contaminants

Each year many more substances are introduced into commercial or industrial use, and become included in the trace contaminant profile dependent on their distribution and fate (or clearance rate). More than occasionally, these compounds are later found to have unanticipated effects, particularly adverse chronic impacts. A typical example is tri-n-butyl tin oxide, a component of marine antifouling paint that impacts shellfish reproduction at low levels (parts per trillion). Since foreign vessels often are unregulated for the use of such materials in Canadian waters, the sources are not easily eliminated. As well, the nearly unique value of organotins as antifouling coatings on aluminum hulls has slowed the elimination of these substances from commerce.

As pointed out in proposals for a National Ecological Monitoring Program in Canada (Freedman et al. 1993), it is necessary to monitor such new sources, and either anticipate stressors to the ecosystem, or identify them at the earliest possible moment. The continually evolving trace toxic contaminant slate then requires a close coordination of pollutant source inventories and ecosystem response data from receiving environment monitoring sites.

Synergistic effects of pollutants, producing complex stressor-response observations, present an even greater challenge. Risk assessment projected from single substance dose-response studies may underestimate the environmental impact.

In summary, the wide variety of sources and mechanisms of entry of pollutants and other materials into the marine ecosystem create a challenge for estimating the total loading and the distribution of the inputs. Current surveys stress qualitative and specific point source data, with less emphasis on total loading. In addition there is a continually evolving slate of pollutants often present at trace levels with poorly understood risks to human health and the environment. While some of the mechanisms of entry are through point sources where pre-treatment or effluent treatment is effective, non-point sources may present a greater strategic challenge.

INFORMATION ISSUES AND INFORMATION MANAGEMENT

The successful integration of scientific research, policy development, management action and public information dissemination begins with credible, widely accepted information; the key element is effective environmental data management. In the sections of the paper that follow, it will be evident that most of the environmental information available on the Strait of Georgia is obtained from three sources:

- large archival databases maintained for permitting and compliance purposes;

- snapshot-in-time data from intensive site-specific studies;
- personal contact to retrieve control data from individual operators in municipal and other government agencies and occasionally from industrial sources.

To obtain basic information, all three sources require a user to have either special knowledge or special contacts. As a result, the accumulated broad base of chemical, physical and biological measurements is not readily available to potential data users (managers, scientists and others). An effective method of environmental data management and retrieval is required. Such a system has been under development in many locations, including at the University of Victoria (UVic) where the UVic Indicators Group has been developing a Continental and Oceanographic Data Information System (CODIS), to explore data management strategies in collaboration with and with the financial support of Environment Canada and Fisheries and Oceans Canada (Fyles et al. 1993).

CODIS is a geo-referenced data information and retrieval system containing meta-data (or data-about-data). On one level CODIS is a powerful index to primary datasets that have been evaluated in terms of data quality based on consensus protocols that span the scientific disciplines represented. Disciplines include: chemistry, plankton, benthos, fish, mammals and ocean physics. It is an outgrowth of the ADCAP/WESCAP data information program of the Institute of Ocean Sciences. The majority of the current data refers to the arctic and west coast oceanographic regions. Under the Aquatic Resources Management Research Program administered by the Science Council of British Columbia (Farrell 1993), the UVic Indicators Group has adapted the basic protocols to the needs of the Fraser Basin and catalogued all organic contaminants data available for that system. As an index, CODIS is envisaged as a tool to speed retrieval of background information at the start of any monitoring program or research project. CODIS reporting features provide summary bibliographic information for historical data sources.

On another level, CODIS offers a new level of information about data. It does not contain raw data, but contains 'meta-data' or 'data-about-data' which can be explored, without reference to the original measurement values, to offer broad insights that are not evident from direct inspection of the primary data. CODIS assumes that the important feature of original data is what is it about: Where was the measurement done? When? What was measured? How was the measurement done? Was the measurement reliable? CODIS meta-data also includes an assessment of data quality.

Meta-data has the potential of greatly aiding future inventory work. By determining the extent and quality of past work, meta-data can increase the efficiency of future spending by directing work towards key locations and constituents. Pre-existing work of high quality can be incorporated into current research, thus shortening the required measurement times. Meta-data systems are also of strategic importance in computer simulation model building and testing, as well as for practical model application by resource managers for decision making; all of which require easy access to good data.

A meta-data approach to establishing inventory priorities for both habitat and contaminants must be developed for the Georgia Basin. A system like CODIS can play a uniting role in integrated environmental management in the Georgia Basin, and could provide a method for the scientific analysis of data at a higher level than is presently possible.

PRESENT WASTE LOADINGS

Point Sources: Strait of Georgia and Juan de Fuca Strait

Data Availability

Information on Canadian point sources reflects the historical emphasis on regulation of maximum allowable flow and contaminant discharge levels in waste management permits. New fee legislation, with fees directly linked to BOD, TSS and toxic contaminant levels, should dramatically enhance the available database.

In order to operate a marine outfall in British Columbia, a permit issued by the BC government is required. The data collected is available through two databases, WASTE (acronym has no meaning) and SEAM (System for Environmental Assessment and Management). The weakness of this system is that only a very few constituents are dealt with in permits. Of these constituents, only three are covered in this paper: Total dis-

charge (volume), total suspended solids (TSS) and biological oxygen demand (BOD). Only the outfalls in the Greater Vancouver Regional District (GVRD) are required to report any metal or organic contaminants values.

Since WASTE and SEAM only keep track of permit maximums and permitted constituents, attempts must be made to obtain more complete 'actual' data from the municipal authorities themselves.

Discharge volume — an example of data comparison

The document most frequently cited when assessing point source loading into the British Columbia marine environment is the 1989 State of the Environment Report on Pollutants in British Columbia's Marine Environment (Kay 1989). The numbers presented in that report have been used as general guidelines in most reports since then. Our study has determined that while the numbers presented in the Kay report are useful, one must be careful in applying them directly to the Strait of Georgia. This is best illustrated by comparing total discharge volumes by source type to the figures in the Kay report (Table 2).

It is evident that the global numbers presented in the Kay report do not adequately deal with the Strait of Georgia. Approximately 70% of all British Columbians live in the region bordering the Strait and much of British Columbia's secondary industry is also located here. However, the majority of the primary resource extraction industries lie outside this region. For example, while mining accounts for 12% of British Columbia's total permitted marine discharge volume, none of it currently occurs in the Strait of Georgia. Non-point source runoff or seepage from abandoned mine sites should also be considered in overall inventories. The pulp and paper industry does have a major influence on discharge volumes. In 1992–1993, six mills made up 38.4% of the approximately 2.4 million cubic metres per day of actual effluent that flowed into the Strait of Georgia.

Differences in flow volume percentages in Table 2 also reflect the definitions used. The Kay report uses maximum permitted flow volumes which are seldom reached by permittees. The Strait of Georgia numbers reflect actual discharge values for major sources, with permit numbers used only for minor sources. Actual discharge volumes were obtained for these major Canadian municipal sources: GVRD, Capital Regional District (CRD), Cowichan Valley Regional District, Nanaimo Regional District and pulp mills (Crofton, Port Mellon, Powell River, Harmac, Elk Falls and Woodfibre). The Kay report also predates the incorporation of secondary treatment at the majority of pulp and paper mills. Currently, B.C government regulations require that pulp and paper producers discharge a maximum of 2.5 kilograms AOX (Adsorbable Organic Halides) per tonne of air dried pulp. This limit will decrease to 1.5 kg/tonne by 1995, and 0 kg/tonne by 2002. As a result of this government policy, coastal pulp mills have been obliged to install secondary treatment which has decreased discharge volumes substantially, resulting in pulp mills using only about 67.9% of their permitted volume in 1992/93 (see Appendix A for comparison). According to a recent British Columbia study (BCMOELP 1994), discharge volumes, total TSS and total BOD from 23 pulp mills in British Columbia continue to decline. However, the quantitative data used in that study was not accessible to the authors for this paper.

Municipal discharge is not evenly distributed in the Georgia Basin. The 46.3% of marine discharges contributed from domestic sources are highly concentrated in the southern part of the Strait of Georgia and Juan de Fuca Strait, mirroring population distribution. Appendix A and additional data shows that 89.9% of all permitted Canadian domestic discharge volume comes from the GVRD and CRD regions (80.1% from GVRD). The breakdown by region and type is shown in Figure 2.

These trends imply that future monitoring programs should focus on population centres in the southern part of the Georgia Basin.

BOD and TSS

A useful sub-system of the WASTE database is the PERFICT (Permit Fee Inventory of Contaminants) system used by the BC Ministry of the Environment, Waste Management Permit Fee Group to determine fees for permit holders. This system calculates the maximum permitted loadings of applicable constituents based on permitted discharge and concentration levels. Data provided by the PERFICT system has been

TABLE 2

Total permitted discharge volume to marine waters by source type (% of total flow)[a]

Industry	*British Columbia*[b]	*Strait of Georgia*[c]
Pulp and Paper	58 %	38.4%
Municipal	19.5%	46.3%
Mining and Smelting	12 %	n/a
Other	10.5%	15.4%

[a] Reprinted from the Georgia Strait Loading Study (West et al. 1993).
[b] From Kay 1989.
[c] For calculation method see text.

TABLE 3

Actual BOD and TSS values compared to permitted values[a]

	BOD Loading (tonnes/year)	*TSS Loading (tonnes/year)*	*% of Permit BOD*	*% of Permit TSS*
British Columbia Pulp and Paper Mills	7,149	11,380	15.6	23.8
GVRD	36,870	20,500	32.5	23.2
CRD (Macauley Point and Clover Point only)	6,667	5,775	84.7	73.2
Nanaimo Regional District	865.5	634	55.2	38.2
Seattle (West Point only)	15,840	8,946		

[a] Reprinted from the Georgia Strait Loading Study (West et al. 1993).

TABLE 4

Actual loading data for major CRD and GVRD outfalls (tonnes/year)[a]

Constituent	*Macauley Point*[b] *(estimates)*	*Clover Point*[b] *(estimates)*	*Annacis*[c]	*Iona Island*[c]	*Lion's Gate*[c]	*Lulu*[c]
Oil and Grease	386	689	3500	3100	350	580
Cyanide	0.34	0.38	<3	<3	<0.7	<0.4
Cadmium	0.059	0.011	<0.07	<0.1	<0.02	0.024
Chromium	0.48	4.96	n/a	n/a	n/a	n/a
Copper	2.85	19.1	19	18	5.8	3.8
Lead	2.38	1.56	1.7	1.8	0.38	0.4
Mercury	0.007	0.003	<0.07	<0.08	<0.02	<0.01
Nickel	0.34	0.53	2.1	0.8	0.2	0.66
Zinc	10.6	12.9	14	10	2	2.4
Phenols	0.44	0.56	7	<3	<0.7	0.8
Dichlorobenzene	0.04	0.05	n/a	n/a	n/a	n/a
PAH	n/a	n/a	n/a	n/a	n/a	n/a

[a] Reprinted from the Georgia Strait Loading Study (West et al. 1993).
[b] CRD loadings are calculated using an average annual flow combined with a single daily concentration and extrapolating for a year.
[c] GVRD loadings are calculated from yearly average flow and yearly average concentration.

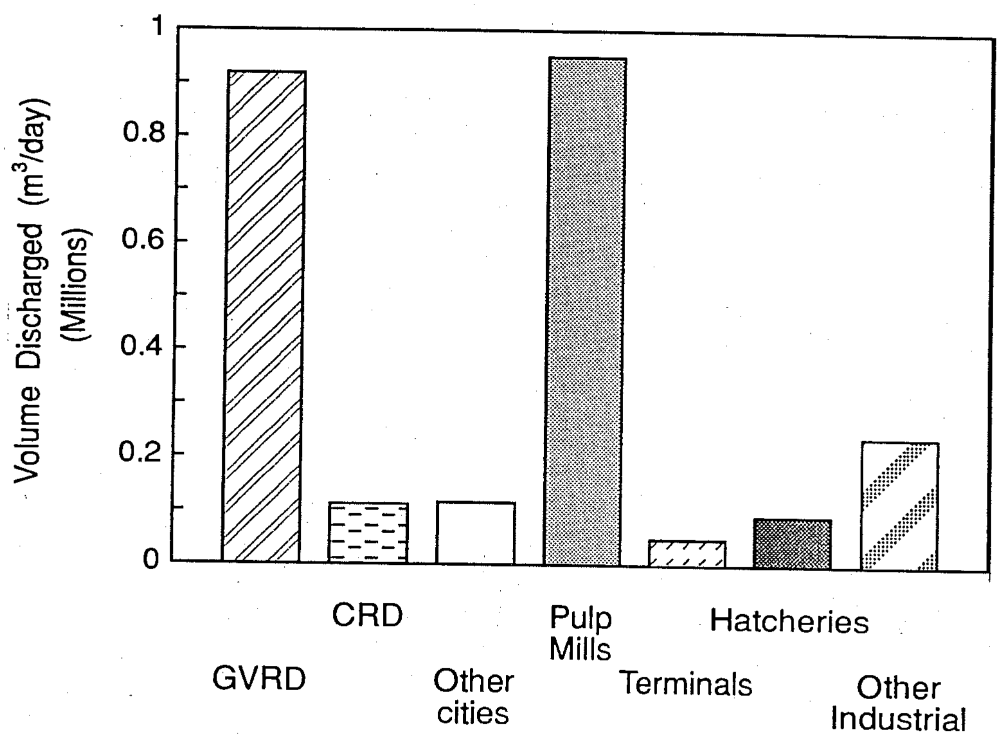

Figure 2. Volume of total discharges: by region and type. Reprinted from the Georgia Strait Loading Study (West et al. 1993).

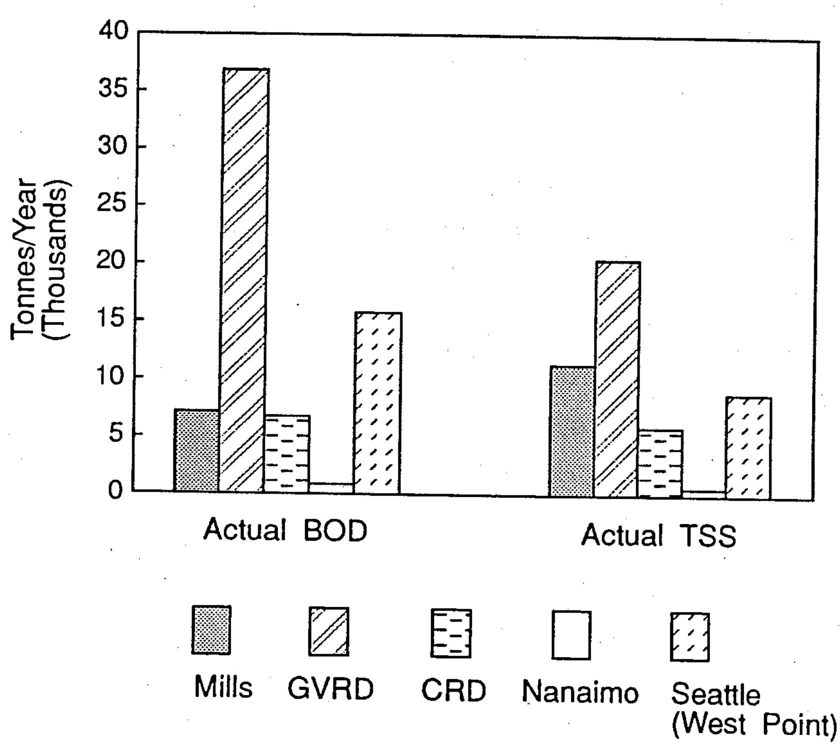

Figure 3. BOD and TSS loading by source. Reprinted from the Georgia Strait Loading Study (West et al. 1993).

used to obtain maximum permitted TSS and BOD loading for municipal and industrial sources.

Municipalities and industrial operations seldom reach their maximum permit values for these parameters. On average only 50.3% of permitted BOD and 38.9% of permitted TSS is discharged. Pulp and paper producers appear to use only 17.5% of permitted BOD and 24.6% of permitted TSS (1992–93 values) (Table 3). The actual loadings by source to the Strait of Georgia, with Metropolitan Seattle-West Point included for comparison, are shown in Figure 3. Total nitrogen and phosphorus, routinely measured in the U.S., is not available in Canadian databases.

Metals and organic contaminants

Most British Columbia municipal sewage treatment facilities are not required to test for metals or organic contaminants in their effluent. Historically, TSS and BOD were considered to be good parameters for monitoring waste treatment plant technology on a day-to-day basis. Note, however, that BOD and TSS bulk parameters may not correlate well with metal/organic values, and should be used as surrogates with great caution.

An ecosystem approach to the Georgia Basin will require a significant change in these reporting practices. Given the expense involved in doing these tests, few do so voluntarily. The majority of municipal officials contacted assured the authors that since their regions were not highly industrialized they had no reason to test for, nor expect, metals in their effluents. The only Canadian effluent data included in this study and listed in Table 4 came from the GVRD (where permits include heavy metals) and the CRD (where once-yearly monitoring is carried out). Some additional data on sludge metal levels was obtained for the CRD and the Cowichan Valley Regional District. Since concentration factors from effluent to sludge could not be determined, the data is not reported here.

A note must be made about the CRD data in Table 4. The loading values have been calculated using a single concentration sample and not an average. As a result, some values may be highly elevated due to the potential of a once-only spike.

Great care must be used in assessing such summary data. For example, the total phenol levels vary from a measured loading as low as 0.44 tonnes per year (Macauley Point) to one as high as 7 tonnes per year from Annacis Island. The upper limits for 'non-detected level' values range tremendously as well, from a high of 3 tonnes per year at Iona Island, to 0.7 tonnes per year at Lion's Gate. Both values are much higher than either CRD value (0.44 and 0.56, Table 4). Clearly a graphical display using 'zero' non-detect values for the large sources would be misleading. The contrast with data available from the US sewage treatment plants — influent, effluent and biosolids (sludge) — is instructive. Clearly non-detect levels in effluent could be estimated from influent (or sludge) values if they were routinely available in Canadian data.

Data Quality

The phenol example given above provides an entry into the general question of data comparison from different locations. In most cases we could not identify even the rudimentary protocols suggested in data management systems or data catalogues such as CODIS. Reported data, particularly that required by permit, might be assumed to follow standard protocols (i.e. B.C. Ministry of Environment, Lands and Parks), but documentation is not readily available, particularly for collection and storage of analytes. Without full documentation of the collection and storage of samples, the resulting analysis values must be viewed with caution. This caution could be eased if certified reference materials were used; and the issue is particularly acute for trace organic analysis. Since there are very few such reference materials in use (Fyles et al. 1993), the accuracy of most data is impossible to establish. Data quality is not synonymous with accuracy. Accuracy is a measure of how close a measurement is to an absolute value. Without a certified reference material, systematic errors in measurements cannot be detected, hence data of apparently 'good quality' (free of obvious errors, best available analytical methods) might still have some systematic error. Conversely some data of apparently 'lower quality' (obvious sources of error, poorly controlled or not reported) might be free of systematic error and be closer to the unknown absolute value. For practical purposes, data quality is frequently judged from the precision of a set of data. Precision is the measure of the random variations in results due to the experimental technique used. The variation can be derived from comparison of replicates, use of internal standards and the use of internal

'spikes' of the analyzed compound. A certified reference is not required to assess precision, but then, data can be precise without being accurate. Should large scale contaminant distribution modelling exercises be contemplated in the Georgia Basin, it will be necessary to rationalize protocols, analytical methods and indeed accuracy (or the relationship to actual concentration). Such exchanges between municipal and senior governments and across the border will serve to enhance true data quality on both sides of the border.

The frequency of sampling can seriously affect values that are reported for total metal and organic loading. Unlike BOD or TSS where daily tests are routine, metals and organics are likely to be tested once a month. The single concentration is converted into an average daily loading, and then extrapolated to give a monthly value. Some questions to be considered are: Should one use the daily flow or monthly flow? How can one be sure the value wasn't a once-only spike? Is there a difference between wet and dry weather? Such refinements in permitting and monitoring requirements have not yet been introduced in British Columbia as far as could be determined. Different calculation methods can also affect total loading values.

Table 5 displays how three different approaches result in very different final loading projections using Puget Sound point source data as an example. The 'Trends' system, which is used in Puget Sound long-term planning, should theoretically be the most accurate, and will therefore be used to compare the other two systems. The 'Trends' system deals with non-detects and missing monthly data in the effluent by observing the biosolids results. If a metal is observed in biosolids, but is below detection in the effluent, it is entered as if it were being input as just below the detection limit in the effluent. In contrast, the two other methods treat missing or non-detected concentrations as zero.

The 'Metro Calculated 1' method uses annual average flows and annual average loadings. It takes monthly flow rates and uses them to calculate the annual average flow and monthly concentration values which are averaged to give a yearly average concentration. These two average yearly numbers are then combined to give a yearly loading. This method has the potential to miss once-only events and allows missing or non-detected monthly values to dilute higher monthly values in the total averages. It can also result in higher values by allowing low-flow, high-concentration months to be combined with high-flow months resulting in higher annual loadings. The 'Metro Calculated 2' method determines monthly loading by combining average monthly flows and the average monthly concentrations to give a monthly loading. The twelve monthly loadings are then added to give an annual loading. The weakness of this system is that any month where the testing showed a concentration below the detection limit would be considered a zero-loading month in the annual calculations. The 'Metro Calculated 2' system has a strong possibility of missing significant daily spikes. This results in more accurate values for constituents that remain constantly above the method detection limit (copper and zinc) but has a lower accuracy for constituents (like mercury) which are usually below the method detection limit but occasionally have daily maximums above (e.g. of 0.0016 mg/L).

TABLE 5

Comparison of loadings based on calculation type for Metro-West Point Municipal Outfall (tonnes/year)[a,b]

Constituent	*Metro Trends*	*Metro Calculated 1*	*Calculated 1 as % of Trends*	*Metro Calculated 2*	*Calculated 2 as % of Trends*
Cadmium	0.50	0.024	4.92	0.023	4.6
Chromium	1.01	0.52	51.7	0.56	55.4
Copper	6.34	5.58	87.9	5.60	88.3
Lead	4.55	0.20	4.31	0.22	4.84
Mercury	0.046	0.025	54.51	0.026	56.52
Nickel	1.73	0.30	17.48	0.031	17.9
Zinc	12.5	10.8	86.4	10.8	86.4

[a] Reprinted from the Georgia Strait Loading Study (West et al. 1993).
[b] Calculation methods are described in the text.

Clearly there is a significant problem if one tests annually or every six months (See Table 4). This results in annual extrapolations based on one or two values. The resulting values are only estimates or more properly anecdotal values.

Treatment Levels

The question of the level of treatment of sanitary liquid waste in British Columbia for communities on marine waters has been controversial. Deepwater marine outfalls, particularly Macauley and Clover Points in Victoria, are deemed locally to pose minimal risk even with only preliminary treatment. The Greater Vancouver Regional District is only now moving to introduce secondary treatment, upgrading from primary treatment under a new Liquid Waste Management Plan (GVRD 1989). The Capital Regional District has a similar liquid waste management process, but currently favours a longer time-horizon for introducing treatment. Current policy of the British Columbia and federal governments is to require secondary treatment. It must be recognized that municipal discharges alone are estimated as the sole cause of 15% of all shellfish harvesting closures in British Columbia waters and are implicated in a further 78% (Wells and Rolston 1991). Other regional districts on the Strait of Georgia are addressing liquid waste treatment issues. Aggressive pre-treatment (source-control), shoreline source clean-up in urban areas, and elimination of illegal and accidental storm — sewer cross-connections may diminish marine loadings and shellfish closures much more rapidly in the short term than enhanced treatment.

There is no other single issue where a comprehensive monitoring and data management program would influence Canadian policy more directly. Changes in treatment levels will affect the relative percentage of loading from distributed non-point sources. Future trends in total loading on the Canadian side will also reflect the impact of source control on permitted discharges. The Marine Sciences Panel will need to carefully weigh the long-term total system assimilative capacity (deepwater outfalls) against the more immediate threats to shoreline benthic ecosystems that can be addressed by broad infrastructure programs. Only a complete system database providing total loading, distribution and fate will allow these questions to be addressed.

Point Sources: Puget Sound

Municipal Treatment Plants

Currently there are 26 major and 44 minor municipal sewage treatment plants (STPs) serving a population of approximately 1.75 million people in the sewered areas of 78 cities, towns and communities in the Puget Sound Basin. The total average dry weather design flow for the 26 major STPs is 1.7 million cubic meters per day.

All STPs within Puget Sound are required to provide at least secondary levels of treatment. Currently all STPs are providing secondary treatment with the exception of Metro-West Point and two smaller Metro STPs which are providing primary treatment. (The two smaller STPs are slated for closure when the Metro-West Point secondary plant is completed in 1995.) The 'LOTT' secondary STP in Olympia will begin providing tertiary treatment in 1994. Total estimated conventional pollutant loads from these STPs is shown in Table 6.

Note that the construction of secondary treatment plants in the 1980s and 1990s results in significantly lowered estimated loadings of BOD and TSS in 1990 and 2000. However, due to continuing population growth by the year 2010, estimated loadings of BOD and TSS are expected to once again approach 1970 levels.

Since typical primary and secondary STPs have little effect on total nitrogen and phosphorous, loadings of these constituents are expected to increase throughout the period. Construction of additional nitrogen and/or phosphorous removal processes at some STPs to reduce nutrient loadings in localized areas, such as the 'LOTT' secondary STP in Budd Inlet, is not expected to significantly lower the total loadings to Puget Sound.

Reliable estimates for loadings of toxicants (metals and organic chemicals) are not yet available for most STPs. Loading of these constituents is highly variable depending on the nature and status of commercial and industrial facilities discharging to the municipal plants. However, trends in loadings of heavy metals from the two largest STPs in Puget Sound, the Metro-West Point and Metro-Renton plants, are available and summarized in Tables 7 and 8. Note the differences between the Metro-Renton (secondary treatment) and Metro-West Point (secondary treatment not installed).

Industries that rely on municipal sewage facilities often use pretreatment processes to first remove pollutants from their waste stream prior to discharge to city sewers. These processes reduce contaminants that may interfere with or pass through the municipal treatment plant. Metro credits pretreatment processes with helping to dramatically improve the quality of its sewage biosolids (sludge) over the past decade. Between 1981 and 1990, the level of metals in Metro's biosolids declined by the following amounts: cadmium 76%, mercury 50%, chromium 70%, nickel 52%, copper 57%, zinc 26%, and lead 60%. Metro attributes much of these declines to an aggressive and successful industrial pretreatment program.

Industrial Process Discharges

Puget Sound is also home to several very large industries that discharge directly to the Sound or its estuaries. These industries include seven pulp and paper mills, six oil refineries, and two aluminum mills.

Although the actual discharge depends on the type of mill and the treatment processes employed, pulp and paper mills typically discharge high amounts of BOD

TABLE 6

Estimated municipal sewage treatment plant loadings to Puget Sound Basin (tonnes/year)

Constituent	*1970*	*1980*	*1990*	*2000*	*2010*
BOD	10,050	120,207	9,933	8,692	9,735
TSS	11,840	14,140	11,310	10,220	11,460
Total N	4,784	5,728	6,490	7,350	8,245
Total P	1,423	1,705	2,003	2,317	2,599

TABLE 7

Heavy metal trends at Metro-Renton STP: influent, effluent (tonnes/year) and biosolids (mg/kg) loadings

Constituent		*1989*	*1990*	*1991*	*1992*
Cadmium	Influent	0.22	0.23	0.23	0.25
	Effluent	0.20	0.22	0.23	0.23
	Biosolids	10.4	8.9	6.3	8
Chromium	Influent	1.5	2.63	1.16	1.89
	Effluent	0.40	1.03	0.50	0.40
	Biosolids	107.1	149.2	82.4	170.5
Copper	Influent	11.2	8.53	8.03	9.57
	Effluent	3.53	2.90	2.68	2.15
	Biosolids	727.7	745.3	730.5	838.4
Mercury	Influent	0.15	0.07	0.07	0.05
	Effluent	0.07	0.03	0.03	0.02
	Biosolids	2.4	1.6	0.7	0.9
Nickel	Influent	0.81	0.91	0.89	1.04
	Effluent	0.75	0.79	0.76	0.99
	Biosolids	35.7	30.7	22.9	28.0
Lead	Influent	2.27	2.43	2.35	2.48
	Effluent	2.17	2.17	2.27	2.28
	Biosolids	109.1	109.5	98.6	101.1
Zinc	Influent	13.2	12.7	10.6	12.7
	Effluent	2.55	2.96	2.80	3.05
	Biosolids	960.8	953.8	847.2	888.2

and TSS. In addition, chlorinated organic compounds and bacteria may also be of concern. Appendix C shows the historic and current discharges of the five operating pulp and paper mills on Puget Sound. Five other mills, including one very large mill, have closed permanently since 1968.

Due to concerns over organochlorine discharges, all of the currently operating mills modified their manufacturing and treatment processes in order to reduce discharges of dioxins, furans, and AOX. Current monitoring shows that all of the mills have dioxin discharges below the level of detection (about 3.5 parts per quadrillion) and are believed to be within permit limits.

Appendix C shows the average production and discharge of oil and grease from the six oil refineries on Puget Sound for the years 1970 and 1992. Note that while the throughput of crude oil has increased by 68%, oil and grease discharge has been reduced by 24% over the same period.

NON-POINT SOURCES OF POLLUTION

Urban Sources

The previous sections have briefly surveyed the permitted point discharges into the Georgia Basin, and more information about nutrient loadings has been reported by Harrison et al. (this volume). The remaining sources are conveniently separated into urban (incorporated) and rural (suburban) areas. The best estimates are available in urban areas. Loadings from collected storm water — designated Urban Runoff (UR) — and the related Combined Sewer Overflow (CSO), have been assessed for some areas, in particular the GVRD (GVRD 1988). Other non-point sources are more readily identified in urban areas as well, though their highly distributed nature makes calculation difficult.

The principal urban non-point sources (NPS) include (1) leachate from existing and closed landfills, (2) seepage and runoff from wood waste dumps, (3) existing and closed forest port terminals and industrial sites

TABLE 8

Heavy metal trends at Metro-West Point STP: influent, effluent (tonnes/year) and biosolids (mg/kg) loadings

Constituent		*1989*	*1990*	*1991*	*1992*
Cadmium	Influent	0.43	0.46	0.46	0.41
	Effluent	0.4	0.45	0.45	0.43
	Biosolids	14	12.7	11	9.2
Chromium	Influent	2.85	3.61	1.56	1.13
	Effluent	1.92	2.37	1.08	0.84
	Biosolids	136	142	85.1	73.9
Copper	Influent	9.52	8.54	8.44	9.24
	Effluent	5.99	5.41	5.48	5.5
	Biosolids	498	532	451	478
Mercury	Influent	0.22	0.1	0.07	0.07
	Effluent	0.1	0.07	0.05	0.03
	Biosolids	1.9	1.7	1	1.4
Nickel	Influent	2.83	2.35	1.82	1.82
	Effluent	2.02	2.04	1.57	1.74
	Biosolids	86.5	82.6	57.2	52.2
Lead	Influent	5.17	5.31	5.05	4.45
	Effluent	4.24	4.62	4.49	4.11
	Biosolids	329	353	280	275
Zinc	Influent	21	20	18.6	19.1
	Effluent	11.9	12.2	9.39	10.9
	Biosolids	1084	1238	1021	1138

(primarily chlorophenols) and (4) agricultural runoff and septic tank seepage within urban boundaries. There are also a host of small incidental or continuing sources including spills along rail lines; waste discharges from boats; direct runoff from bridges, roadways and parking lots, and direct runoff from docks and wharves into receiving waters.

Rural Sources

Given the nature of the development in the region (Figure 1) it is possible that total loading from rural sources may surpass the urban point source loadings. Other sources will become increasingly important as source control measures are applied to liquid waste streams. For human settlement in the unincorporated 'urban sprawl' areas sewerage is provided by septic tank systems, often receiving little monitoring after installation. Rocky shoreline locations, natural seepage and even direct discharges contribute to bacterial contamination, shellfish and swimming closures and to eutrophication of small embayments via nutrient loading. Importantly, the second highest cause of shellfish closures in BC after sewage (municipal) was rural runoff, at nearly twice the area of closure due to urban runoff (Wells and Rolston 1991). In a recent assessment by the Science Council of British Columbia (Spark Oceans Committee 1993), it is asserted that the majority of coastal oil pollution results from runoff, not ship discharges or leaks.

Direct Use of the Marine Environment

When both probability and magnitude are considered, catastrophic spills involving crude oil or petroleum products remain one of the greatest risks to the marine environment. Regulation is multi-jurisdictional, beginning with the International Maritime Organization (IMO) convention. In British Columbia and Washington State, oil spills were an important factor in establishing the Environmental Cooperation Council. Several enquiries have been held on marine oil transportation, most recently in British Columbia by David Anderson (Anderson 1991). Recommendations on double-hulling, on spill practices and control equipment, and on enhanced navigational precautions have been difficult to introduce. The extensive use of flags-of-convenience by international tankers, and the difficulty of coordinating regulations among the federal and state governments, are clearly outstanding barriers to improved safety.

Beyond marine oil spills, major industrial accidents on land are of concern. Large quantities of toxic materials could enter riverine or estuarine environments and be conveyed to the Georgia Basin. Emergency diversion and holding ponds are not available to contain these events.

Other major categories of direct marine use of concern include:

- Nutrients from aquaculture activities. These have not been totaled and compared with nitrogen and phosphorus loadings from other sources. Bacterial and viral contamination and antibiotics used in aquaculture are also concerns.
- Deposits of materials from dredging operations in harbours and inlets and dumping sites in the Strait of Georgia provide a continuing reservoir of trace contaminants. As standards and guidelines change, the metals and organics in these materials can retrospectively be designated as special industrial waste.
- Emptying of small craft holding-tanks, incidental oil spills from pleasure boats, and maintenance (washing, painting and preserving) are sources of marine pollution that will become increasingly significant as source control is applied more rigorously through point source pre-treatment programs.

Quantitative Estimation of Non-point Sources

Urban areas

Estimation or calculation of shore-based sources remains a periodic project-oriented exercise, usually under special planning programs such as the GVRD Liquid Waste Management Plan Stage 1 (GVRD 1989), and in Metro-Seattle under the Environmental Protection Agency (EPA) National Urban Runoff Program (EPA, 1983). It is instructive to consider the GVRD study for two reasons. First, it represents part of the input to the Fraser River, the major tributary of the Georgia Basin. Secondly, it includes an extensive analysis of the comparison between STP, UR, CSO and other non-point sources and the composition (in terms of contaminants) of urban runoff. The study estimates that less than 10% of the contaminants exit-

ing to the Strait of Georgia arise from all sources in the GVRD including trace contaminants such as cadmium, copper, lead and zinc.

Within sources from the GVRD, interesting trends arise (Table 9). It should be noted the combined sewers carry only 14% of the stormwater flow in the GVRD. The remaining stormwater exits into the Fraser River and coastal waters through over a thousand outfalls.

While UR and CSOs account for a small percentage of the BOD and TSS loading (compared to sewage treatment plants) the same is not true for trace metals, oil and grease and toxic organics. Composition of the urban runoff is detailed in Table 10.

For some receiving waterbodies such as Boundary Bay the entire loading arises from urban runoff and non-point sources. Tables 11 and 12 give a breakdown of non-point source loading and agricultural inputs by waterbody in the GVRD.

The inputs from agricultural activity have not been stressed in this paper. However, the potential for trace biocide, nutrient, coliform and sediment loading from agricultural practices is significant. Given the river valley location of much of the agricultural activity, tributary and estuary loadings are particularly affected in the Georgia Basin.

River system (tributary loading)

More sophisticated models are needed to extend these useful studies to the entire Fraser River, and to refine estimates of upstream loadings. A number of approaches have been used including the HSPF (Hydrologic Simulation Program Fortran) model (Donigan et al. 1991), which addresses only nutrients. Such models should be systematically applied to the tributaries of the Georgia Basin to achieve meaningful audits of land-based inputs into the marine environment. The model needs to be run in conjunction with long-term monitoring of water quality and inputs to the river from point and non-point sources.

Persistent toxic loadings have also been modelled for the Fraser River, with particular reference to the distribution and fate of species such as 2,3,7,8-TCDD and chlorophenols. The Ecosystem Simulation Model was developed at Simon Fraser University in Vancouver. As shown in Figure 4 the model predicted the amount of TCDD that left to the Fraser River (Farrell 1993). The significant aspect of the model is the amount of material retained in the river sediment and potentially available at a later date.

Net transfer to the Strait of Georgia

In discussing non-point sources, it is extremely important to stress that many of the effluents discharged to freshwater will be bound to river and wetland sediments and will not be conveyed directly to the marine environment. Careful estimation of the net loading based on retention and release from sediments and biota must be undertaken. The rural land-based sources similarly will have large attenuation factors between the source and the Strait of Georgia. For example, while total nutrient loading by septic tanks may equal STP values in Washington State, only a fraction of the loading will be transported to the marine environment.

SUMMARY AND RECOMMENDATIONS

At first glance, estimating contaminant loadings and pollution for the Georgia Basin marine system, and even projecting trends for the future might appear to be straightforward. We have shown that there are severe impediments to data availability that prevent ready calculation of the environmental impacts. In this paper there has been a recurrent theme of the pressing need for data management. A suitable program would include the following steps:

1. Establish common protocols for monitoring, including sample design, collection, storage and analysis. Protocols for calculation of estimated loadings must also be established.

2. Develop a rational mechanism for the retrieval and dissemination of data related to loadings and marine environment quality. Two issues are involved: (a) timely access, or freedom of information; and (b) entry of data about the datasets into a common catalogue defining location, time, constituents, methods and QA/QC. Such a data catalogue could include elements of the CODIS system developed at the University of Victoria. Free access to the necessary information for development of the data management system is essential.

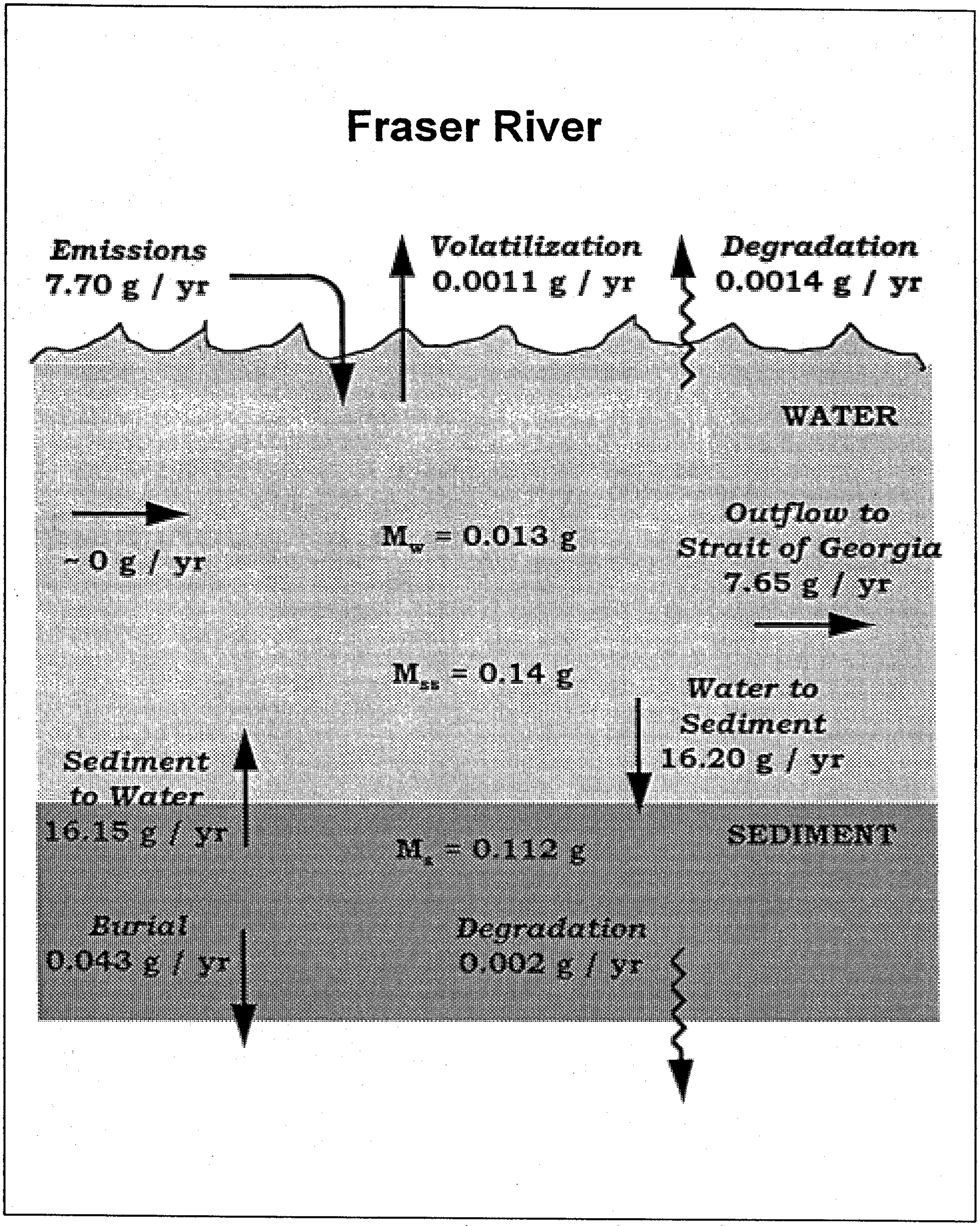

Figure 4. Schematic diagram illustrating the environmental fate of 2,3,7,8-TCDD in the entire Fraser River. Reprinted from Farell (1993) by permission.

TABLE 9

Annual contaminant loadings from urban runoff, combined sewage outflows, non-point sources and sewage treatment plants to the Fraser River receiving water system[a]

Contaminant	*Annual load (tonnes)*	*Urban runoff (% of total)*	*Combined sewer overflows (% of total)*	*Non-point sources (% of total)*	*Sewage treatment plants[c] (% of total)*
Flow (× $10^6 m^3$)	570	29	4	19	48
BOD_5	33,450	5	4	1	90
Fecal Coliform[b]	3,000	0	3	1	96
Suspended Solids	26,150	30	5	1	64
Ammonia (N)	3,400	1	2.6	0.4	96
Total Phosphorus	1,050	2	4	1	93
Cadmium	1	73	8	no data	19
Copper	40	16	4	1	79
Lead	25	48	8	1	43
Zinc	60	36	3	1	60
Chlorophenol	3	no data	no data	100	no data

[a] Data from GVRD 1988.
[b] Fecal coliform values in 10^{15} organisms.
[c] STP loadings from Annacis Island, Lulu Island and Iona Island sewage treatment plants.

TABLE 10

Estimated concentration of conventional pollutants in urban runoff (mg/L)[a]

Contaminant	*Mean conc Wet[b]*	*Mean conc Dry[b]*	*Mean conc Wet[c]*	*Mean conc Dry[c]*
BOD_5	10	10	14	39.2
COD	33.2	38.4	77.6	176.3
TSS	19.8	13.6	241.6	34.3
Oil and grease	3	3.3	7.8	7.2
Nitrogen				
Ammonia	0.172	0.214	0.092	0.601
Nitrate/rite	0.54	1.11	0.36	0.17
Kjeldahl	1.07	1.34	1.0	2.14
Total Phosphorus	0.089	0.067	0.42	1.6
Arsenic	<0.05	<0.005	ND	ND
Cadmium (µg/L)	10	ND	10	10
Chromium	<0.01	ND	0.02	0.013
Copper	0.037	0.04	0.04	0.048
Lead	0.071	0.02	0.22	0.15
Zinc	0.12	0.086	0.24	0.095
Phenol (µg/L)	13	5	9	10
Phthalate (µg/L)	ND	ND	ND	ND

[a] From GVRD 1988.
[b] From Swain 1983.
[c] From Lawson et al. 1985.

3. Initiate a comprehensive international program to establish transboundary collaboration in monitoring the total loadings to the Georgia Basin. Cooperative research programs on appropriate models, and critical information for rational risk assessment, will be necessary. Much of the necessary framework has been presented in the proposals of the International Joint Commission on Great Lakes Water Quality, and could be adapted from their Toxic Persistent Substances Control Program (International Joint Commission 1993).

4. Establish priorities for pollution prevention based on comparative risk assessment. This should include definitions of the critical sources, and the desired margin of safety for human health and the environment.

The British Columbia Round Table on the Environment and the Economy has defined sustainability as:

> "A balance between human impacts and the capacity of the natural world that can be sustained indefinitely."

If we agree that addressing quality of life today while maintaining environmental integrity for future generations is indeed our underlying goal, then action to better understand those human impacts on the environment should be an urgent priority. Working together across the border, as communities and individuals, and through governments at all levels, that task can be accomplished.

TABLE 11

Total estimated non-point source loadings by water body in tonnes/year[a]

Water Body	*BOD*	*TSS*	*NH_3*	*CP*[b,c]	*TP*[b,c]	*TN*[b,c]	*Cu*[c]	*Pb*[c]	*Zn*[c]
Total Fraser[d]	431	431	14.6	3.09	11.5	231	0.35	0.35	.35
Total Boundary[e]	352	352	0.76	0	11.5	230	0.34	0.34	.34
Total Burrard[f]	56.9	56.9	6.33	0.43	0	0	0	0	0
Total	840	840	21.7	3.5	23.0	461	0.69	0.69	.69

[a] Data from GVRD 1988.
[b] CP refers to chlorophenols, TP is total phosphorus and TN is total nitrogen. TN does not include NH_3.
[c] Inputs from agricultural runoff. See Table 12.
[d] Fraser includes: Main Stem, Main Arm, North Arm, Roberts Bank, Kanaka Creek, Coquitlam River and Pitt River.
[e] Boundary Bay includes: Nicomeckl River, Serpentine River, Little Campbell River and Boundary Bay.
[f] Burrard Inlet includes: Indian Arm, First and Second Narrows, English Bay, Port Moody Arm and False Creek.

TABLE 12

Loadings from agricultural activity[a,b]. Loadings in tonnes/year.

Area	*Land area (km^2)*	*Yearly rainfall (mm)*	*Yearly irrigation (mm)*	*BOD_5*	*TN*	*TP*	*Cu*	*Pb*	*Zn*
Total Fraser[c]	244.9	9,450	72	346	231	11.5	0.35	0.35	0.35
Total Boundary Bay[d]	279.7	5,330	154	344	230	11.5	0.34	0.34	0.34
Total	524.6	14,780	226	691	460	23.0	0.69	0.69	0.69

[a] Data from GVRD 1988.
[b] Agricultural loadings estimates were obtained from the Greater Vancouver Liquid Waste Management Plan, and were calculated by multiplying the average annual rainfall + irrigation volume by a runoff coefficient of 0.3 (runoff coefficient is derived from the WPCF Manual of Practice No. 9 1970. It represents the top range of coefficients for unimproved land.) The volume of water runoff was then multiplied by the estimated concentration of runoff as determined by Ferguson and Hall (1979): (3 mg/L BOD_5 and TSS; 2 mg/L total nitrogen; 0.1 mg/L total phosphorus; 0.003 mg/L for each of total Cu, Pb, Zn).
[c] Fraser includes: Main Stem, Main Arm, North Arm, Roberts Bank, Kanaka Creek, Coquitlam River and Pitt River.
[d] Boundary Bay includes: Nicomeckl River, Serpentine River, Little Campbell River and Boundary Bay.

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APPENDIX A

A1. Actual flows for major Canadian municipal dischargers, and maximum permitted flows for minor Canadian Canadian dischargers, with four actual flows in Puget Sound for comparison.[a]

Municipality	Actual Flow (m^3/day)	Municipality	Permitted Flow (m^3/day)
CRD Clover Point	60,900	Campbell River	15,060
CRD Macauley Point	40,700	Ladysmith	6,100
CRD Remainder (includes some permit value)	10,400	Comox-Strathcona	18,500
Nanaimo Regional District	29,510	Powell River Regional District	18,860
Cowichan Valley Regional District	371	Sunshine Coast Regional District	171
GVRD Iona Island	397,000	District of Sechelt	1,700
GVRD Annacis Island	380,000	District of North Cowichan	11,600
GVRD Lulu Island	54,000		
GVRD Lion's Gate	87,600		
Puget Sound			
Alki	24,980		
Carkeek	10,220		
Renton	178,900		
Metro West Point	369,800		

[a] Reprinted from the Georgia Strait Loading Study (West et al. 1993)

A2. Flow values for the six Canadian pulp and paper mills around the Georgia Basin [a]

Mill Owner	Location	Receiving Water	Permitted Flow (m^3/day)	Actual Flow (m^3/day)
British Columbia Forest Products	Crofton	Osborn Bay	245,900	167,000
Canadian Forest Products	Port Mellon	Thornbrough Channel	117,000	69,120
Fletcher Challenge	Elk Falls	Discovery Passage	250,000	220,000
Macmillan Bloedel	Powell River	Malaspina Strait and The Powell River	381,000	190,100
Macmillan Bloedel	Nanaimo	Northumberland Channel	265,000	160,000
Western Pulp Ltd.	Woodfibre	Howe Sound	136,600	67,540

[a] Reprinted from the Georgia Strait Loading Study (West et al. 1993)

APPENDIX B

B1. Actual BOD and TSS loadings for various outfalls around the Georgia Basin (tonnes/year) 1992 values[a]

Outfalls	BOD Loading (tonnes/year)	TSS Loading (tonnes/year)
Macauley Point (CRD)[b]	2,428	2,466
Clover Point (CRD)[b]	4,239	3,309
Annacis Island (GVRD)[c]	19,000	8,200
Iona Island (GVRD)[c]	12,100	9,300
Lion's Gate (GVRD)[c]	2,920	1,900
Lulu (GVRD)[c]	2,850	1,100
Nanaimo Regional District	865.5	633.7
Cowichan Valley Regional District	2.11	4.19
Ladysmith Sewage Treatment Plant	98.21	47.26
Renton (Seattle Area)	1,594	1,544
West Point (Seattle Area)	15,840	8,946

[a] Reprinted from the Georgia Strait Loading Study (West et al. 1993)
[b] CRD loadings based on monthly averages
[c] GVRD loadings are calculated from yearly average flow and yearly average concentration

B2. Actual BOD and TSS loadings for pulp and paper mills around the Georgia Basin, compared to permitted values[a]

Pulp and Paper Mill	Actual BOD (tonnes/year)	Actual TSS (tonnes/year)	% of Permit BOD	% of Permit TSS
Crofton	2,828	2,260	46.3	24.7
Elk Falls	1,606	2,701	24.5	27.4
Port Mellon	1,071	1,327	18.2	16.8
Powell River	401.5	1,277	6.59	14.1
Woodfibre	73.86	1,479	3.29	31.4
Harmac	1,168	2,336	6.15	33.0

[a] Reprinted from the Georgia Strait Loading Study (West et al. 1993)

APPENDIX C

C1. Loading from pulp and paper mills within Puget Sound Basin

Name	Flow	1970	1980	1990
Port Townsend Paper	n/a			
BOD		4,940	544	363
TSS		544	1,400	408
Rayonier	148,000			
BOD		136	81	5.0
TSS		381	5.0	10
Scott Paper Co.	n/a			
BOD		91,000	n/a	1,000
TSS		6,600	n/a	1,200
Georgia-Pacific	136,000			
BOD		28,200	n/a	1,000
TSS		142,000	n/a	2,000
Simpson Tacoma	n/a			
BOD		4,800	498	430
TSS		25,700	2,013	1,100

C2. Production and loadings of oil refineries on Puget Sound 1970 and 1992

Refinery	1970 Discharge Oil and Grease tonnes/year	1992 Discharge Oil and Grease tonnes/year	1970 Crude Oil Throughput (bbls/day)	1992 Crude Oil Throughput (bbls/day)
ARCO	18.11	10.58	85,500	188,570
BP	6.27	3.61	61,100	77,660
Shell	17.81	9.52	86,500	87,300
Texaco	15.51	20.18	60,000	132,060
Sound	0.73	0.13	4,110	1,601
U.S. Oil	2.07	1.75	9,700	27,860
Totals	60.51	45.76	306,910	515,051

DISCUSSION

Andrea Copping *(Panel)*: Thank you Paul. In your opinion, as we urbanize further and start to bring in some of the unincorporated areas, are we going to see the non-point sources become that much more significant than the point sources? Obviously, they are much harder to deal with in many ways, but at what point are we going to have the point sources pretty much under control, but have this growing problem of non-points?

Paul West: Well, in fact as you bring a lot of areas that are unincorporated into a point source program, you may actually see a surge of the inputs to water bodies, of toxics and BOD and TSS. But it actually isn't a surge at all. What you are doing is capturing that which made its way in by other methods. As the population expands differentially in unincorporated areas, and with septic fields and no waste management, particularly stormwater management, then of course per unit population can have a much more serious effect on the marine environment than orderly expansion where you have source control programs and legislated or mandated treatment programs.

Andrea Copping *(Panel)*: How good do you think our data on non-point sources is?

Paul West: Well, we came to — I wouldn't call it despair exactly — but we found that we didn't really have any quantitative handle on it in terms of this morning's presentation. Some of it may be available by test studies, but to try to provide integrated and scaled-up data which gives you the total point/non-point source loading, is extremely difficult. There are models based on population and estimation of the inputs per capita, etc., but I think that they have not been applied in the basin that we are looking at.

Curtis Ebbesmeyer *(Panel)*: If you had to make an estimate, what fraction of the data that you would like to analyze is available?

Paul West: Well I think there is a continuum between virtually 100% availability of the permitted volume and contaminant loadings, less from actual point sources, and then it decays exponentially through the non-point sources and the very minor point sources. It is the integration of the tail which is our real serious problem in terms of the overview, and the fact that the availability of data dips so dramatically with metals and toxic substances which may be of paramount importance in terms of determining the fate of the ecosystem. We have a lot of information on data which may not be the most critical factors, and very little data on some of those inputs that may be critical.

Chris Garrett *(Panel)*: Secretly, haven't you done a back-of-the-envelope estimate of, for example, the non-point sources of metals, so that you can tell us that, even though you don't know within a factor of five, they are still every bit as big as the point sources, or are negligible by comparison.

Paul West: Does anyone in the audience know of non-point source estimation of the population in the Basin?

John Dohrmann *(Puget Sound Water Quality Authority)*: I can't give you the numbers because I distrust them so much that I immediately lost them, but the National Oceanic and Atmospheric Administration in the United States developed some models for estimating non-point loadings to coastal basins, and published those estimates for various estuaries around the United States. My agency, the Water Quality Authority, did extract and reprint their estimates for Puget Sound in our State of the Sound report in 1988. They have estimates for metals, and then included for comparison the industrial sources. But even there, as far as I understand, they didn't use any actual information from the point sources in Puget Sound. They simply said 'a pulp mill has this much of each contaminant per volume' and then just got the volume number and multiplied. So some of those estimates are available, and on a magnitude basis it tells me that we have achieved a sufficient level of treatment of our point sources now that it, by comparison, makes the non-point sources significant today. Some of these estimates are available in the literature.

Robie Macdonald *(Institute of Ocean Sciences)*: Since I am going to talk in a little bit, I don't want to say a bunch of things that I'm going to repeat, but you can estimate some emission sources, for example lead out of automobiles, by looking at the amount of gasoline that has been used in the various basins.

There have been other studies done, I know. Puget Sound is probably the best example, the paper in *Geochim. Cosmochim.* by Paulson et al. who tried to do a

box budget of the copper, lead, zinc, cadmium, I think it was. So they are actually measuring the container and not worrying too much about trying to estimate exactly what the loadings were, although they did try to break down where the stuff was coming in. So the previous speaker, I think, is right in that there is this information out there, and we certainly find that it's a compound-by-compound issue. Some of them you get very much by point sources and some of them the distributed source is far more important.

Physical Oceanography of the Strait of Georgia-Puget Sound-Juan de Fuca Strait System

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ABSTRACT

The Strait of Georgia, Puget Sound, and Juan de Fuca Strait form a major coastal waterway linking the marine basins of the southern Georgia Depression to the open waters of the Pacific Ocean. Oceanographic variability within these interconnecting basins is driven by regional forcing mechanisms that are strongly coupled to oceanic processes taking place over the continental margins of British Columbia and Washington State. I discuss the four principal mechanisms affecting transboundary transport within the waterway: *Buoyancy (freshwater) fluxes; the tide-generating force; surface wind stress; and coastal ocean variability.* Case studies of real and simulated spills are used to document possible transboundary advection within the basins. A status report on numerical modeling efforts is presented and the effects of natural and anthropogenic change on the physical oceanography of the region are discussed. Based on our present knowledge of the integrated system, the likelihood of transboundary transport is high. This statement simply acknowledges the fact that the oceanic boundary separating British Columbia and Washington State does not coincide with any natural barriers. Less certain statements can be made about the "degree of harm" caused by spills, discharges and other materials entering the waterway. In addition to biochemical considerations, the degree of harm will depend on proximity to the source, the effective transport processes, the degree of turbulent mixing, and the presence of local retention mechanisms. Viewed solely from the perspective of flow energetics, we would expect "quiescent" regions such as southern Puget Sound and the central Strait of Georgia to be more susceptible to chronic contamination than highly energetic regions like the southern Strait of Georgia and eastern Juan de Fuca Strait. Future marine research in the shared waters of the region would benefit considerably from cooperative transboundary programs.

INTRODUCTION

The inland waterway formed by the Strait of Georgia, Puget Sound, and Juan de Fuca Strait (the Georgia-Fuca system) is part of an extensive estuarine regime situated between southern Vancouver Island and the mainland coasts of British Columbia and Washington State (Figure 1). Much of the waterway occupies submerged portions of the Georgia Depression whose formation began 150 million years ago as part of a general downfolding of the earth's crust along the Pacific coast following the commencement of the latest era of continental drift. The present configuration reflects the regional restructuring that has occurred during Quaternary ice ages and the tectonic adjustment that continues to take place along the active continental margin. At the peak of the most recent ice age between 15,000 and 20,000 years ago, glaciation extended as far south as Seattle. At that time, regional sea levels were about 100 m higher than they are today. Puget Sound, the largest of the multitude of fjords left behind by the retreating coastal glaciers, emerged from its blanket of ice about 14,000 years ago.

The Georgia-Fuca system is directly linked to the Pacific Ocean through the broad reaches of Juan de Fuca Strait. To the north, a narrower, more circuitous connection exits through the narrow and constricted channels of Johnstone and Queen Charlotte straits. First charted by Captain George Vancouver of the

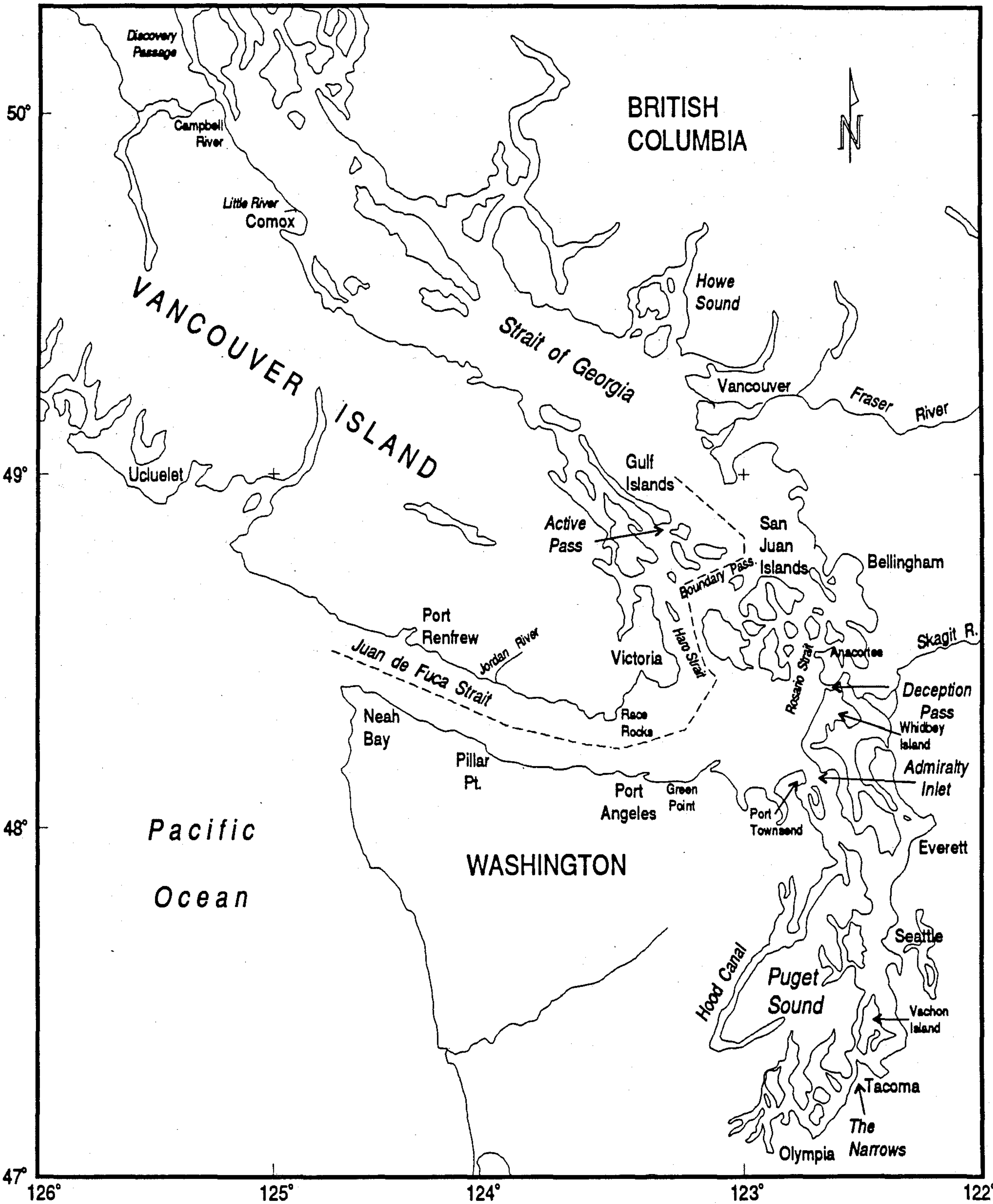


Figure 1. Map of the Georgia-Fuca system. Scale: 1° latitude ≈ 111 km.

British Admiralty during his voyages to the west coast of North America from 1792 to 1794, the waterway has been of fundamental importance to United States and Canadian interests since the international border negotiations of the mid-19th century. These negotiations culminated in the Treaty of Oregon (1846) between England and the United States which decided the oceanic boundary between Washington State and British Columbia. More recent concerns in the region center around the detrimental environmental effects that invariably accompany increased population and industrialization.

Scientific reviews covering the physical oceanography of the Georgia-Fuca system can be found in Hutchinson and Lucas (1931), Waldichuk (1957), Barnes and Ebbesmeyer (1978), Thomson (1981), LeBlond (1983), and Crean et al. (1988). As indicated in these reviews, the *estuarine* component of the circulation is a dominant factor throughout the system. Driven primarily by winter rainfall and summer snowmelt, estuarine flow is characterized by a net (daily-averaged) seaward outflow in the upper portion of the water column and a net landward inflow in the lower portion of the water column. The net seaward flow of brackish water depends on the amount of freshwater entering the system and the degree of entrainment of deeper salty water into the surface layer. The prevailing winds also can have a major impact on the nature of the estuarine flow. Shallow sills deposited by the retreating glaciers help define the geometry of the interconnected basins and play a pivotal role in the dynamics of each basin through their ability to control lateral water exchange. Sills are of prime importance to the oceanography of the many fjord-like estuaries adjoining the main channels.

In addition to the buoyancy-driven (estuarine) component of the flow, we can identify three other fundamental forcing mechanisms that affect flow in the Georgia-Fuca system: *Tidal forcing* arising through rhythmic changes in the effective gravitational attraction of the moon and sun on the earth; *wind forcing* generated by atmospheric thermal gradients and passing frontal systems; and *coastal ocean forcing* triggered by inward propagation of oceanic "events" originating over the continental margin.

This report focuses on transport mechanisms that affect the distribution and dilution of materials within the Georgia-Fuca system and across the international border. Due to the diligent efforts of oceanographers over the years, the amount of information available on the system is impressive. The most difficult aspect of this summary was deciding what to include in the review. My approach is to present a general oceanic overview of the Georgia-Fuca region followed by a detailed examination of transport processes. Other oceanographic factors such as wind waves and regionally-generated tsunamis are not addressed. To simplify the regional oceanography as much as possible, we can think of the Georgia-Fuca system as a number of interconnecting basins separated by a series of shallow sills (Figure 2). The system responds to two primary forcing mechanisms: The quasi-steady *buoyancy (estuarine) forcing*, and the time-dependent oceanic *tidal forcing*. Instantaneous motions consist of oscillating tidal flows superimposed on a steady estuarine flow. Spatial and temporal alterations to this basic flow pattern are brought about by the *winds* and by the inward intrusion of *oceanic events* along Juan de Fuca Strait. Further modifications to the flow result from topographic "steering", back-eddying near coastal promontories, inertial effects, and from the non-linear interactions of energetic oscillating flows. The generation of both coherent and turbulent-like eddies, as well as wave-like phenomena such as internal tides, provide yet another level of complexity to our simplified picture of estuarine flow and tidal oscillations.

BASIN CHARACTERISTICS

The purpose of this section is to provide a brief overview of the water properties and basin characteristics of each of the three major basins. This sets the stage for discussion of the different forcing mechanisms affecting transport within the Georgia-Fuca system. Although controlled by the same physical processes, the basins differ markedly in their integrated responses to the major forcing mechanisms.

STRAIT OF GEORGIA

Basin Geometry

Of the major basins within the Georgia-Fuca system, the Strait of Georgia is probably the most difficult to characterize. The basin's large areal extent and convoluted network of islands and shallow tidal passes, combined with a major year-round source of freshwater

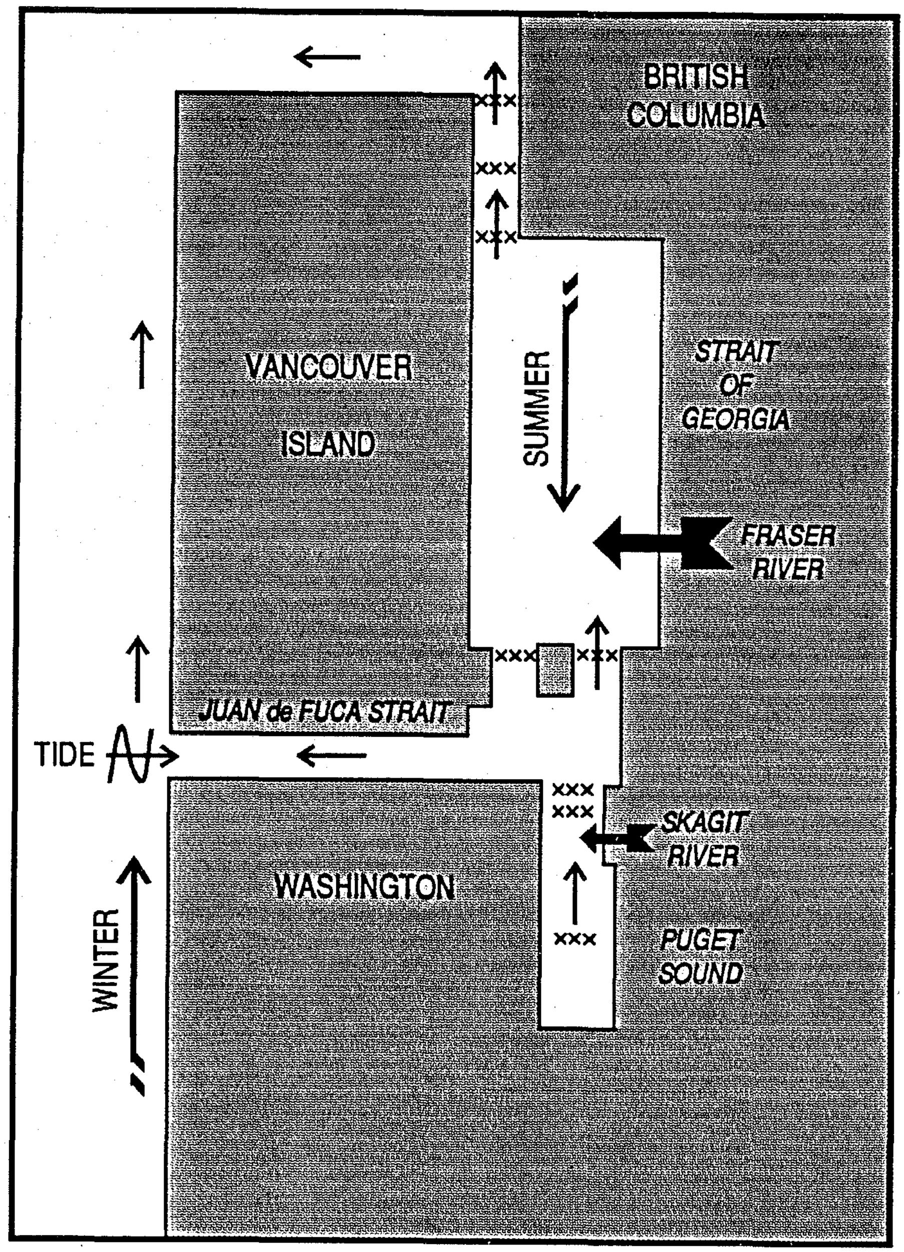


Figure 2. A simplified box model of the Georgia-Fuca system showing the locations of the major sills (xxx), direction of mean surface flow (→), locations of major rivers (large arrows) and direction of the prevailing winds (barbed arrows) that most strongly affect the southern portion of the inland waterway.

(the Fraser River), relatively large tidal range and marked seasonal cycle in the prevailing winds, give rise to complex flow dynamics and water property structure. Limiting the present discussion to the southern portion of the strait only partially alleviates the problem since the oceanography of this sector of the strait is notoriously difficult to decipher. Reviews specific to this region can be found in Waldichuk (1957), Thomson (1981), LeBlond (1983), and Crean et al. (1988).

The Strait of Georgia is a 222 km long, 20 to 40 km wide, partially-mixed estuary extending from about 48°44′ to 50° north latitude. The strait covers a surface area of roughly 6,800 km^2 and has an approximate volume of 1,050 km^3. Depths average 155 m, with only 5% of the strait having depths in excess of 360 m. The maximum water depth of 420 m is located immediately south of Texada Island in the central portion of the strait (Figure 1). The northern boundary of the strait terminates in a series of narrow channels with the main channel, Discovery Passage, having a moderately deep (100 m) sill. Flood currents entering the northern strait from Discovery Passage are noted for their strong jet-like flows and heavy tidal rips (Thomson 1981).

The southern boundary of the strait is defined by the shores of the San Juan-Gulf Islands and a group of narrow tidal channels. In order of descending importance, these are: Haro Strait, Rosario Strait and Middle Passage. Haro Strait is a vigorous tidal channel characterized by strong vertical and lateral current shears. Especially turbulent flow can be found in the vicinity of Boundary Passage at the northern end of Haro Strait where the well-mixed waters of the strait interact with those from the Strait of Georgia in the vicinity of a topographically convoluted sequence of sills. On the western side of the passage, the flow is partially blocked by a shallow (60 m) finger-like sill which terminates in a 295 m deep "hole" in the central portion of the channel. The curved ridge-like sill protruding into the Strait of Georgia to the north of this deep hole gives an apparent sill depth for Boundary Passage of 200 m. However, the true effective sill depth for flow into the Strait of Georgia is found 11 km to the southwest along Haro Strait, where a 2.5 km wide sill extends across the entire channel at a typical depth of 90 m (Table 1). Effective sill depths in Rosario Strait and Middle Passage are ≈50 m. Flows in these channels are weaker than those in Haro Strait. Examination of the cross-sectional areas of all channels leading into the Strait of Georgia reveals that southern channels account for 93% of the cross-sectional area and northern channels only 7% (Thomson 1981).

TABLE 1

Some characteristic features of the three main basins of the Georgia-Fuca system.
HS = Haro Strait; RS = Rosario Strait; AI = Admiralty Inlet; V-GP = Victoria-Green Point.

	Strait of Georgia	*Puget Sound*	*Juan de Fuca Strait*
Type of estuary	Partially-mixed	Partially-mixed	Well-mixed
Area (km^2)	6,800	2,330[a]	3,700
Volume (km^3)	1,050	169[a]	402
Mean depth (m)	155	62[d]	200
Maximum depth (m)	420 Texada Is.	284[d] Pt. Jefferson	300+ (at mouth)
Yearly Mean Runoff (m^3/s)	5,800[b]	2,200[b]	500[b]
Drainage Area (km^2)	286,890[b]	40,327[b]	7,420[b]
Sill Depths (m)	90 (HS); 50 (RS)	65; 105 (AI)	130 (V-GP)
Basin flushing time, summer	50–75 days	120–140[c] days	30–60 days
Basin flushing time, winter	100–200 days	120–140[c] days	30–60 days
Transport ($\times 10^6$ m^3/s)	variable/ill-defined	0.01–0.10	0.10–0.90

[a] Puget Sound mean lower low water (Lavelle et al. 1988)
[b] LeBlond et al. (1983)
[c] R. Macdonald (pers. comm. 1994)
[d] McGary and Lincoln (1977)

Oceanographic overview

The oceanography of the southern Strait of Georgia is strongly influenced by surface freshwater discharge from the Fraser River, by intermediate-to-deep water intrusion of partially-mixed high salinity oceanic water from Haro Strait, and by the strength and direction of prevailing surface winds. In addition to driving the estuarine circulation, the Fraser River provides significant nutrient and contaminant loads to the upper portion of the Georgia-Fuca system. Roughly 2.4% of the nutrient load comes from the Fraser River while most of the remaining load (96.6%) originates with coastal upwelling over the continental margin (Harrison, this volume). The twelve monthly basin-wide surveys conducted during 1967 by Crean and Ages (1971) remain the best set of "simultaneous" hydrographic data yet collected for the region (Figure 3). In winter, intense cooling can lead to strong vertical convection and a near homogeneous upper layer (Figure 3A and C). In summer, the upper layer of the strait becomes highly stratified through the influence of freshwater runoff and solar heating (Figure 3B and D).

According to LeBlond (1983), the "Fraser River plume is the showpiece of the Strait of Georgia. Strikingly colored by its suspended sediment load it presents to the aerial observer a pattern of spreading river influence, in milky, brown and green hues." The plume is especially prominent in summer during freshet when it forms an extensive sediment-laden layer 2 to 10 m thick that spreads over much of the southern strait. Solar radiation absorbed by this layer tends to increase the density contrast of the plume with the underlying water and enhance its ability to "slip" over the oceanic water like a decoupled slab (Thomson 1981). The opacity of the layer also affects the surface biological productivity of the strait by reducing the thickness of the euphotic zone. Satellite imagery commonly shows the plume piling up in the southern strait under the influence of prevailing summer northwesterly winds (Figure 4). At other times the plume turns directly northward with the flood or may "jet" directly across the strait toward the Gulf Islands (Giovando and Tabata 1970). Surface manifestations of large amplitude (>10m) internal gravity waves formed over the sills at Active Pass and Boundary Passage during the flood can be seen to travel slowly up-strait in complex "megaripple" patterns. One also can anticipate the formation of internal oscillations of tidal semi-diurnal frequency since the internal deformation radius is typically about 10 km. Rotational and seasonal effects on stratification will modulate the vertical structure of these waves.

A description of deep water renewal in the Strait of Georgia was first presented by Waldichuk (1957) who suggested that in summer, relatively warm, low salinity outflow on the surface mixes with high salinity deep intruding water to form an intermediate-depth layer that then penetrates into the Strait of Georgia. In winter, cold but relatively low salinity near-surface water was thought to mix with the deep salty water to form a deep inward penetrating layer in the strait. At all times, water leaving and entering the system is made up of waters originating from both the Strait of Georgia and Juan de Fuca Strait. According to Samuels (1979), deep-water replacement in the strait is more nearly a continuous process, with occasional intensification, rather than an intermittent process with occasional strong overturns. LeBlond (1983) states that "Deepwater renewal in the Strait of Georgia should be viewed as an ongoing process, part of the return flow of the estuarine circulation, which occasionally penetrates to greater than usual depths because of varying water conditions at the well-mixed extremities of the Strait." Most of the intrusion comes through Haro Strait. Studies of turbulent mixing in Haro Strait and other tidal passes in the region in winter have been conducted by Ann Gargett using a narrow-beam acoustic Doppler current profiler and microscale probe (Gargett 1988). Additional research on the mixing characteristics of the Georgia-Fuca system is continuing.

The intruding waters at either end of the Strait of Georgia may also effect a net circulation within the strait. Crean et al. (1988) argue that the mixed water intruding at depth in the north tends to favor the western side of the strait while the deeper water intruding northward from Haro and Rosario straits tends to favor the eastern side of the strait. The net effect is a counter-clockwise mean circulation within the lower layer of the Strait of Georgia. In the upper layer, both observations and numerical modeling indicate the presence of a counterclockwise eddy to the north of Boundary Passage. Such an eddy will obviously affect transboundary transport in the southern Strait of Georgia (Figure 5).

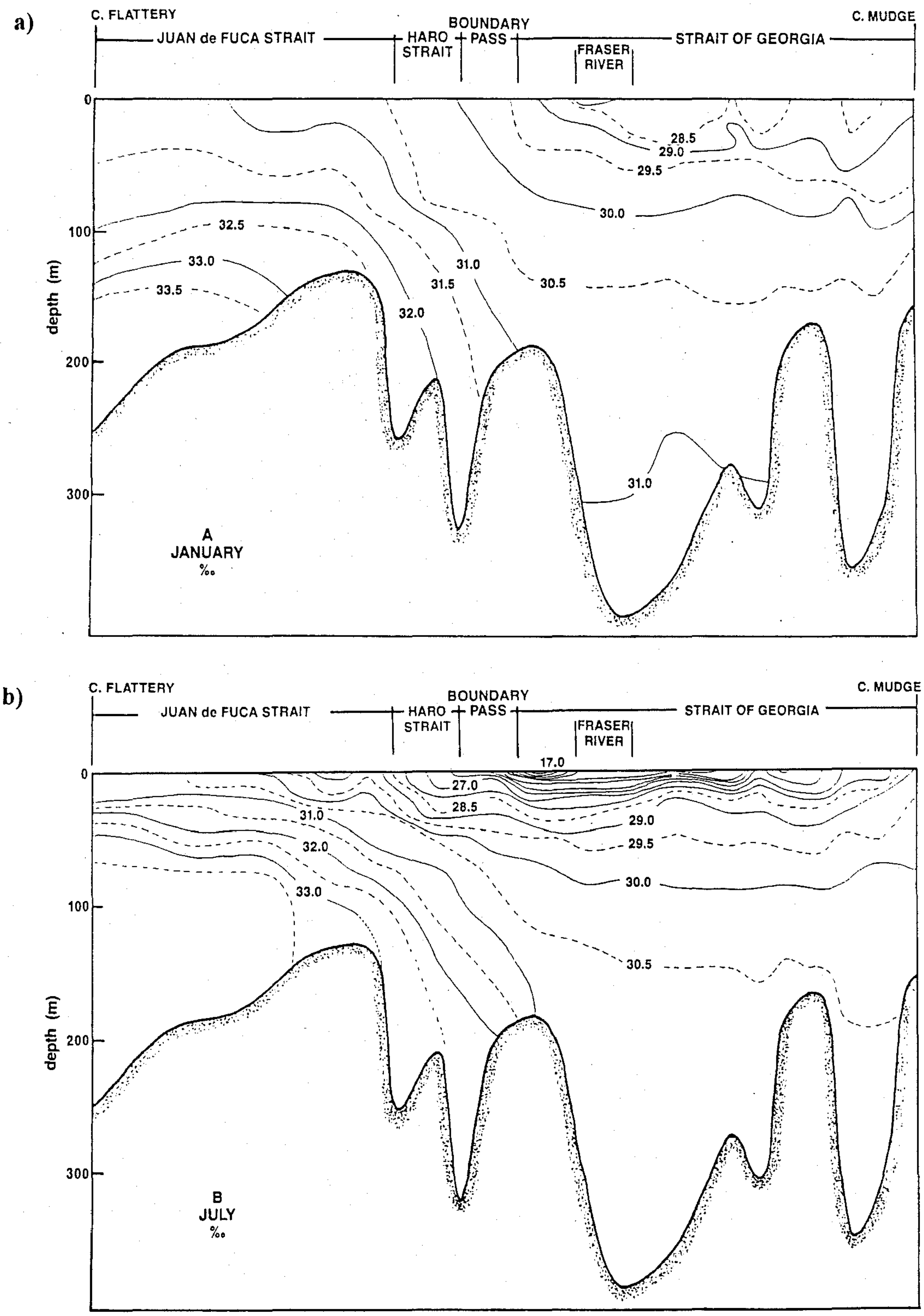
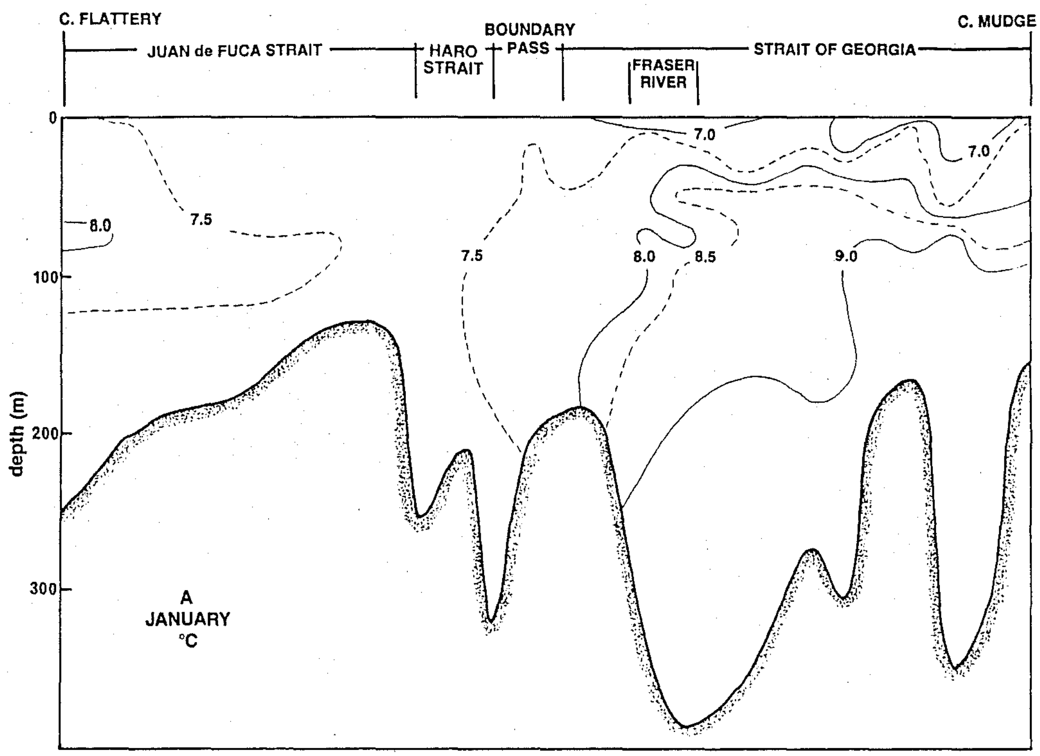


Figure 3. Cross-sections of temperature (°C) and salinity (‰) for the Georgia-Fuca system from the entrance to Juan de Fuca Strait to the northern end of the Strait of Georgia. A. winter temperature; B. summer temperature; C. winter salinity; D. summer salinity. (Adapted from Thomson 1981)

c)



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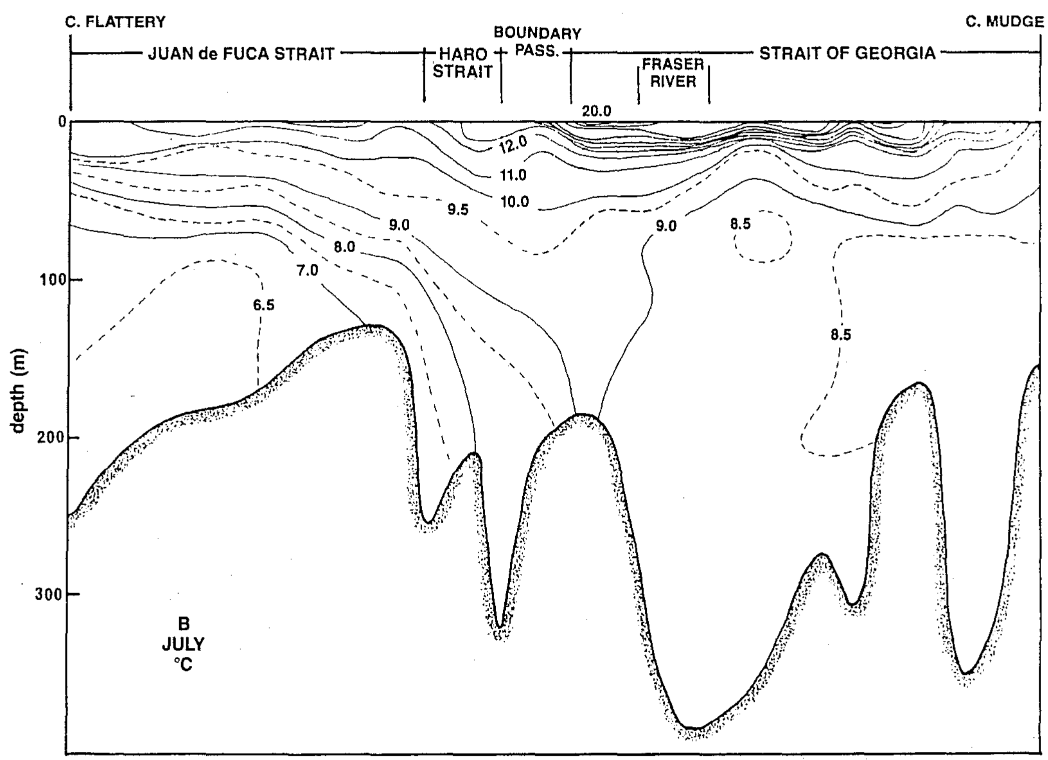


Figure 3. *Continued*

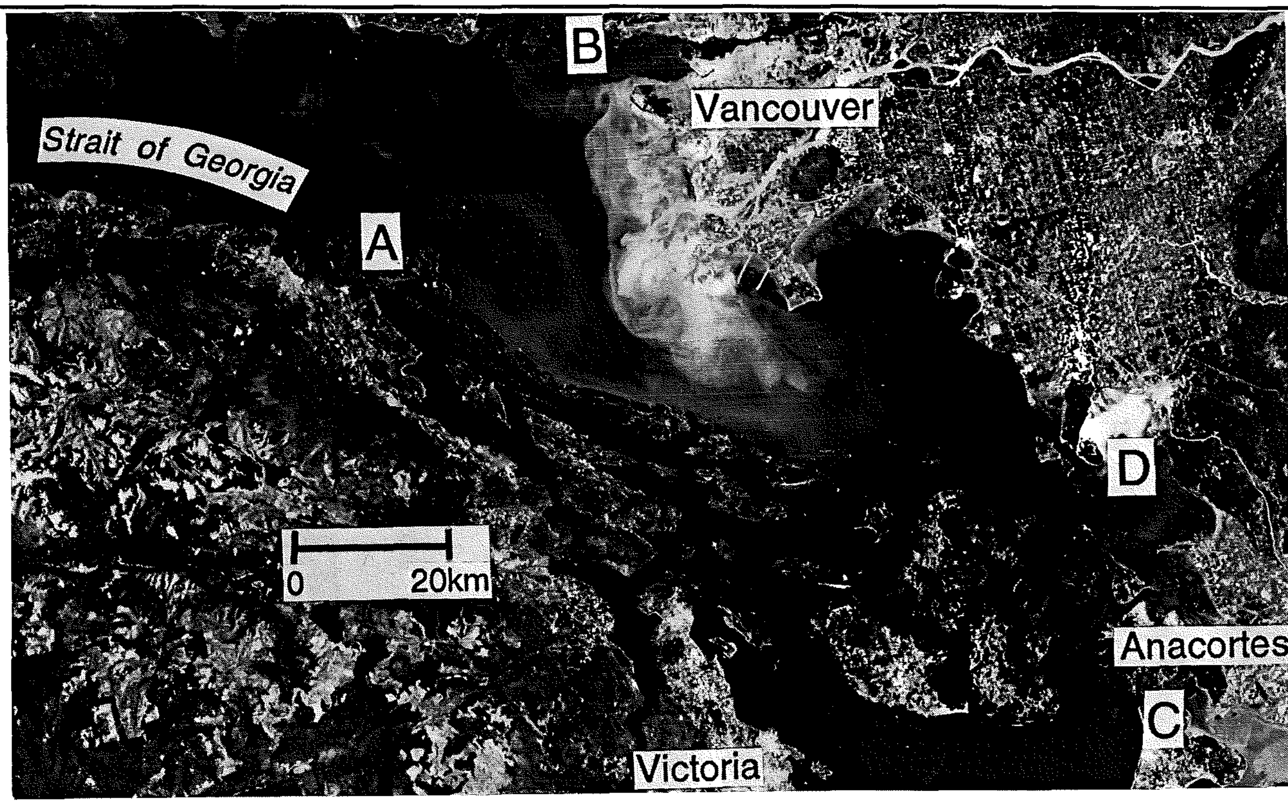


Figure 4. Landsat image for July 20, 1974 showing the surface movement of the Fraser River and Skagit River sediment plumes. (From Thomson 1981)

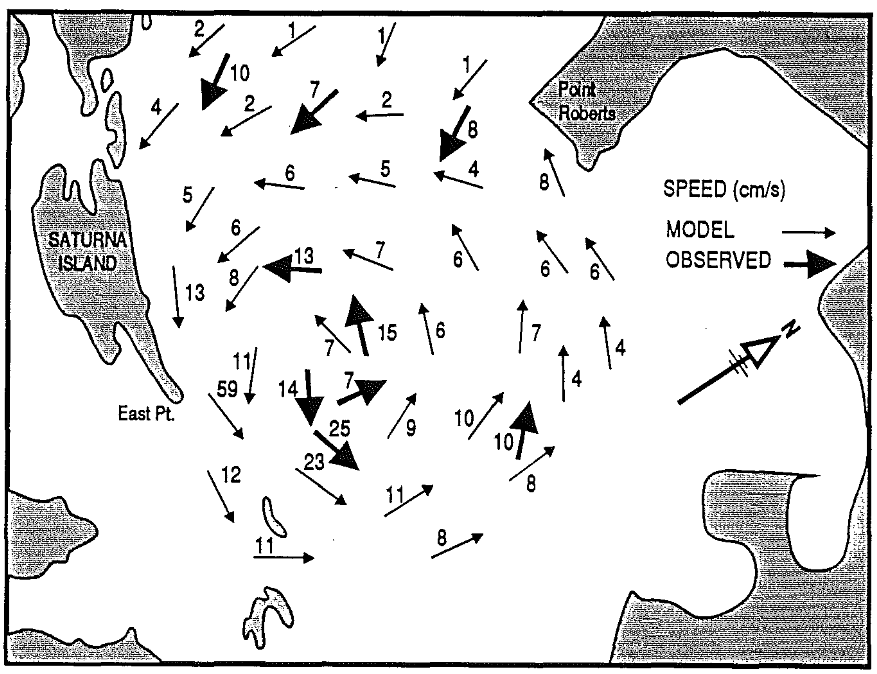


Figure 5. Plot of residual (non-tidal) currents at the southern end of the Strait of Georgia, north of Boundary Passage. Thin arrows are from a depth-averaged numerical model; thick arrows are from current meter observations. Numbers give speeds in cm/s. (From Crean et al. 1988)

A recent study by LeBlond et al. (1991) has helped to clarify the deep-water renewal process in the Strait of Georgia. The model by Waldichuk (1957) is only partially correct. Using historical water property data as well as cyclesonde current meter records from a grid of stations in the central strait from 1984 to early 1985, LeBlond et al. (1991) conclude that only *summertime* replacement consistently reaches the lower layers of the strait. Wintertime replacement generally is confined to intermediate depths but can on occasion penetrate to lower layers of the strait. At best, deep wintertime replacement is episodic. Relative to the ambient water, the wintertime signal at 150 to 200 m depth is characterized by low temperatures, slightly lower salinities and an increasing trend in dissolved oxygen, consistent with recent exposure of the water mass to the atmosphere. Formation of the intermediate water mass takes place through winter cooling and tidal mixing in the southern strait. In contrast, the coherent warming of the deep (250–350 m) waters in summer is associated with a continuing decrease in oxygen and increase in salinity, suggesting the penetration of dense bottom water from Juan de Fuca Strait, as described by Waldichuk (1957). Figure 6 is my attempt to revise Waldichuk's figures using the results of LeBlond et al. (1991) together with data I collected through a contract with Arctic Sciences Ltd. (Sidney). The latter study documented deep intrusions into the southern Strait of Georgia from June 1989 to September 1990 by recording temperature, salinity and currents at selected along-channel sites from the eastern Juan de Fuca Strait to the southern-central portion of the Strait of Georgia (Richard Birch, unpublished report).

Assuming an average salinity of 33.8‰ for seawater entering the Georgia-Fuca system, the volume of freshwater in the Strait of Georgia computed by Waldichuk (1957) ranged from 11% for January 1949 to 23% for August 1950. This freshwater volume in the strait is equivalent to about 1.3 years of discharge from the Fraser River for the given oceanic salinity value. Using water property data collected in July 1968 and time-averaged results from a three-dimensional numerical model for the region, Crean et al. (1988) obtain a freshwater concentration of 15% for the region. The net freshwater outflow from the Strait of Georgia was 0.72 km^3/day for July 1968. If this value were sustained, it would take 1.4 years to the replace the volume of freshwater in the overall system at the mean flow rate of the Fraser River. The model computation also shows that 83% of the freshwater leaves through Juan de Fuca Strait and the remaining 17% through Johnstone Strait. Thus, the relative importance of the northern channels is somewhat greater than would be expected based on their cross-sectional area.

England and Thomson (1994) have used a series of empirical tidal prism models to estimate seasonal flushing times for the Strait of Georgia-Juan de Fuca Strait system. These models include the Tidal Prism (salinity) Model (Ketchum 1951), the modified Tidal Prism Model (Ketchum and Keen 1953) and the Segmented Prism Model (Dyer and Taylor 1973). In each case, the system is divided into segments. For each segment, fractional changes in freshwater and oceanic water are used to compute replacement times. The early Ketchum model uses mean observed salinities over specified depth ranges to estimate the degree of mixing, whereas the later models deal with tidal ranges and specified mixing-depths. In all models, the flushing times are inversely proportional to the river discharge and directly proportional to the downstream rate of exchange of freshwater between segments. Results are variable, highly dependent on assumptions made about the mixing process and somewhat inconsistent from model to model. However, some general conclusions can be made. In particular, river discharge is a dominant factor in determining the rate of basin flushing (Figure 7) and basin-scale flushing times in winter are considerably longer than in summer mainly because of the lower winter runoff rates. Characteristic flushing rates are 100 to 200 days for winter and 50 to 100 days for summer. The shorter time scales for the summer estimates are close to those of LeBlond et al. (1991) who estimate summer replacement times below 250 m depth of 26 days based on an average volume flux from Boundary Passage by deep intrusions of 0.046×10^6 m^3/s.

PUGET SOUND

Basin Geometry

Puget Sound is the southern-most, glacially-carved fjord-like estuary on the west coast of North America. Located 135 km from the Pacific Ocean and covering an area of 2,632 km^2 at mean high water, the Sound is a partially-mixed estuary comprised of several basins and interconnecting channels with an approximate length of 165 km and a highly variable width ranging up to

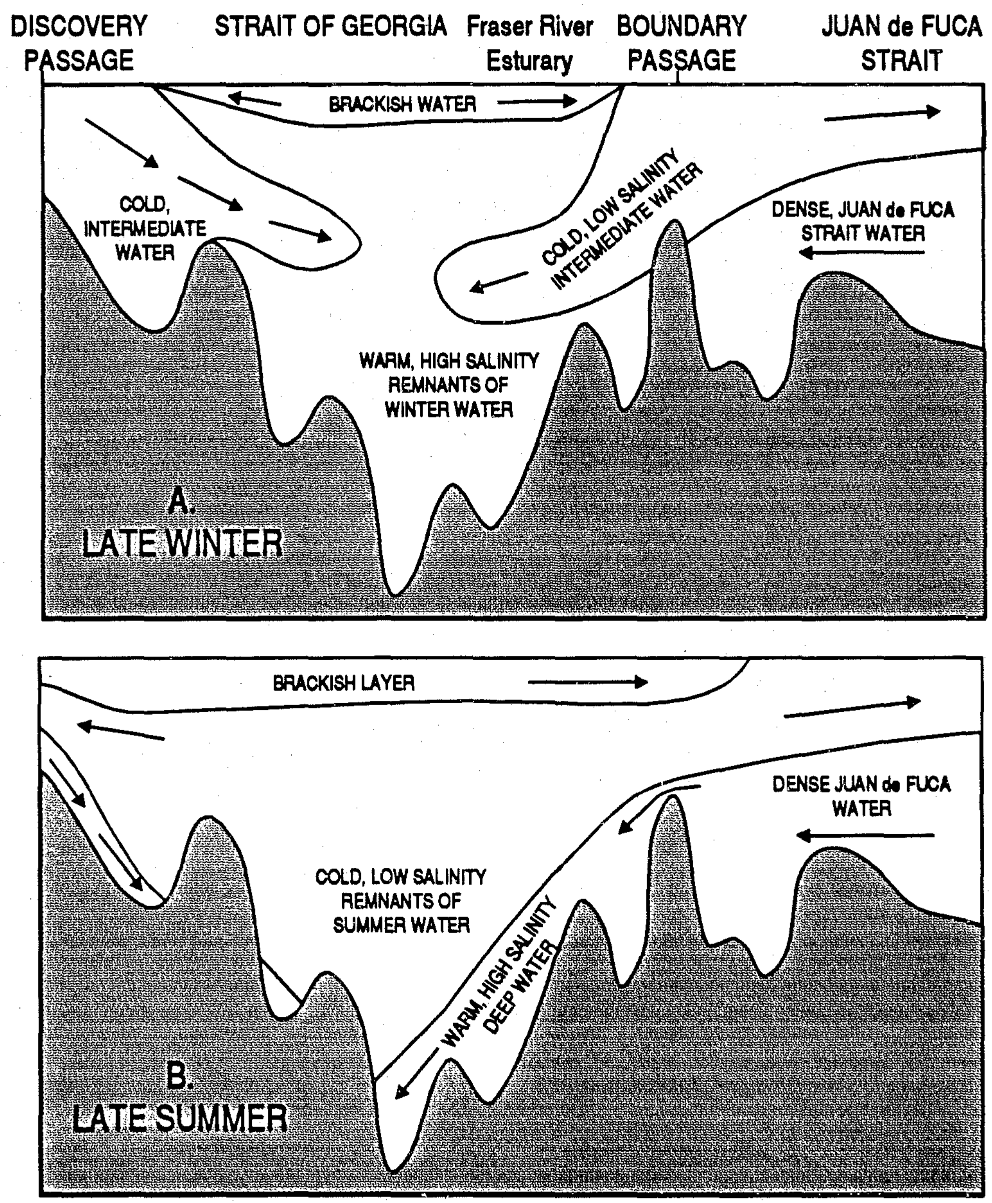


Figure 6. Revised model of (A) winter and (B) summer deep-water intrusions into the Strait of Georgia based on Waldichuk (1957), LeBlond et al. (1991) and observations conducted by author with Arctic Sciences Ltd. during 1989 and 1990.

about 10 km (Figure 1). Puget Sound has a shoreline length of 2,143 km and a total volume of 168 km^3 below mean high water. The main basin has depths exceeding 200 m and extends 75 km from the entrance to Admiralty Inlet to The Narrows near the city of Tacoma. The mean depth is 62 m and a maximum depth of 284 m is found off Point Jefferson. The entrance sill at Admiralty Inlet is 30 km long and is made up of an outer (65 m) sill and inner (105 m) sill separated by a deeper area (Cannon et al. 1990). A 45 m sill separates the main basin from a fairly extensive southern basin. Approximately two-thirds of the water column in the main basin lies below the depth of the shallower sill in Admiralty Inlet. The two other major branches of Puget Sound are Hood Canal, extending southwest from Admiralty Inlet, and the series of basins lying to the east of Whidbey Island which connect with Juan de Fuca Strait through Deception Pass. About 98% of the tidal prism flows through Admiralty Inlet and only 2% through Deception Pass.

Oceanographic Overview

The total freshwater inflow into Puget Sound is roughly 10–20% of that entering the Strait of Georgia. Most of the inflow (60%) is from the Skagit River which enters the Sound in the extreme northeast corner, roughly 13 km from the entrance to Deception Pass. About 50% of this freshwater is thought to enter the main basin of Puget Sound while the remainder is thought to work its way through Deception Pass into Rosario Strait (Barnes and Ebbesmeyer 1978). Stratification is greatest in summer due to the combined effects of river discharge and solar heating; it is least in winter as a result of winter cooling and increased wind mixing (Figure 8). Tide heights and tidal currents in Puget Sound are mixed, mainly semi-diurnal with maximum tidal elevations occurring in the southern basin of the Sound and maximum flows in Admiralty Inlet. (For an excellent summary of observed and modeled tidal elevations for the region, the reader is referred to Lavelle

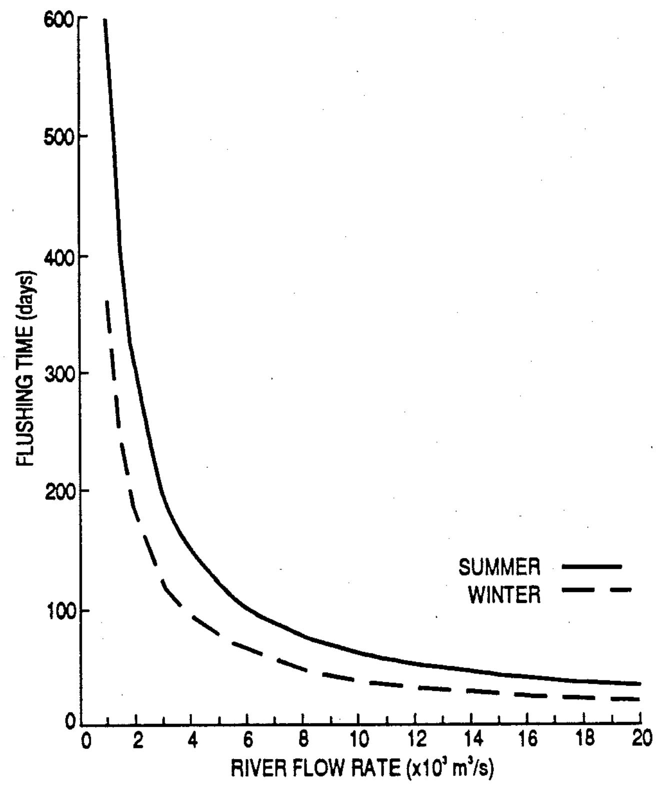


Figure 7. Basin-scale replacement times (days) for the Strait of Georgia and Juan de Fuca Strait for summer and winter oceanic conditions for variable Fraser River discharge rates (in units of 1000 m^3/s). Based on the salinity tidal prism model of Ketchum (1951). (From England and Thomson, in preparation).

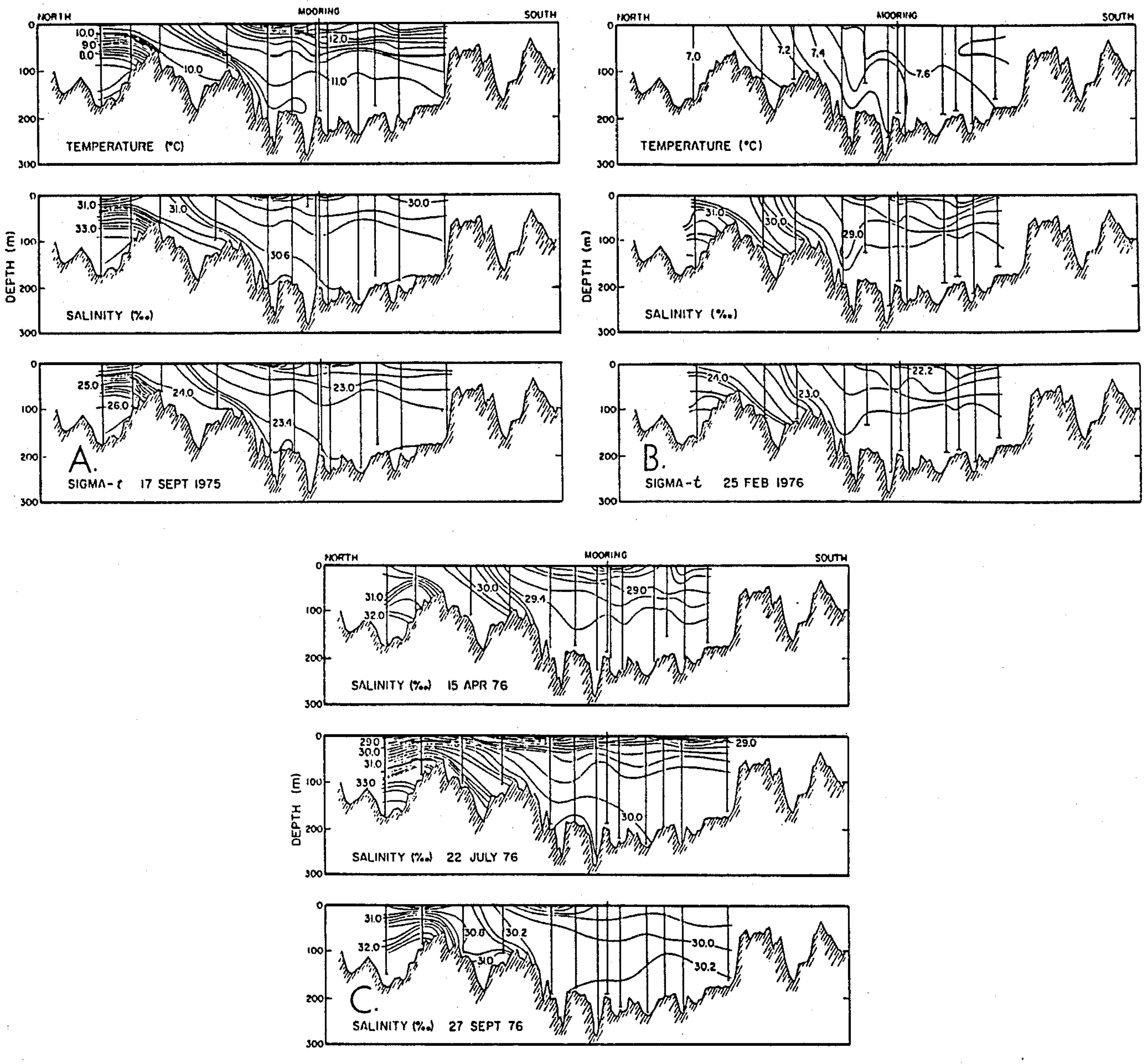


Figure 8. Cross-sections of temperature (°C), salinity (‰) and density (sigma-t) for the main basin of Puget Sound. (A) Late summer (September 17, 1975); (B) mid-winter (February 25, 1976); (C) Salinity for spring to fall 1976 (From Cannon et al. 1990)

et al. 1988.) The energetics of nontidal (residual) flow variability are dominated by winds (50%). Intrusive events account for about 20% of the residual energy.

Tidal motions over the shallow sills in Admiralty Inlet maintain a vigorous two-layer vertical circulation with a *null-velocity* depth (the depth of zero mean flow) somewhere near the sill depth (Ebbesmeyer and Barnes 1980; Mofjeld and Larsen 1984). North of Seattle, the estuarine circulation mainly consists of outflow in the upper layer and inflow at depth. Owing to the particular geometry of the region and to the impact of outflow from The Narrows, mean flows are mainly northward on the west side of Vashon Island and southward on the east side (Cannon et al. 1990). Transports in both the upper and lower layers of the main basin of the sound are in the range 0.01 to 0.10 × 10^6 m^3/s. Ebbesmeyer et al. (1989) have regressed the mean (28-day average) along-channel vertical current shear ($\partial v/\partial z$) over the depth range 0 to 90 m against the corresponding surface current (v_o) for selected periods from 1972 to 1979 for observations in the main basin of the Sound (Figure 9). The slope of the regression line in Figure 9 gives the mean null-velocity depth, z_o = 55.8 ± 12.5 m. At this depth, the estuarine flow changes from outflow to inflow.

Episodes of deep water renewal by denser water intruding over the outer sill can occur throughout the year with the most dense intrusions occurring in early fall (Cannon and Laird 1978). Marked fortnightly fluctuations in the intrusions are attributed to the degree of turbulent tidal mixing over the entrance sills and the neap-spring cycle in the tidal currents (Geyer and Cannon 1982). Observations by Cannon et al. (1990) have shown that the deep water intrusions into the main basin — which occur during neap tides when mixing over the sill is at a minimum and gravitational circulation can develop — are strongly modified by salinity (density) changes at the entrance to Admiralty Inlet. The salinity changes are brought about by propagation

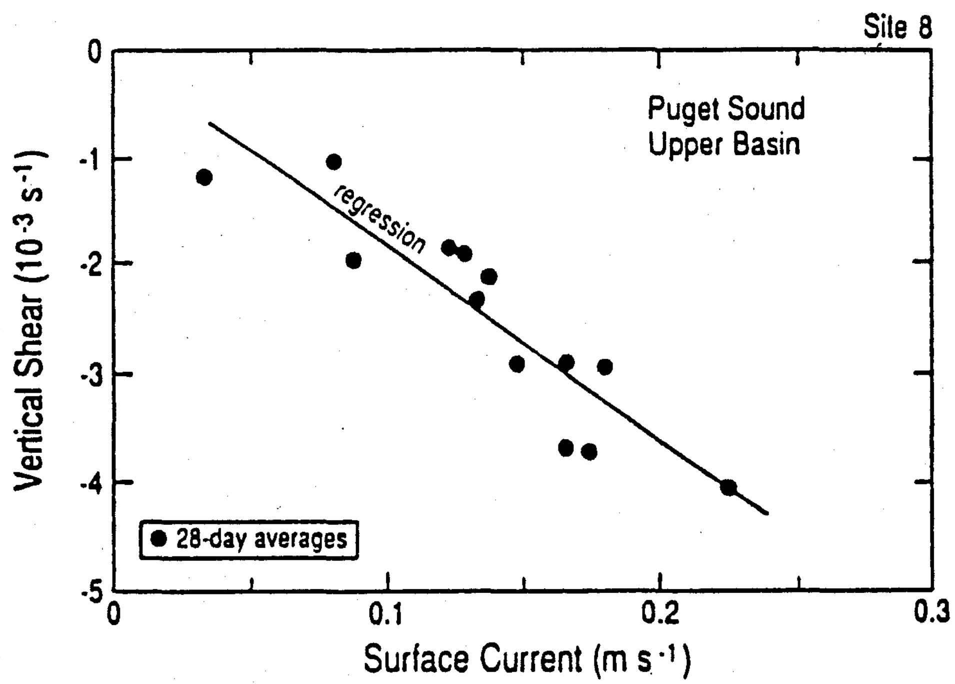


Figure 9. Regression of mean (28-day average) along-channel vertical current shear over the depth range 0 to 90 m against the corresponding surface current speed for selected periods from 1972 to 1979 at site 8. The slope of the regression line of 55.8 ± 12.5 m represents the mean null-velocity depth. At this depth, the estuarine flow changes from outflow to inflow. Site 8 is in the middle of the main basin near Seattle. (From Ebbesmeyer et al. 1989)

along Juan de Fuca Strait of wind-induced offshore oceanic influences. Water below sill depth is replaced roughly once per month, a rapid circulation compared with other coastal fjords where water may remain below sill depth for years (Ebbesmeyer and Barnes 1980). In winter, deep and intermediate water replacement is quite rapid and occurs within a period of about two weeks (Cannon et al. 1990).

In addition to the well-known seasonal cycle in the estuarine circulation of the Georgia-Fuca system, Ebbesmeyer et al. (1989) have found strong correlations between low frequency variability in the North Pacific meteorology and decadal scale (10 to 20 year) variability in the water temperatures and estuarine flow into the main basin of Puget Sound. This important aspect of the flow is discussed in more detail in a later section. Cannon et al. (1990) note the importance of up-strait propagation of salinity variations and their effect on deep-water intrusions into Puget Sound. The cross-sill salinity differences are very large (2‰) and affect the depth and strength of the deep intrusions into Puget Sound where near-bottom intrusion speeds can reach 10 to 20 cm/sec.

Juan de Fuca Strait

Basin Geometry

Juan de Fuca Strait is a 160 km long, U-shaped estuary with a surface area of 3,700 km^2, an overall volume of 402 km^3, and mean depth of around 200 m. The width of the strait varies from 22 km over the first 100 km from the mouth to greater than 40 km over the remaining 60 km to the eastern boundary (Figure 1). The "outer strait" gradually forms a V-shaped channel that reaches depths of over 300 m at its seaward entrance (Thomson 1981). Juan de Fuca Strait is classified as a weakly-stratified, positive estuary with strong tidal currents (Holbrook et al. 1980a). The western end of the strait is influenced by oceanic processes over the adjacent continental shelf while the eastern end of the channel is modified by intense tidal motions occurring through, and near, the entrances to the numerous tidal passages. Seasonal extremes are relatively small in this basin and waters are vertically well mixed. Crean et al. (1988) estimate a freshwater concentration of about 7% for the strait. The irregular Victoria-Green Point sill stretching southward from Victoria is the single major topographic obstruction to deep flow in the channel. The sill depth is about 100 m but there is a narrow 130 m channel through the sill on the United States side of the mid-strait boundary.

Oceanographic Overview

The distributions of temperature, salinity, density and dissolved oxygen in Juan de Fuca Strait are described by Herlinveaux and Tully (1961) and Crean and Ages (1971). Data from these studies show that there are only minor seasonal changes in the density distribution during the year. In particular, the near-surface layer becomes moderately stratified in summer whereas the lower layer below about 75 m depth remains weakly stratified year-round. Estuarine circulation in Juan de Fuca Strait consists of a seaward surface flow of relatively fresh water in the upper layer and a landward flow of more saline oceanic water at depth. Fresh water enters mainly through the Strait of Georgia from the Fraser River during the spring and from streams along Vancouver Island during the winter. The fresh water input maintains the normal estuarine circulation by setting up a longitudinal sea surface slope and internal density gradients (Holbrook et al. 1980a).

Surface up-strait intrusions of relatively warm, high salinity coastal Pacific water are observed in Juan de Fuca Strait under certain conditions in the winter and, rarely, in the summer (Frisch et al. 1981). These density intrusions result in a reversal in the direction of the long-strait residual (non-tidal) currents within the strait so that surface flow becomes landward and deep flow becomes seaward (Cannon 1978; Holbrook and Halpern 1982). Observations indicate that these flow reversals are initiated by northward winds associated with storms passing over the coasts of Washington State and Vancouver Island. The onshore Ekman transport produced by these winds increases the coastal sea level elevation and decreases the longitudinal sea surface slope in the strait, leading to a deceleration of the seaward component of flow. Southerly winds can force low salinity Columbia River water into the entrance to the strait which then hugs the United States side of the channel. Low-frequency variability at the entrance to the strait possibly involves a coupling between wind-induced shelf waves on the outer coast and standing baroclinic modes at the entrance to the strait (Proehl and Rattray 1984). During summer, the surface flow and density also can be modified through fortnightly

variability in the freshwater outflow from adjoining basins (LeBlond et al. 1994). In this case, modulation of the outflow is regulated primarily by hydraulic control associated with the spring-neap cycle in tidal mixing at the tidal passes joining Juan de Fuca Strait to the Strait of Georgia.

Holbrook et al. (1980b) estimate that diurnal and semi-diurnal tidal currents account for most (65 to 88%) of the long-strait variance, although significant variance (27%) also was observed at subtidal frequencies in the winter. They further observed that the current variance at low-frequencies was much lower in the summer than in the winter for the western portion of the strait. Holbrook et al. (1980b) and Proehl and Rattray (1984) found that subtidal motions were highly correlated with the large-scale coastal wind forcing rather than with local wind forcing.

Labrecque et al. (1994) show that geostrophy dominates the dynamic balance for the long-strait component of residual (non-tidal) flow. They "geostrophically leveled" pairs of tide gauges on either side of the strait relative to a geopotential surface and demonstrated that there is a linear relationship between the long-strait surface flow and the cross-strait sea surface slope. This relationship arises from the near-geostrophic balance of along-channel residual currents in the main body of the strait. The frequency-dependent structure of the flow variability in the strait also was examined. Calculation of the amplitude ratio and phase difference between shallow and deep currents revealed a weakly frequency-dependent current variability with depth, suggesting that the along-strait flow was baroclinic (density-dependent) within all subinertial frequency bands.

Because of the regularity of the channel, well-mixed nature of the water column, and absence of shallow sills, the flow structure of Juan de Fuca Strait is considerably less complex than that of the other two basins. Estuarine flow typically consists of net outflow in the upper 75 to 125 m depth range and net inflow beneath (Figure 10). Results from current meter measurement

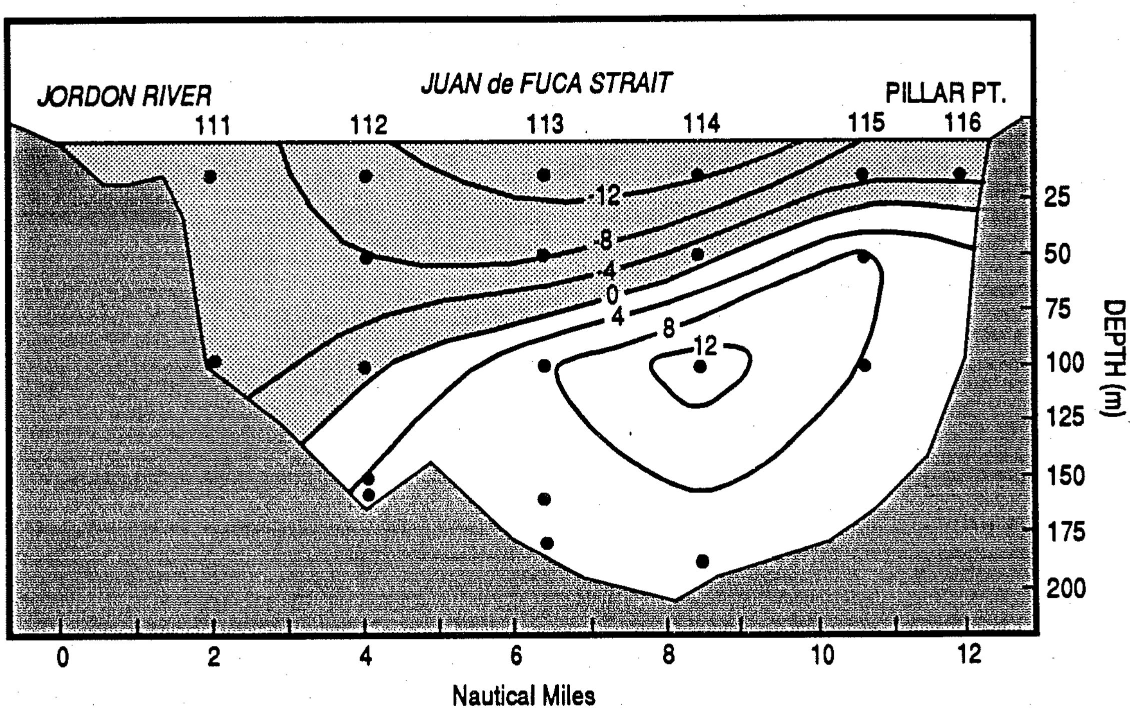


Figure 10. Cross-section of residual along-channel flow in the central portion of Juan de Fuca Strait for the period 6 March–14 June 1973 (speeds in cm/s). The view is up-strait toward the east. Negative values (shaded) are seaward and positive values are landward. The transport in each layer is about 0.1×10^6 m^3/s. (Adapted from Godin et al. 1980)

programs indicate that the null-velocity level slopes downward toward the Canadian side of the channel (greater outflow on the Canadian side, greater inflow on the United States side) and that the net transport in the upper layer is time-variable, but is typically greater than 0.1×10^6 m^3/s. Using data from a string of current meters moored across the strait from Jordan River to Pillar Point from April and May, 1973, Godin et al. (1980) found that the daily-averaged flows in the upper and lower layers ranged from approximately 0.09 to 0.16×10^6 m^3/s while the net flows (totals for the counter-flowing upper and lower layers) was $\pm 0.02 \times 10^6$ m^3/s. Similar data were collected during a 51-day field program from 26 May to 15 July, 1975 across a section of Juan de Fuca Strait from Sheringham Point to Pillar Point (Fissel 1975; Fissel and Huggett 1976) and during the summer of 1984 at the entrance to the strait (Thomson et al. 1989; Hickey et al. 1991). Estimated magnitudes of the volume transports in both the upper and lower layers of the channel were 0.25×10^6 m^3/s at the mid-strait section and 0.15×10^6 m^3/s at the outer section (Labrecque et al. 1994). The upper layer transport of 0.25×10^6 m^3/s observed through Juan de Fuca Strait greatly exceeds the upper layer transport of 0.03×10^6 m^3/s observed through Johnstone Strait (Thomson 1977) and the much smaller discharge of 1.22 m^3/s from the combined Victoria sewage outfalls (Table 2). Note that roughly 88% of the combined surface outflow from the Strait of Georgia is through Juan de Fuca Strait, which is close to the 93% estimated on the basis of channel cross-sectional area alone.

PRIMARY FORCING MECHANISMS

The discussion in the previous section alluded to a few of the main geographical and oceanographic features of the three main basins of the Georgia-Fuca system. In this section, the common mechanisms forcing the circulation of the region are considered in more detail.

Estuarine Currents

The Fundamental Driving Mechanism

Although the details of the estuarine flow structure vary in time and space, the basic driving mechanism remains the same. Runoff provides the hydraulic head (pressure gradient) to drive the surface layer seaward. If this thin layer of fresh water were able to "slip" unimpeded over the underlying oceanic water, all the fresh water entering the system would eventually work its way to sea with little or no interaction with the underlying oceanic regime. In reality, there is considerable turbulent mixing between the two regimes and entrainment of salty water into the surface layer leads to the removal of salt from the lower layer. This alters the along-channel density and pressure gradients in both layers to produce the classic estuarine circulation consisting of a net (daily-averaged) seaward outflow of brackish water in the upper portion of the water column and a net landward inflow of salty water in the lower portion of the column (Figure 11). Clearly, the two-way depth-dependent estuarine flow is needed to maintain a steady-state salt balance within the waterway. This process is so robust that observed along-channel changes in the salinity structure can be used to infer the flushing rates of the basins (Ketchum 1951).

The dominant contributor to the fresh water flux in the Georgia-Fuca system is the Fraser River. The river drains approximately 217,300 km^2 of the province of British Columbia and discharges over a large flood plain near the Canada-US border south of Vancouver (Figure 1). The Fraser River discharge can vary from less

TABLE 2

Volume discharges for the Victoria Sewage Outfalls for 1992. To convert to units of m^3/s multiply by 1.157×10^{-5}. Discharge is strongly related to rainfall; minimum discharge is in the summer months and maximum in the winter months. The last column is the annual average. Discharge takes place at depths of 60 and 65 m. (Courtesy Laura Taylor, Capital Regional District, Victoria).

Outfall Site	*Min ($\times 10^3$ m^3/day)*	*Max ($\times 10^3$ m^3/day)*	*Mean ($\times 10^3$ m^3/day)*
Macaulay Point	31.9	121.8	40.7
Clover Point	41.6	168.3	60.9

than 1000 m³/s in winter to more than 10,000 m³/s at the peak of the freshet in late spring. This river alone accounts for about 80% of the mean annual freshwater discharge of 4,400 m³/s into the Strait of Georgia. Considerably lower flow volumes for the Georgia-Fuca system are provided by secondary rivers such as the Skagit River which flows into northeastern Puget Sound and the Squamish River which flows into Howe Sound near the central portion of the Strait of Georgia (LeBlond et al. 1983). As indicated by Table 1, the annual discharge into the Strait of Georgia is several times that for the other major basins. For all rivers entering the Georgia Depression, runoff is maximal during spring (Figure 12), when there is peak snowmelt from the inland mountain ranges, and during early winter with the arrival of moisture laden storms and heavy precipitation along the coast.

Basic Water Property Structure

The background water property structure in the Georgia-Fuca system is closely linked to the estuarine circulation and consists of relatively warm, low salinity, low density water in the upper portion of the water column and relatively cold, high salinity, high density water in the lower portion of the water column (Figures 3, 8). At a given depth, temperatures tend to decrease along-axis in the seaward direction while salinity and density increase. Non-conservative variables such as dissolved oxygen and nutrients (nitrate, phosphate and silicate) tend to be less structured. In general, nutrients increase while dissolved oxygen values decrease with depth and distance seaward along-channel. Because of the effects of varying runoff, vertical mixing, bottom topography and oceanic influence, this background structure is variable in space and time. In general, vertical gradients in water properties are linked to the intensity of the tidal currents and the degree of isolation of the basins by shallow sills.

The water property structures of each of the basins of the Georgia-Fuca system are quite distinct. For example, the waters of Juan de Fuca Strait are characteristic of a well-mixed estuary in which density gradients are relatively small and vertical mixing is intense (Figure 3). Puget Sound (Figure 8) is characteristic of a

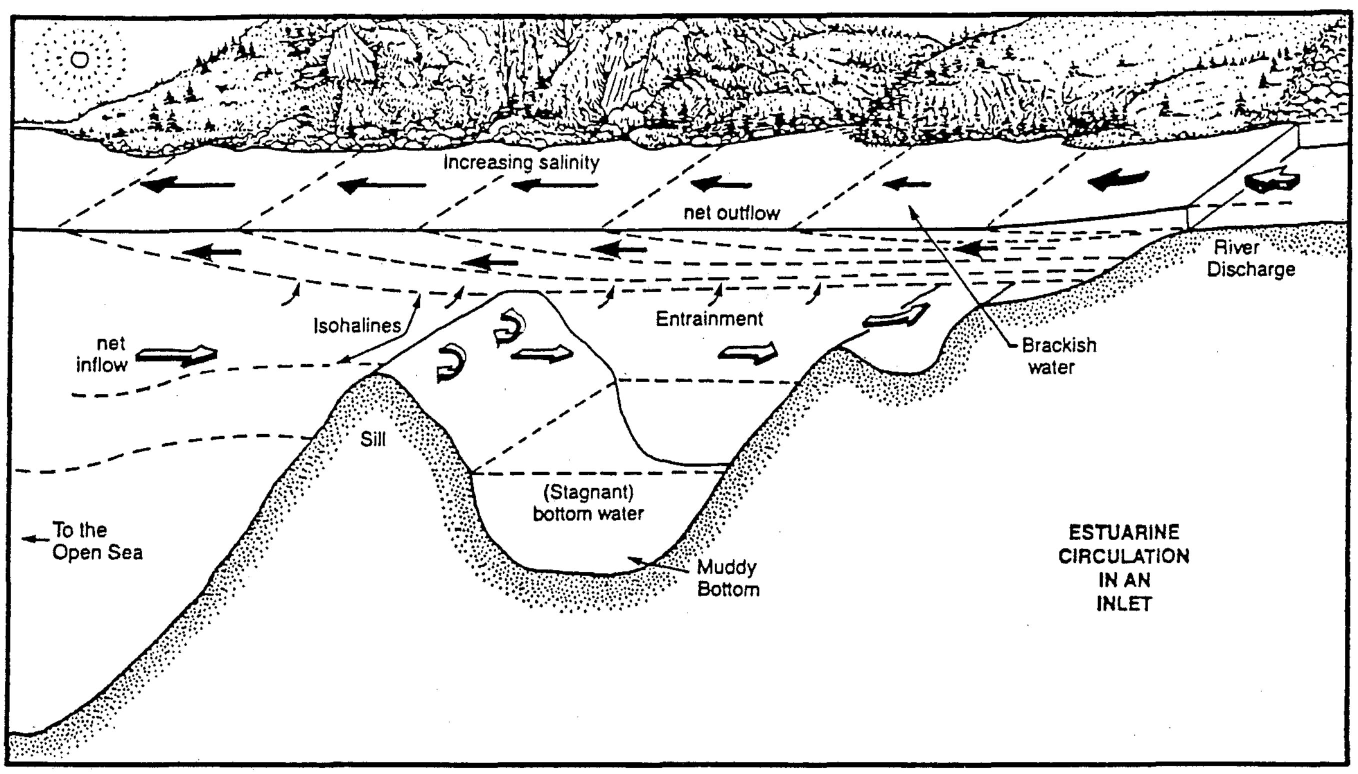


Figure 11. Estuarine circulation in a typical fjord setting on the British Columbia-Washington coast. (From Thomson 1981)

partially-mixed estuary consisting of highly stratified water in a shallow upper layer overlying more thoroughly mixed water in a deeper lower layer. The structure of the Strait of Georgia varies according to location. In the central region of the strait where currents are relatively weak and runoff from the Fraser River is a dominant factor, the strait resembles a partially-mixed estuary. In the extreme southern sector of the strait, tidal mixing on the flood can give rise to well-mixed estuarine conditions.

Factors Affecting Spatial Variability

The simple picture of the estuarine flow outlined in the previous sections is distorted by factors that affect the hydraulic pressure gradient along the channel, the amount of runoff entering the system and the degree of mixing. The Coriolis force, which arises from the influence of the earth's rotation, has an important effect on the cross-channel structure of the waterway, and modifies the depth of the null velocity. The null-velocity depth marking the transition from net outflow to net inflow is an important parameter since it influences the ultimate fate of materials dumped into the Georgia-Fuca system. Bottom friction and non-linear interactions affect the relationship between the baroclinic and barotropic responses of the system. As a result of these factors, estuarine circulation is highly variable in time and space. For example, we find that the spatial structure of mean estuarine flow in highly stratified regions such as the Strait of Georgia and Puget Sound differs markedly from that in well-mixed tidal channels such as Juan de Fuca Strait and Haro Strait.

Haro Strait has inflow at depth and outflow at the surface. Webster (1977) found that the dividing line between the two was 40 to 100 m on the eastern side of the strait and 100 m on the western side of the strait. There is a strong fortnightly signal in water properties with minimal temperature, salinity and vertical current shear during large tides and maximal values of these quantities during small tides.

One way to categorize the spatial structure of the waterway is in terms of the length scale ratio r/L. Here, L is

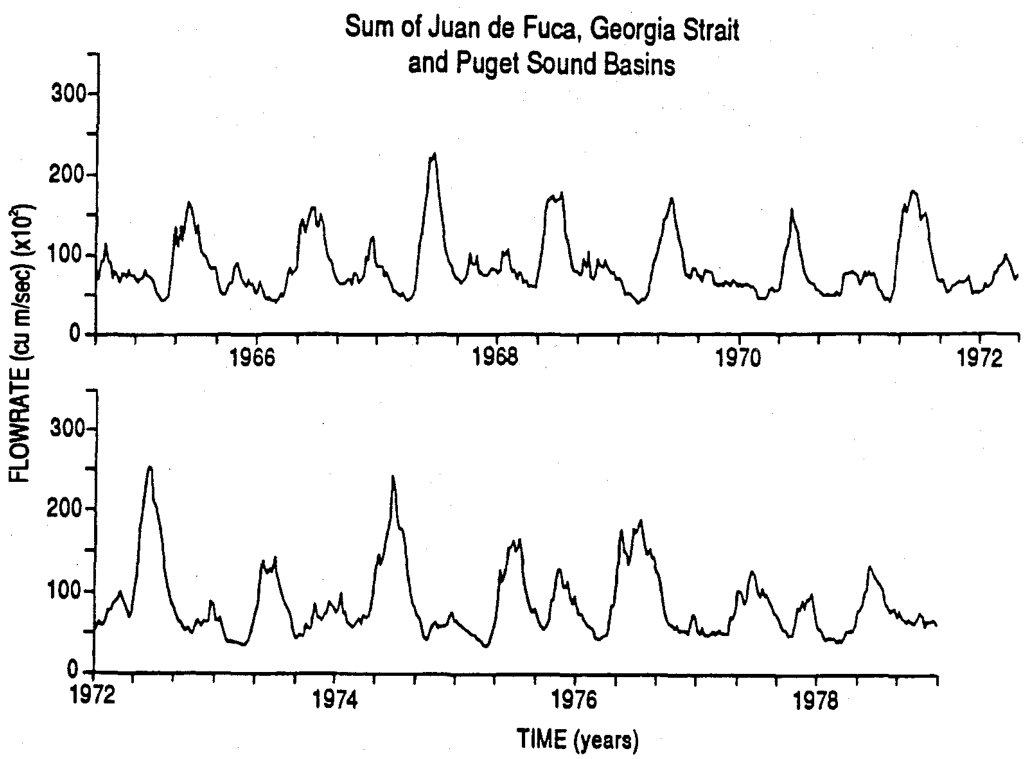


Figure 12. Combined weekly runoff flowing into all three main basins (Strait of Georgia, Juan de Fuca Strait and Puget Sound) for the period 1965 to 1979. The flow rate is in units of 100 m^3/s. Note the annual variability in both the volume and timing of the total runoff. (Modified after LeBlond et al. 1983)

the width of the channel and $r = NH/f$ is the internal deformation radius which characterizes baroclinic (density-dependent) motions in the ocean. The depth-dependent stability frequency $N(z) = [-gd\rho/dz]^{1/2}$ measures the maximum frequency of oscillation permitted for a parcel of water in the water column for given gravitational acceleration, g, and density gradient, $d\rho/dz$. H is the water depth and f is the local Coriolis frequency. Where r/L is large (narrow and/or deep channel), we can expect little influence of the earth's rotation on the cross-channel structure of the estuarine circulation and low-frequency motions, whereas when r/L is small (wide and/or shallow channel), cross-channel structure will be a dominant factor in the motions. Rotation-induced cross-channel structure also will be important for weakly-stratified estuarine regimes (N small) but less important for strongly stratified estuarine regimes. Thus, for Juan de Fuca Strait, we find $r/L \approx 1$ (Labrecque et al. 1994) whereas for the south central portion of the Strait of Georgia $r/L \approx 0.1$ (Stacey et al. 1988). Rotational effects show up in the cross-channel tilt of isopycnal surfaces and in modification of the basic depth-dependent estuarine flow structure within the major basins.

At the entrances to the main channels, large vertical and horizontal current shears develop due to the highly nonlinear nature of the flow in the narrow channels and the abrupt changes in topography associated with these regions. These spatial scales are not associated with the earth's rotation but with changes in topography, coastline orientation, or shear instabilities in the currents. Upwelling "boils" and other topographically-induced features are common to these highly nonlinear flow regimes. Near the entrance to Juan de Fuca Strait, the estuarine flow is further disrupted by oceanic winds and coastally-trapped propagating current systems (Proehl and Rattray 1984). During periods of strong southerly winds, brackish water from the Columbia River also may enter Juan de Fuca Strait along the United States side of the channel. Again, the internal deformation radius, r, is of the order of 10 km, so that internal oscillations of tidal frequency can be expected in the major basins. These will lead to tidal period excursions in water property surfaces and to localized variations in currents due to formation of standing or propagating internal tides.

Tidal Currents

Basic Characteristics

Superimposed on the background estuarine flow are time-varying currents associated with the rhythmic rise and fall of the tide. These tidal motions are responsible for the daily back-and-forth sloshing of the water through horizontal excursions of the order of several kilometers and for much of the vertical mixing and dispersion that characterizes the Georgia-Fuca system. Unlike open ocean regions, however, tidal motions in coastal regions can be responsible for highly nonlinear flow structure. In areas adjacent to tidal passes, coastal promontories and embayments, or bottom topographic features, frictional effects and nonlinear interactions can strongly modify the oscillatory flow. Nonlinear features include tidally-rectified flow (Foreman et al. 1992), coherent tidal jets and isolated eddies (Marinone and Fyfe 1992). Near the entrances to tidal passages and to the estuaries of the larger rivers, zones of intense horizontal current shear can lead to the formation of strong tidal rips where the wind opposes strong surface currents. These rips, more than any other feature, are the cause of small boating accidents by "natural causes" in coastal waters.

Generated through the astronomical tide-generating force arising from the combined gravitational pull of the moon and sun, tides and tidal currents are the most readily predictable components of oceanographic variability. Through a combination of long-term tide gauge observations and high resolution numerical models, tide heights can be accurately predicted within a few centimeters. Though tidal currents are considerably less predictable, our ability to predict them continues to steadily improve.

Direct forcing of tidal motions by the astronomical tide-generating forces in the Georgia-Fuca System is negligible. Instead, tidal period oscillations in the system originate with the northward propagation of the oceanic tide past the entrances to Juan de Fuca Strait and Queen Charlotte Sound. Since the oceanic tide is a mixture of diurnal and semi-diurnal constituents, the co-oscillating motions it sets up in the adjoining basins also are a mixture of these two constituents. The net effect is that there are 2 ebb and 2 flood currents per lunar day (25 hours) but successive ebbs and floods are of unequal strength. (This effect can be seen by examin-

ing the Tide Tables.) The actual response of the basin to the oceanic forcing depends on the shape and depth of the basin as well as the characteristics of external forcing. In the case of the Georgia-Fuca Basin, co-oscillation with the longer wavelength diurnal component differs markedly from co-oscillation with the shorter wavelength semi-diurnal component. Moreover, while the passage of the unimpeded semi-diurnal tide along the entire west coast of Vancouver Island takes about 20 minutes, it takes this component of the tide about 5 hours to transverse the myriad of passages and straits within the Georgia-Fuca system. This leads to significant differences in tidal elevations through the narrow passages within the system and produces some of the strongest tidal streams in the world.

Co-oscillation of the Georgia-Fuca system occurs as follows. A portion of the tidal wave enters the system through Juan de Fuca Strait in the south and to a lesser degree through Johnstone Strait in the north. The incoming tide entering the system from the north meets that from the south in the northern sector of the Strait of Georgia (Thomson 1981). Because of the match between the length of the basin and the quarter-wavelength of the semi-diurnal component of the incoming tidal wave, the propagating wave reflects from the northern boundary of the strait to produce a standing-type wave pattern at semi-diurnal periods within the Strait of Georgia. Semi-diurnal tidal oscillations in the Georgia-Fuca System are close to a ¾ wave resonance with a minimum amplitude in height near Victoria — which is a degenerate amphidrome for these motions — and maximum amplitude in the northern Strait of Georgia (Godin et al. 1980). Tide heights occur nearly simultaneously throughout the Strait of Georgia system but are nearly 180 degrees out of phase with tidal heights at the western end of Juan de Fuca Strait. As a result of this pattern, maximum flood in the Strait of Georgia occurs mid-way between low and high water while maximum ebb occurs midway between high and low water. Times of high and low water correspond to times of slack water. In contrast, diurnal amplitudes and phases increase monotonically from the mouth of Juan de Fuca Strait to the northern end of the Strait of Georgia. Within Juan de Fuca Strait, the tide is a mixture of propagating and reflected waves and the relation between the tide height and tidal currents varies as a function of position along the channel. Because of the flow restrictions imposed by the narrow openings, things are a little different in Puget Sound. Here, standing waves also prevail but are highly damped because of "friction" of islands and narrow channels.

The close relationship between tidal oscillations in the Georgia-Fuca System and those in the open Pacific can be found in the numerical modeling of Flather (1988). By closing off the mouth of Juan de Fuca Strait he was able to remove the strong diurnal period continental shelf waves that are observed to dominate the tidal currents over the outer shelf of Vancouver Island (Crawford and Thomson, 1984; Crawford and Thomson 1991).

Tidal Current Constituents

The tides and associated tidal currents in the Georgia-Fuca system consist of a mixture of diurnal (K_1, O_1) and semi-diurnal (M_2, S_2, N_2) constituents whose periods derive from the relative positions of the earth, sun and moon. Semi-diurnal tidal constituents with subscript "2" undergo 2 cycles of high and low tides (two flood and two ebb currents) per lunar day of 25 hours while diurnal constituents with subscripts "1" undergo 1 cycle per day. The relative importance of the two main types of variability is measured by the ratio $(K_1+O_1)/(M_2+S_2)$. When this ratio is less than 0.25, the tide is classified as semi-diurnal; if it is lies between 0.25 and 1.50 the tide is mixed, predominantly semi-diurnal; between 1.50 and 3.00 the tide is mixed, predominantly diurnal, and greater than 3.00 it is classified as diurnal. For tidal elevations, this ratio is around 1.5 to 2.0 at the oceanic end of Juan de Fuca Strait, 1.00 near Seattle and 1.17 at Point Atkinson near Vancouver (Table 3). Near the amphidrome for the semi-diurnal oscillations off Victoria, the tides are mixed mainly diurnal and the ratio rises to a local maximum of around 2.6 (Crean et al. 1988). Tidal currents are basically mixed, mainly semi-diurnal throughout most of the Georgia-Fuca system, reflecting the fact that there is rarely a one-to-one correspondence between tide height and the tidal current in the system. The two daily ebbs and floods are of unequal strength.

Holbrook et al. (1980b) found that diurnal and semi-diurnal tidal currents account for most (65 to 88%) of the long-strait variance although significant variance (27%) also was observed at subtidal frequencies in the winter. They further observed that the current variance

at low-frequencies was much lower in the summer than in the winter for the western portion of the strait. Holbrook et al. (1980b) and Proehl and Rattray (1984) find that subtidal motions were highly correlated with the large-scale coastal wind forcing rather than with local wind forcing. Parker's (1977) estimate of flood volume transport during ½ of an M_2 cycle showed that of the total M_2 flood volume entering the eastern part of Juan de Fuca Strait, 24% enters Admiralty Inlet, 20% flows into Rosario Strait, 51% goes to Haro Strait and 5% through Middle Passage. The tidal wave is delayed by about one hour at the southern end of the Strait of Georgia relative to that in Haro Strait.

In addition to the daily variability, "beat" frequencies among the semi-diurnal and diurnal constituents give rise to significant long-term tidal variations. The beating between the M_2 and S_2 constituents and between the M_2 and N_2 constituents gives rise to a fortnightly (15 day) modulation of the tide heights and currents known as the spring-neap cycle. When the M_2 and S_2 components are in phase, the gravitational pull of the moon and sun are nearly in line and tides are higher than the mean (spring tides). During neap tides, M_2 and S_2 are out of phase and the gravitational pull of the moon on a line which is orthogonal to that of the sun and the earth. The spring-neap cycle associated with the M_2 and N_2 constituents arises from orbital distance of the moon from the earth. Maximal values occur about 3 days after the time that the moon is closest to the earth and the M_2 and N_2 constituents are in phase. The beating between the K_1 and O_1 constituents due to monthly movement of the plane of the moon's orbit around the earth leads to a third contribution to the spring-neap cycle in the tides over an interval of 13.36 days. During the neaps, diurnal tides are minimal and the tides in the Strait of Georgia are nearly semidiurnal. Other tidal components are the monthly cycle and there is a semi-annual constituent that leads to a spring-fall difference in the heights of the fortnightly spring-neap cycle (Thomson 1981).

Wind-Driven Currents

Wind forcing has a significant effect on the oceanography of the Georgia-Fuca system. In addition to generating surface waves and helping mix the surface waters, winds directly force surface drift currents and lead to low-frequency flow responses within the main oceanic basins. Of the different processes affecting the circulation of the system, wind effects are probably the least well understood due, in part, to inadequate wind field measurements. Exceptions are the work by Holbrook and Halpern concerning reversals of the estuarine circulation by winds along the outer Washington coast and by Griffin and LeBlond regarding the surface flushing of the southern Strait of Georgia during northwesterly winds. The lack of oceanic wind fields also hampers the development of accurate numerical models of the system.

Winds in the region are dominated by two major seasonal atmospheric pressure systems centered in the North

TABLE 3

Type of tide height in the Georgia-Fuca system based on the amplitude ratio $(K_1 + 0_1)/(M_2 + S_2)$ of the major tidal height constituents.
JdF = Juan de Fuca Strait; SoG = Strait of Georgia; PS = Puget Sound; DP = Discovery Passage.

Location of tide gauge	*Ratio*	*Type of tide*
Sooke (JdF)	1.614	Mixed, mainly diurnal
Victoria (JdF)	2.128	Mixed, mainly diurnal
Port Angeles (JdF)	1.625	Mixed, mainly diurnal
Port Townsend (JdF)	1.526	Mixed, mainly diurnal
Whidbey Basin (PS)	0.987	Mixed, mainly semidiurnal
Hood Canal (PS)	1.018	Mixed, mainly semidiurnal
Seattle (PS)	0.979	Mixed, mainly semidiurnal
Pt. Atkinson (SoG)	1.165	Mixed, mainly semidiurnal
Little River (SoG)	1.130	Mixed, mainly semidiurnal
Campbell River (DP)	1.314	Mixed, mainly semidiurnal

Pacific Ocean. These are the North Pacific High pressure system which dominates the region in summer and the Aleutian Low which prevails in winter. Variations in the location and intensity of these systems greatly influences the winds over the offshore waters and affects winds over the inner coastal regions. From October to March cyclonic winds associated with the Aleutian Low result in mostly southeasterly winds while in summer anticyclonic winds associated with the North Pacific High produce winds from the west and northwest (Figure 13).

In late fall and winter, strong southeast winds drive the brackish flow to the north in the Strait of Georgia while strong southerly winds along the outer Washington coast are responsible for reversals in the normal estuarine flow pattern throughout Juan de Fuca Strait. Winds accompanying fall and winter storms cause the surface outlfow to reverse to inflow. Cold outbreaks, which occur in winter when cold interior air flows seaward as a density current, can augment the normal estuarine flow pattern.

In summer, "fair weather" northwesterly winds are responsible for driving the surface brackish layer southward into the southern Strait of Georgia. Thus, winds from the north offset the tendency of the Fraser River plume to turn northward under the Coriolis effect while winds from the south augment this effect (Tabata 1972). The northwesterly winds combined with summer runoff and tidal mixing are responsible for the propagation of fortnightly bulges of freshwater seaward through the system. The fortnightly and monthly generation of relatively warm, low salinity bulges is due to the spring-neap cycle of the tidal currents within the major tidal passes and the associated Froude number control of vertical mixing. In this case we have a perfect example of winds, runoff and tidal mixing all contributing to the generation of a special process in the strait. In Juan de Fuca Strait, strong to gale-force inflow (westerly) winds occur during warm summer days as a result of diurnal heating of the land. This *sea breeze* typically commences abruptly around noon, reaches peak intensity by late afternoon, then dies off by early evening. It is this same sea breeze phenomenon that makes the Columbia River Gorge of southern Washington State famous worldwide as a "Mecca" for high-end windsurfing conditions in summer.

Coastal Ocean Forcing

Oceanic processes on the outer coasts of British Columbia and Washington State cause changes in the water properties and circulation of the Georgia-Fuca system in several important ways.

Reversals in the Estuarine Circulation

Observations taken by Cannon (1972) in the winter of 1971 at the mouth of Juan de Fuca Strait indicated that major winter storms could reverse the normal estuarine flow pattern for periods of several days. Similar flow reversals also were observed at the edge of the continental shelf within Juan de Fuca Canyon (Cannon and Bretschneider 1986). The winter 1976/77 moorings in Juan de Fuca Strait and subsequent moorings in the winter and summer of 1978 east of Port Angeles helped document the timing and extent of estuarine flow reversals associated with strong southeast winds off the west coast of Washington State. Currents from these moorings show that the onshore Ekman transport generated by strong southerly coastal winds increases sea level along the outer shelf which then overcomes the seaward sea surface slope associated with freshwater runoff into the Georgia-Fuca system. This effectively decelerates the surface currents and may lead to eastward intrusions of low density water into the strait (Holbrook and Halpern 1982). The latter study documented five intrusions of 1 to 3°C warmer offshore water into the strait lasting for durations of 1 to 10 days (Figure 14). The 25 cm/s up-strait speed of the intrusive lens was in general agreement with wave speed computed for a simple surface gravity current. Frisch et al. (1981) also have presented evidence for reversals in surface drifter measurements in the eastern strait (Figure 15). The surface reversals are accompanied by current reversals within the lower layer where flow directions become seaward. Southerly winds also can force low salinity Columbia River water into the entrance to Juan de Fuca Strait.

Holbrook et al. (1983) suggest that surface intrusions of relatively low density water in Juan de Fuca Strait and the accompanying deep outflow are major recurring features of the circulation throughout the year. In winter, there are 2–3 reversals per month each lasting 2–7 days. Penetration of the baroclinic (density-dependent) current takes place at 25–30 cm/s or 12–14 nautical miles/day. The intrusions may extend 135 km up-strait and produce significant changes in the along- and cross-

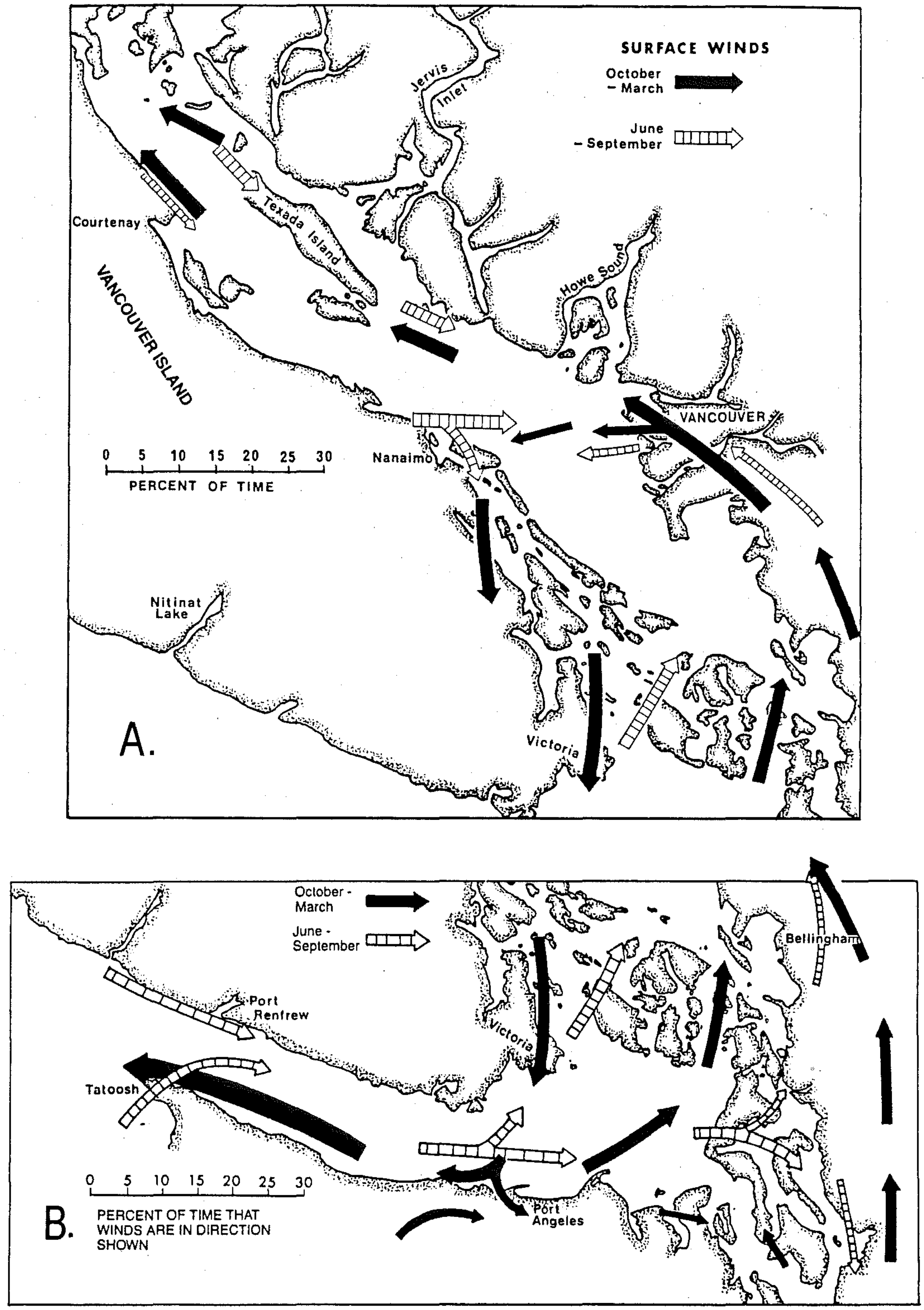


Figure 13. Prevailing surface wind patterns over the Strait of Georgia region (A) and Juan de Fuca Strait (B) in winter (solid arrows) and summer (hatched arrows). Thick arrows correspond to speeds of 4.5 to 9 m/s (8.7–17.5 knots); thin arrows to speeds less than 4.5 m/s. Comparison of length of arrow to scale on left yields the frequency of occurrence of a particular wind. (Adapted from Thomson 1981)

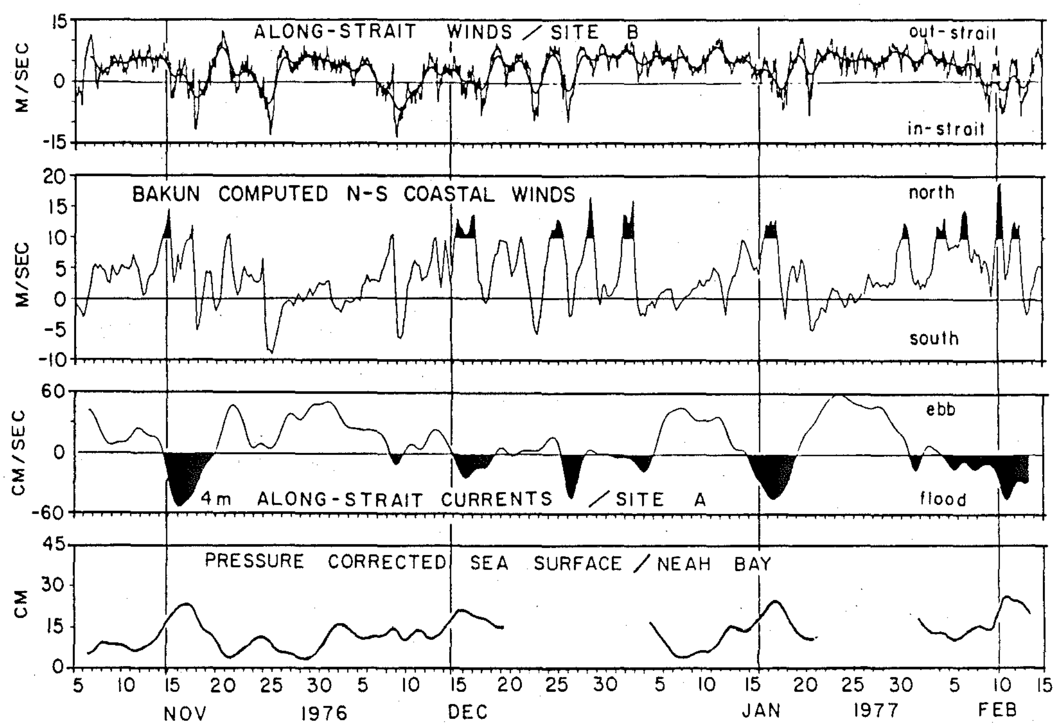


Figure 14. Mid-strait (Site B) along-channel winds, Bakun coastal winds (computed from sea level pressure gradients), along-channel currents at 4 m depth at the mouth of Juan de Fuca Strait (site A), and sea-level elevations at Neah Bay for the period November 1976 to February 1977. Vertical lines indicate various correlations (From Cannon and Bretschneider 1986; Hollbrook and Halpern 1982).

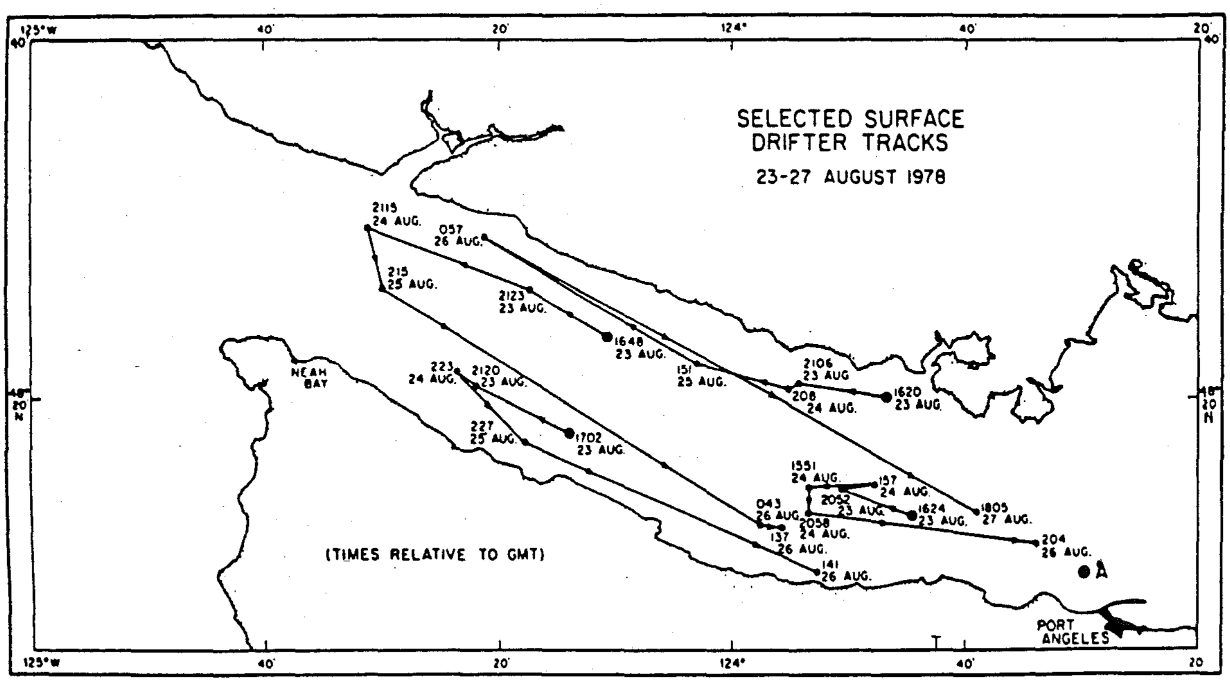


Figure 15. Surface drifter tracks showing a flow reversal event in Juan de Fuca Strait. (From Frisch et al. 1981)

strait flow structure for periods of several days. In addition, the summer upwelling and winter downwelling cycle over the continental shelf is responsible for changes in the density of the deep water which slowly moves into the system and makes its way along Juan de Fuca Strait into the Strait of Georgia. High density water in summer off the coast arrives at the eastern end of Juan de Fuca Strait by early winter and eventually spills into the Strait of Georgia as a density current. Moreover, the spilling processes are fortnightly and monthly as a result of the same mixing processes that control surface outflow in the passes.

Holbrook et al. (1983) find that the sea level anomaly within the system in winter is the sum of two main components: A barotropic component with high spatial coherence propagating quickly (44 m/s) along the strait from the shelf; and a lower speed baroclinic component associated with intrusions of low-density coastal water that is driven into the strait by southerly winds along the outer coast. The baroclinic signal decreases in amplitude eastward through the strait but on occasion may extend as far as the entrance to Puget Sound. Once there, it influences intrusions into the Sound. Cannon et al. (1990) find cross-sill salinity differences as large as 2‰ that strongly affect the depth and strength of the intrusions.

Klinck et al. (1981) developed a two-layer model that relates coastal and fjord circulation. Model results for southerly wind forcing generate a realistic distortion of the density structure and circulation near the mouth of the strait. However, coastal effects only penetrate 10 to 30 km up-strait in the model, even after 5 days of forcing. The lack of agreement between the model and observation (intrusions are observed as far inland as the entrance to Puget Sound 135 km up-strait) suggests that rotational effects and density contrasts between the strait and ocean may be important. According to a more recent theoretical study by Proehl and Rattray (1984), the intrusions that result from the winds and onshore Ekman drift also may involve the up-strait propagation of long, internal Kelvin waves generated in the stratified shelf waters during coastal wind events. These waves may effect reversals in the estuarine circulation in the strait. The Coriolis effect and the short baroclinic radius confine the baroclinic intrusions to the southern side of the strait. Also, coastally-trapped waves which can only propagate poleward along the west coast of North America first arrive on the United States side of Juan de Fuca Strait where they become trapped along the southern side of the channel.

Up-strait Influence of Coastal Upwelling

Oceanic conditions along the continental shelf of British Columbia and Washington State are strongly influenced by the prevailing alongshore winds. From late spring to early fall, the North Pacific High pressure system dominates the northeast Pacific and coastal winds are predominantly from the north to northwest. The combined influence of the northwest winds and the earth's rotation (Coriolis effect) is to produce an offshore transport of water in the upper 100 m of the water column (the surface Ekman layer) and a compensating onshore transport at depth. This process leads to upwelling of relatively cold, high salinity, low oxygenated nutrient-rich water over the continental margin in summer. From late fall to early spring, winds are predominantly from the southeast as the Aleutian Low Pressure system is reestablished in the Gulf of Alaska. These downwelling favorable winds lead to increased temperatures, lower salinities and higher dissolved oxygen levels over the continental margin.

The properties of the water mass that is being transported eastward in the lower layer of Juan de Fuca Strait will clearly depend on the duration and intensity of the upwelling-downwelling processes that take place over the continental shelf. As a result of upwelling favorable winds, the water mass that slowly makes its way inland during the summer and fall will have lower temperatures, higher salinity and lower oxygen levels than the ambient waters of the strait. Similarly, in winter, the water mass making its way along the strait will have higher temperatures, lower salinities and higher oxygen values than the ambient waters. As a consequence, the water that eventually spills into the various basins of Puget Sound and the Strait of Georgia is modulated by conditions on the outer coast. The deep density structure then affects the density at the sills in the basins. Moreover, because of the time lag associated with the propagation of the bottom water along the strait, the times of salinity, temperature and oxygen maxima will differ with distance from the entrance to Juan de Fuca Strait. Long-term changes in the strength and duration of upwelling off the coast, such as those associated with strong El Niño-Southern Oscillation events will impact

on the water properties of the channels adjoining Juan de Fuca Strait. Movement of higher salinity water into the strait at depth in summer as a result of upwelling on the adjacent continental shelf also will affect the generation of internal tides in the vicinity of sills or marked topographic features.

Subtidal Sea Level Fluctuations

Mofjeld (1992) has examined observed oscillations in sea level at periods of 2 to 10 days at the southern end of Puget Sound. He shows that these fluctuations result from quasi-steady inverse barometer compensation to large-scale atmospheric pressure and to the propagation along Juan de Fuca Strait of sea level fluctuations from the continental shelf. The coastally generated fluctuations are a barotropic response that accompanies the reversal of the estuarine currents along the coast during periods of strong southerly winds. Baroclinic processes also may have some influence on the sea level changes within the fjord system. In their 6-day simulation of Puget Sound during the time of a major winter storm, Crean et al (1988) found that 60% of the sea level response at Seattle was due to the landward propagation of the sea level signal from the coast, while 30% was due to the response of the system to local atmospheric pressure fluctuations. Only a small (<10 cm) response was related to local winds.

SECONDARY FORCING MECHANISMS

Spatial and temporal variability in the primary driving mechanisms, combined with the formation of eddy or wave-like responses can alter the basic circulation produced by the main forcing functions.

Hydraulic Control

Marked fortnightly fluctuations in horizontal exchange rates for silled basins are attributed to the degree of turbulent tidal mixing over the entrance sills brought about by the neap-spring cycle in the tidal currents (Geyer and Cannon 1982). The tidal mixing intensity at the main entrance sills provides a *hydraulic control* mechanism for the depth-dependent estuarine circulation, limiting seaward outflow in the surface layer and landward inflow at depth. Hydraulic control at entrance sills in the Georgia-Fuca system has been addressed by numerous authors including Ebbesmeyer and Barnes (1980), Stucchi and Giovando (1984), Cannon and Bretschneider (1986), Griffin and LeBlond (1990). In essence, strong mixing over the shallow sills during periods of spring tides, when tidal currents are at their strongest, curtails the ability of the brackish water in the upper layer and the salty water in the deep layer to slide over one another. The opposite occurs during neap tides. An analogy can be made with a divided two-lane highway which has built-in U-turn lanes at selected locations along the route. The two lanes of traffic easily slide by one another except near the U-turn sections where turbulent "mixing" and exchange of slower and faster traffic will lead to major (and dangerous) disruption of the normal flow of traffic. The effect of these "bottle necks" is to seriously impede the flow.

In the oceanographic case, the exchange across the sills is possibly controlled through vertical entrainment related to the presence of large internal hydraulic "jumps" (Griffin and LeBlond 1990). The jumps (Figure 16) are formed during times when the flow speeds are large enough for the flow to become super-critical with respect to interfacial waves. A measure of this effect is given by the internal Froude number, $F = |U/c|$, where U is the depth-averaged tidal flow and c is the phase speed of interfacial waves separating the upper and lower layers in the vicinity of the sill. For $F>1$, the flow is super-critical and enhanced entrainment will impede the horizontal exchange across the sill.

Since the spring-neap cycle in the tidal currents varies over periods of months to a season, the hydraulic control mechanism also can be expected to vary over periods longer than a fortnight. However, the most important factor affecting modulation of the mechanism appears to be the density difference at depth between the oceanic water seaward of the sill and the water within the estuarine basin. For example, observations by Ebbesmeyer et al. (1989) and Cannon et al. (1990) have shown that deep water intrusions into the main basin of Puget Sound — which occur during neap tides when mixing over the sill is at a minimum and gravitational circulation can develop — are strongly modified by salinity (density) changes at the entrance to Admiralty Inlet brought about by propagation along Juan de Fuca Strait of wind-induced offshore oceanic influences. The analysis of Ebbesmeyer et al. (1989) goes one step further by linking variations in hydraulic control in Puget Sound to interannual decadal scale changes in meteorological forcing and hydrology in the

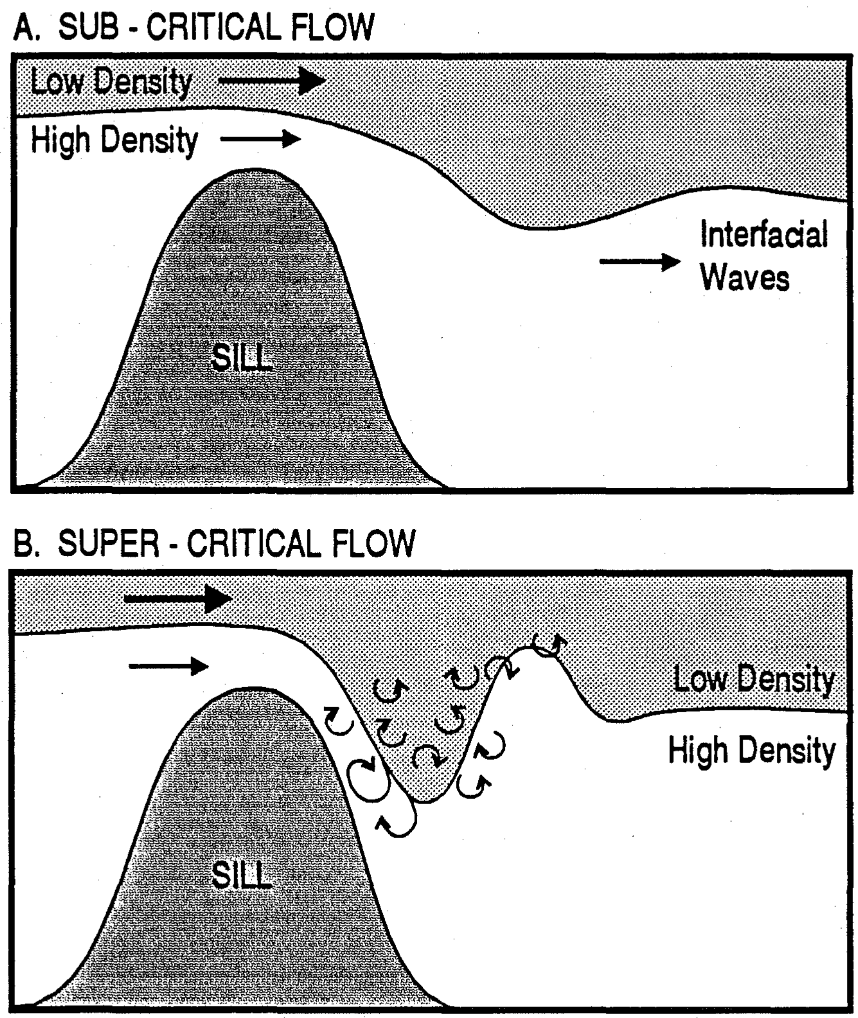


Figure 16. Schematic of a turbulent mixing associated with the formation of a hydraulic jump over a shallow sill in a two-layer fluid with relatively low density water overlying higher density water. (A) Sub-critical (smooth) flow over the sill; (B) Super-critical turbulent flow over the sill. Arrows indicate vigorous mixing.

Pacific Northwest. The position of the Aleutian Low pressure system in the North Pacific is a key factor in the long-term variability of Puget Sound oceanography.

Griffin and LeBlond (1990) noted the importance of the spring-neap cycle in mixing over the sills leading into the southern Strait of Georgia. They hypothesized that Boundary Passage, and to a lesser extent the narrower and shallower Rosario Strait, act like a "leaky" gate which opens wider during periods of low vertical mixing (neap tides) to release "bulges" of low salinity surface waters into Juan de Fuca Strait. This effect is greatly enhanced during periods of strong northwesterly winds in summer when winds drive the thin Fraser River plume southward toward Haro and Rosario straits. A predictive box model of the Griffin and LeBlond mechanism is presented by LeBlond et al. (1994). In particular, the model attempts to reproduce observed upper layer salinity variations in eastern Juan de Fuca Strait for the years 1973–84 using a two-layer system modified by observed values for Fraser River runoff, surface winds in the Strait of Georgia and tidal currents given by the GF7 numerical model of Crean et al. (1988). The model is calibrated using salinity observations from Race Rocks for the period 1967–72. According to LeBlond et al. (1994) the quantitative results confirm the "leaky gate" model in which tidal mixing and favorable wind events in the Strait of Georgia modulate the export of fresh water from the strait in the summer months (Figure 17).

The hydraulic control mechanism has helped us understand deep-water renewal in the Strait of Georgia. Specifically, effective two-layer tidal exchange from Boundary Passage only occurs during times of highly stratified, low tidal mixing periods (neap tides). At monthly periods in summer, when the runoff establishes strong stratification and the tidal currents are too weak to destroy it, the control is sufficiently weak to allow deep salty water from Juan de Fuca Strait to spill over the Boundary Passage sill as a density current that runs along the bottom of the southern strait on the eastern side. At other times, low density surface water mixes with deeper water from Juan de Fuca Strait and the mixture is not dense enough to sink below intermediate depths. The study found that the monthly observations reported for the entire system by Crean and Ages (1971) were sufficient to explain the penetration of intermediate depth water to 100 to 200 m depth in winter. This phenomenon arises from a combination of winter cooling and tidal mixing in the southern Strait of Georgia. Over the depth range 250 to 350 m, deep-water intrusion takes the form of daily pulses of bottom-trapped relatively high salinity, high temperature water whose formation is closely linked to fortnightly and monthly variations in the tidal current in Boundary Passage. (In this case, the monthly data are not sufficient to resolve the intrusive process.) The pulses are gravity currents originating in Boundary Passage during periods of minimal tidal mixing. This picture is consistent with the one year mooring program in Juan de Fuca Strait, Haro Strait and the southern Strait of Georgia conducted by the Institute and Arctic Sciences Ltd. from 1989 to 1990 using current meters and a dissolved oxygen probe.

Tidal Mixing and Nutrient Flux

An estimate of the importance of local tidal mixing can be obtained from the stratification parameter (Fernhead 1975; Simpson and James 1986)

$$M = \mathrm{H}/[\rho C_D \langle U^3 \rangle]$$

where H is the total water depth (m), $\rho \approx 1.025$ is the specific gravity of seawater, $C_D = 0.002$ is the drag coefficient, U is the tidal velocity and $\langle\rangle$ denotes a time average. This relation expresses the importance of surface buoyancy fluxes (runoff and insolation), which tend to restratify the water column relative to the intensity of tidal mixing, which tends to destroy the stratification. In particular, $\log(M) < 1$ for well-mixed regions while $\log(M) > 2$ for well-stratified regions. Since we can't measure currents everywhere in the system, U has been estimated from tidal currents calculated by a finite-element numerical tidal simulation model developed by Foreman et al. (1992; 1993). For each U there is a corresponding depth element H. Values of maximum current speed U plotted in Figure 18 are based on tidal currents calculated for the period January 1 to 31, 1992 using tidal constituents (Q_1, O_1, P_1, K_1, N_2, M_2, S_2, and K_2). The corresponding values for $\log(M)$ appear in Figure 19. The obvious inference from these plots is that maximum mixing is found generally in regions of strongest tidal currents such as Haro and Rosario straits, the entrance to Admiralty Inlet, and off Discovery Island and Race Rocks near Victoria. Water depth is of secondary importance. Very

Figure 17. Satellite-derived sea surface temperature maps showing a monthly pulse of warm, fresh water leaving the Strait of Georgia from July 14 to July 24, 1984. (From Hickey et al. 1991) In this reproduction, surface water between about 15°C and 20°C appears white.

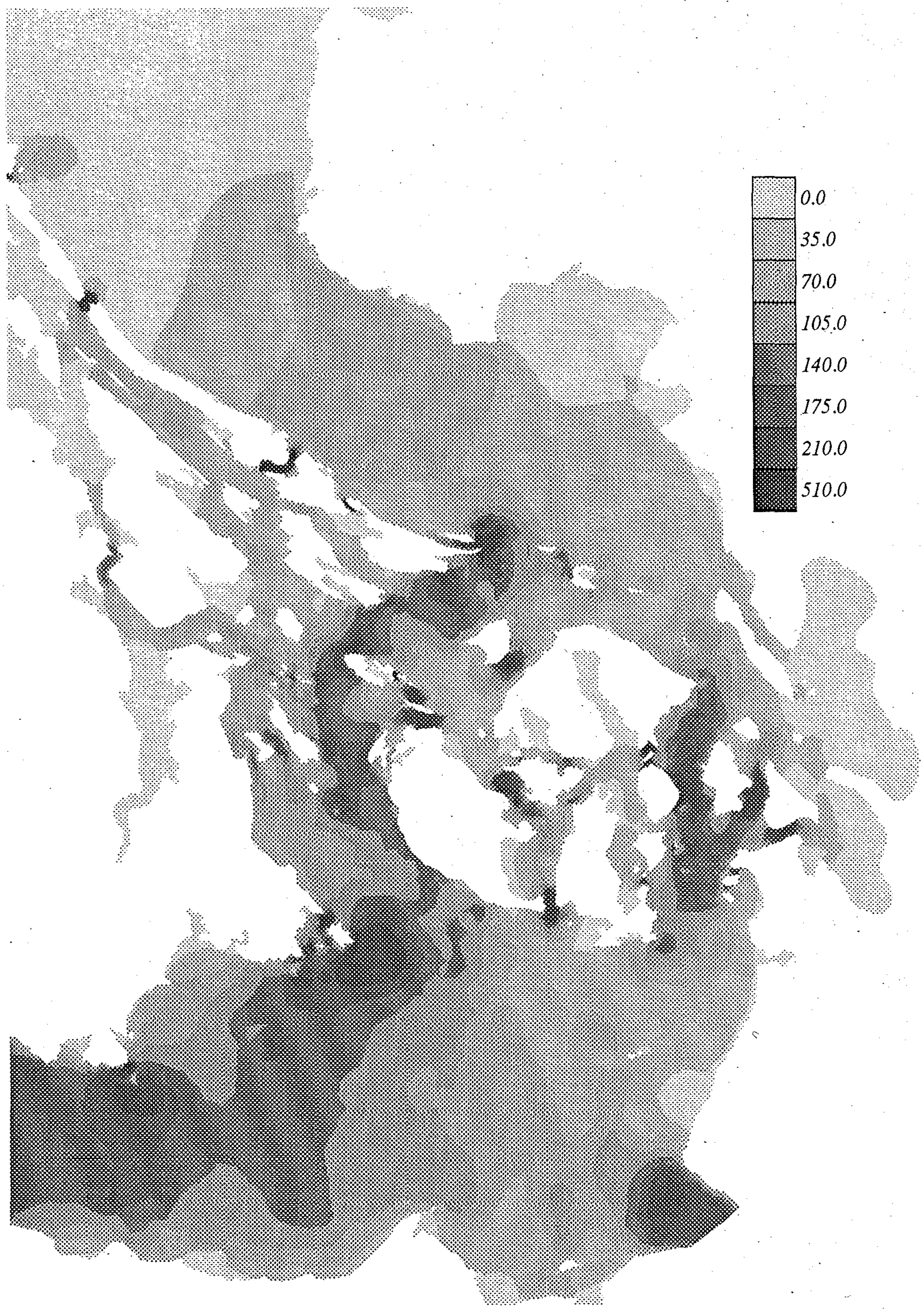


Figure 18. Maximum tidal currents for the Georgia-Fuca system based on a finite-element numerical model and observations for the period January 1–31, 1992. Colours give ranges of speeds: for example, the value 140.0 cm/s corresponds to maximum currents in the range 105.0 to 175.0 cm/s. (Courtesy Mike Foreman, Institute of Ocean Sciences)

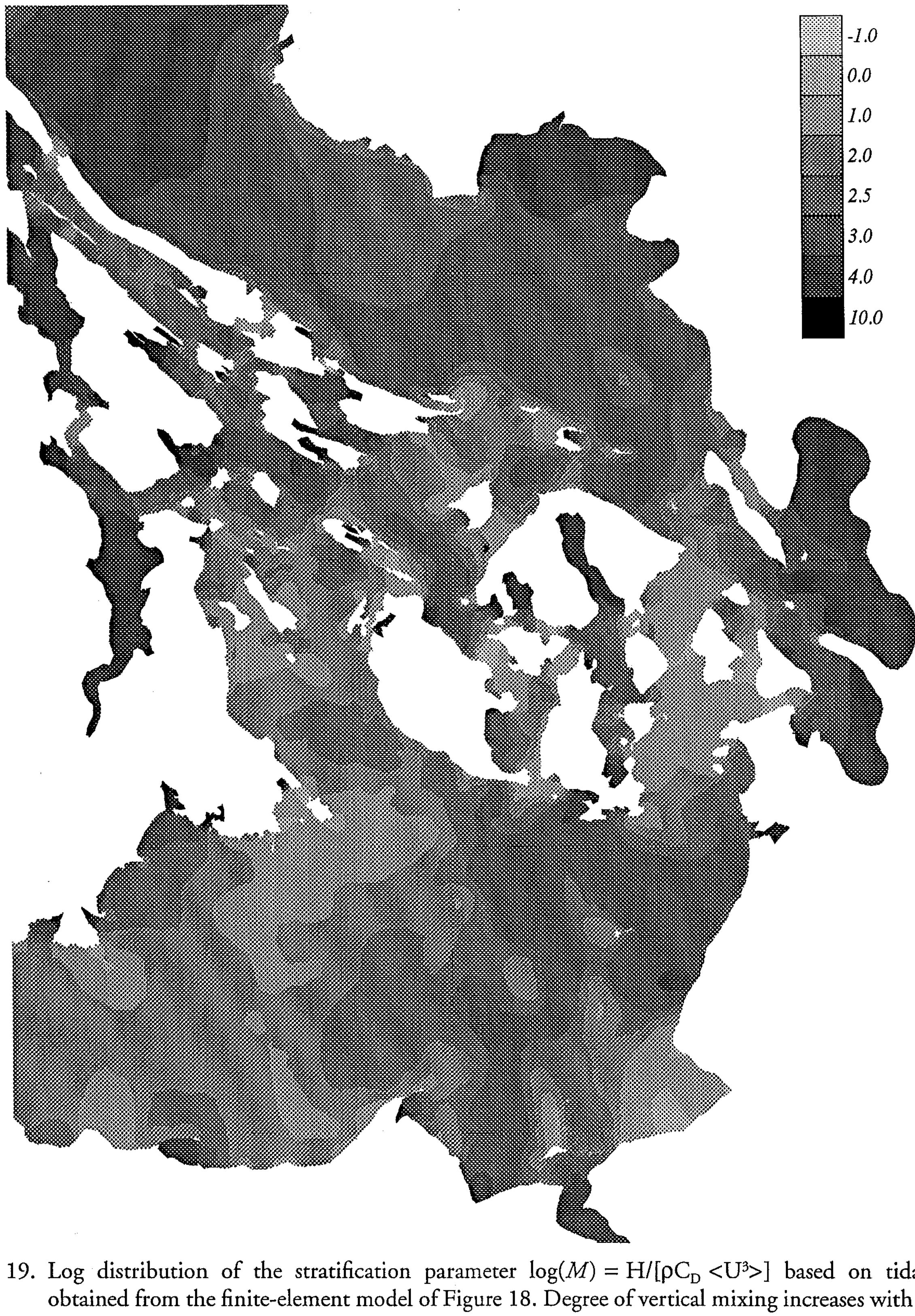


Figure 19. Log distribution of the stratification parameter $\log(M) = H/[\rho C_D \langle U^3 \rangle]$ based on tidal currents obtained from the finite-element model of Figure 18. Degree of vertical mixing increases with decreasing value of $\log(M)$. Intense mixing can be seen off Victoria, Race Rocks, the entrance to Admiralty Inlet and within the major passes through the Gulf and San Juan islands. (Courtesy Mike Foreman, Institute of Ocean Sciences)

weak mixing takes place in the central and northern regions of the Strait of Georgia and eastern Puget Sound.

The role of turbulent tidal mixing in bringing nutrients to the surface layer was addressed by Crawford and Dewey (1989) using a current shear probe to measure turbulent dissipation within the water column off the southwest coast of Vancouver Island. Based on examination of oceanographic conditions off the west coast in late spring and early summer, they concluded that among the major possible contributors to the nutrient flux — local upwelling, local tidal mixing and outflow from Juan de Fuca Strait — outflow from the strait was the largest contributor. Crawford (1991) extended his work by examining mixing intensities in the eastern portion of Juan de Fuca Strait. Dissipation rates within the Georgia-Fuca system are clearly sufficient to provide the observed outflow of nutrients. Dissipation estimates provided by the GF7 model indicate that mixing rates in Juan de Fuca Strait are too low to provide the required nutrients. However, direct measurements of turbulent dissipation in Boundary Passage using a current shear probe suggest that vertical mixing in the passage combined with seaward estuarine outflow may be the source for the high nutrients throughout the region downstream of the passage, including the continental shelf of southwest Vancouver Island. Tidal mixing in the channels of the Gulf and San Juan islands also provides nutrients to the Strait of Georgia and Puget Sound, but these nutrients are injected below the buoyant surface layer.

According to Harrison et al. (this volume), the high nutrient outflow is part of a natural supply of nutrients provided by two main sources: (1) Nutrient rich water that moves up-strait from Juan de Fuca Canyon in summer and is then mixed into the surface outflow layer at the eastern tidal passes. This accounts for 96.6% of the total mean nutrient (nitrogen) load of the ≈2,070 tonnes N/day; and (2) Fraser River runoff that has worked its way seaward from the southern Strait of Georgia, and which accounts for 2.4% of the total nitrogen load. The supply of nutrients to the surface layer by the upwelling-estuarine circulation process is roughly 40 times that of the Fraser River runoff and 300 times that from the Victoria sewage outfall. Metropolitan Seattle accounts for roughly 15 tonnes N/day or about three times that of Victoria (5–6 tonnes N/day).

Low-Frequency Motions in The Strait of Georgia

The central portion of the Strait of Georgia has been one of the more intensely studied regions of the Georgia-Fuca System. As such, it offers some insight into the kind of three-dimensional flow structure that may be occurring in other sectors of the Georgia-Fuca System. An analysis of current meter data collected in this region in the 1960s has been presented by Chang et al. (1976) who first showed that fluctuations at periods of 5 to 30 days account for about half the kinetic energy of the system, with the remaining half in the diurnal and semi-diurnal currents. Additional moorings were placed in this region from June 1984 to January 1985 (Stacey et al. 1988). Data from these moorings showed that of the total variance in the low frequency motions, about 37% is explained by long-period (fortnightly, monthly and semi-annual) tidal fluctuations. The low-frequency motions have short horizontal scales of roughly 4 km and their statistics were consistent with homogeneous, horizontally non-divergent and isotropic turbulence or "eddies" (Stacey et al. 1988). A follow-up study by Stacey et al. (1991) indicates that the thermal wind relation holds fairly well and that a geostrophic mean state provides a reasonable approximation to the mean flow. Evidence was presented for the existence of baroclinic and barotropic instabilities. At 100 m depth, the transfer from the fluctuating to mean flow through barotropic instability was found to take place over an e-folding time of 4 days with an eddy viscosity of 60 m^2/s. Baroclinic instability also was present but energy transfer from the low frequency currents to the mean flow appears to be suppressed by horizontal variations in the flow field.

In an attempt to account for the high proportion of kinetic energy in the residual motions in the central Strait of Georgia, Marinone and Fyfe (1992) used a spatially-nested, depth-averaged, non-linear finite difference numerical model forced by a number of tidal harmonics. As with the data for the region, the residual model data were obtained using a low-pass 25-hour running mean filter. The modeled mean currents formed an 8 km diameter cyclonic (counterclockwise) eddy in the middle of the Strait consisting of a northeastward jet on the mainland side of the model domain and a meandering southwestward current on the Vancouver Island side. Superimposed on this mean flow was

a 14-day oscillatory flow associated with the M_f (fortnightly) tidal constituent originating from the non-linear interaction of the two major diurnal constituents (K_1 and O_1). Comparison of the model results with observations shows that the position and rotation direction of the residual eddy are realistic but that flow speeds are underestimated by a factor of ten. Holloway (1993) suggests that non-linear interaction of the daily tidal motions may indeed account for the observed residual motions in the central strait but that important aspects of the physics are missing and that the model might be improved by reformulation of the eddy viscosity.

Decadal-Scale Fluctuations in Estuarine Flow

As noted earlier, Ebbesmeyer et al. (1989) report strong correlations between low-frequency variability in North Pacific meteorology and decadal scale (10 to 20 year) variability in the water temperatures and estuarine flow into the main basin of Puget Sound. In particular, "Covariations were evident in correlations between 21 environmental parameters, and decadal fluctuations accounted for a substantial fraction of interannual variability. On average the amplitude of an environmental parameter at decadal period equals approximately two-thirds of the annual values' standard deviation. For basin currents this percentage increased to 97 percent." The position of the Aleutian Low in winter, as measured by the Pacific Northwest (PNW) index, plays a critical role in the estuarine dynamics of the waterway leading into the Sound. For example, as the Aleutian Low shifts eastward (PNW positive), the density difference across Admiralty Inlet increases and the depth of fastest inflow into the basin increases. At decadal period, the 0.18 kg/m^3 amplitude of the density difference is sufficient to deepen the inflow into the basin from mid-depth to the bottom.

Of the major oceanic parameters, only the mean basin salinity showed no correlation with the decadal scale variability in the PNW index. Basin salinity remains steady during the strong interdecadal variability of other parameters. The reason lies in the opposing contributions made to the basin by freshwater input from variations in runoff and that from the salinity of the source water at the mouth of Admiralty Inlet. Basin salinity is directly correlated with source water salinity, which tends to increase the basin salinity, and inversely correlated with river discharge, which tends to decrease the mean basin salinity (Figure 20). When the PNW index is negative (positive), river water discharge and source water salinity are above (below) normal. Thus, the enhanced salinity brought about by the more saline source water is offset by vertical mixing of greater runoff into the basin.

Tidal Rectification (Net Transports by Tidal Currents)

Although tidal currents are oscillatory, non-linear processes in a spatially-variable frictional flow can lead to net (time-averaged) tidal residual flow. Known as *tidal rectification*, the effects of bottom topography and friction are to produce a mean residual flow which is independent of the estuarine circulation. Crean et al. (1988) use various forms of the GF-series of models (barotropic and baroclinic) to study net tidal circulation in several regions of the Georgia-Fuca system. Model results are compared with available current meter records for eastern Juan de Fuca Strait and southern Strait of Georgia. Directions but not magnitudes are correctly predicted by the model. It is worth noting that the counterflow predicted by the models for the vicinity of the Victoria outfall sites (Figure 21) agrees closely with current meter data being collected in this region. Foreman et al. (1992) have used a finite-element model to examine tidal rectification and eddy retention mechanisms over Swiftsure Bank at the eastern end of Juan de Fuca Strait. In this region, the tidally rectified flow appears to be strong enough to completely counteract the Lagrangian drift of particles released into the tidal flow.

STATUS OF NUMERICAL MODELING

Because of its complexity, the oceanography of the Georgia-Fuca system is a prime candidate for numerical modeling. Process-related studies in the field or in the laboratory enable us to understand the physical, chemical and biological processes driving the system. However, only through numerical simulation will we be able to achieve the needed insight into the integrated response of the entire system as a function of time and space. Motions in numerical models may be forced by tidal variations or other processes introduced at the open boundaries of the model, or by surface wind stress, variations in atmospheric pressure, and by tide-generating forces acting over the interior. Reliable numerical

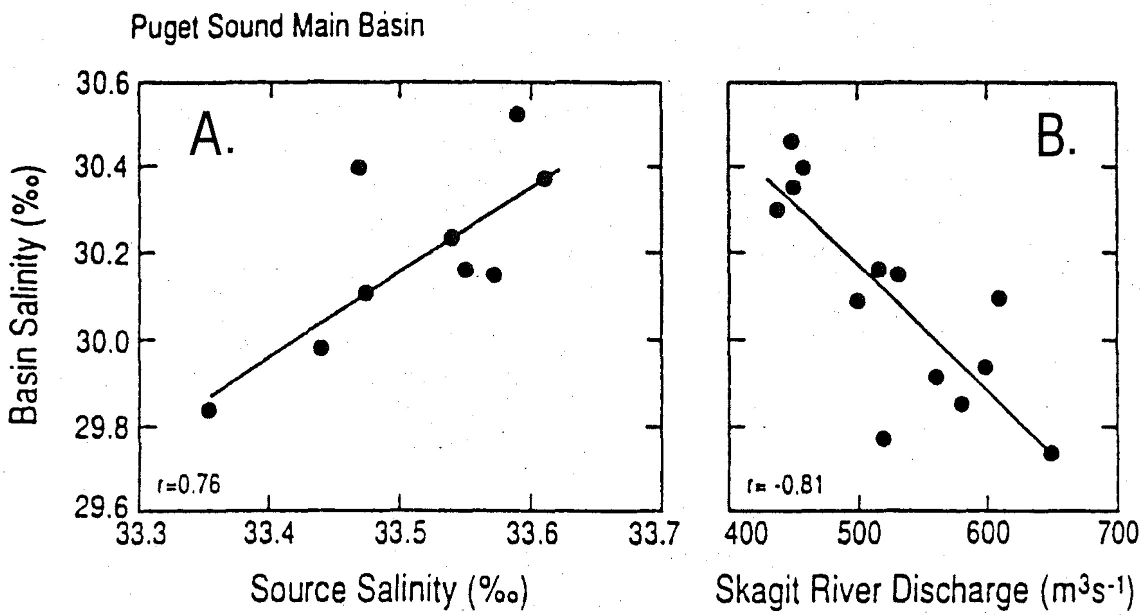


Figure 20. (A) Puget Sound main basin salinity versus source salinity in the central portion of Juan de Fuca Strait; and (B) Main basin salinity versus Skagit River discharge. Each dot is the annual average; r is the correlation coefficient; lines are linear regressions. (From Ebbesmeyer et al. 1989)

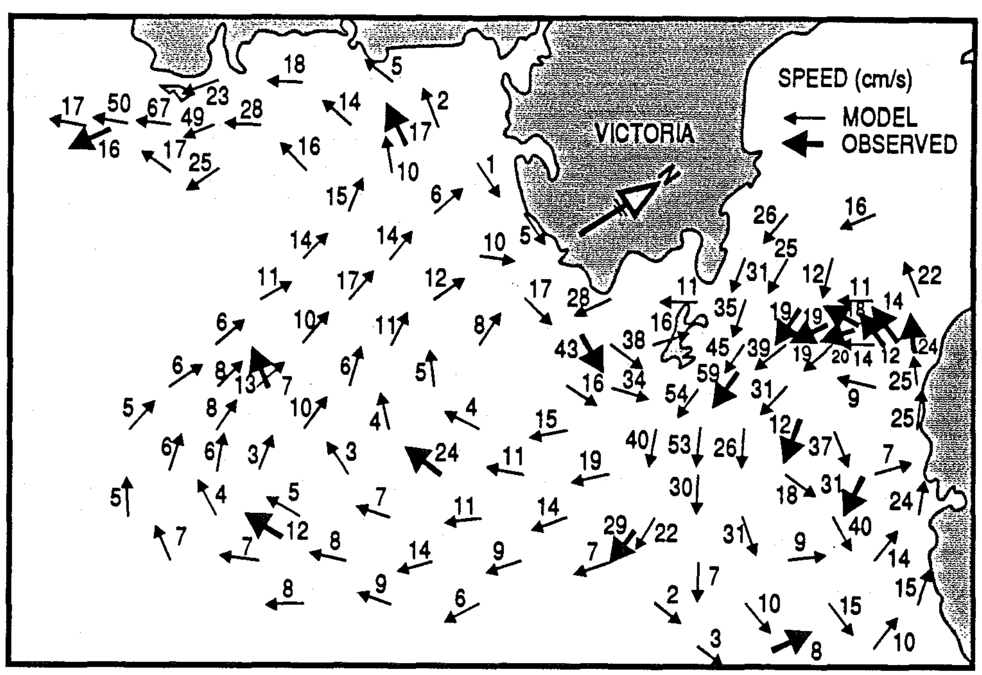


Figure 21. Comparison of residual tidal velocities obtained from a depth-averaged finite difference numerical model and from moored current meters for the region extending from Haro Strait to Race Rocks. (From Crean et al. 1988.)

models allow us to both decipher the processes affecting variability in the system and to make predications of future alterations to the system brought about by changes in external factors such as changes in rainfall and prevailing winds. The following section is an attempt to survey the present status of modeling efforts in the Georgia-Fuca system.

Northeast Pacific Tidal Models

Since the Georgia-Fuca system co-oscillates with tidal motions in the northeast Pacific, it is of fundamental importance to know the oceanic tide as correctly as possible before attempting to model tidal motions in the inner passages. The oceanic solution forms the important outer boundary conditions for the tidal motions in the inland waterway. Most tidal modeling efforts in the waterway make use of the basin-scale numerical tidal model developed by Flather (1987) for the principal diurnal (K_1) and semi-diurnal (M_2) barotropic tidal constituents in the northeast Pacific from Washington State to Alaska. The tidal height model for the northeast Pacific also has been used to drive the higher resolution tidal model for the west coast of Vancouver Island (Flather 1988).

The equations are solved by means of an explicit finite-element difference technique using an Arakawa "C" grid, conveniently represented as an array of elemental boxes each with the tidal elevation defined at the center of the box and the two components of current (u,v) at the midpoints of the meridional and zonal sides, respectively. The model grid for the Vancouver Island shelf has box dimensions of $1/18°$ in latitude and $1/12°$ in longitude, equivalent to about 6 km distance on a side. The grid covers the shelf and slope waters out to 2000 to 2500 m depth and includes the outer reaches of Juan de Fuca Strait. From the point of view of this review, an important aspect is the control that the mouth of the strait has on diurnal period tidal motions over the southwest shelf of Vancouver Island. By closing off the entrance to the strait in his model, Flather was able to show that the large diurnal tidal current oscillations at the mouth of the strait were the source region for diurnal period continental shelf waves which are observed to propagate poleward over the shelf and slope (Crawford and Thomson 1982, 1984). Thus, the ocean influences the strait but the strait also has a profound effect on the oceanography of the ocean.

The Georgia-Fuca (GF) Finite Difference Models

Development of a series of finite difference models for the Georgia-Fuca system began in the late 1960s with Dr. Patrick Crean of the Pacific Biological Station in Nanaimo. These models use fluid dynamic equations of motion similar to those described in the previous section to calculate oceanic parameters such as sea level height and horizontal flow velocity at the center and corners of a regular grid. The numerical formulation of the governing equations follows the semi-implicit scheme of Flather and Heaps (1975). From an IBM 1130 ". . . used at night because of the prodigious amounts of time required by the one-dimensional model GF1, tenderly nurtured as each increase in core saw the growth of an additional side channel", the work soon progressed to larger and faster machines and ever increasing layers and channels (Crean et al. 1988). The relevant field observations needed to calibrate and verify the model were obtained with the assistance of the Canadian Hydrographic Service, the Department of Fisheries and Oceans, and the National Oceanic and Atmospheric Administration. Since those humble beginnings, the model has evolved into a series of commercially applied models for specific uses. Seaconsult Marine Research Ltd. markets three models suitable for pollution studies in coastal regions: GF8, GF9 and EDIS (Jim Stronach, Seaconsult Marine Research, pers. comm. 1994).

The three-dimensional GF8 model is a prognostic, fully-nonlinear baroclinic model that uses finite differences in space and time (Arakawa "C" grid) to compute sea levels, currents, temperatures and salinities averaged over fixed depth levels throughout the entire basin including Puget Sound (Figures 22, 23). The model is forced by specified amplitudes and phases of the known tidal constituents and allows for imposition of a time-and space-varying surface wind. Tidal and density fluctuations are imposed at the open coastal boundaries. Results from the model include realistic tides, tidal currents and the appearance of denser water at the seaward entrance to Juan de Fuca Strait, as well as the generation of internal waves off Boundary Passage.

The GF9 model is similar to the GF8 model except that the interface between the brackish surface layer 1 and the underlying salt water layer 2 is allowed to move vertically to simulate the strong pycnocline between the

A.

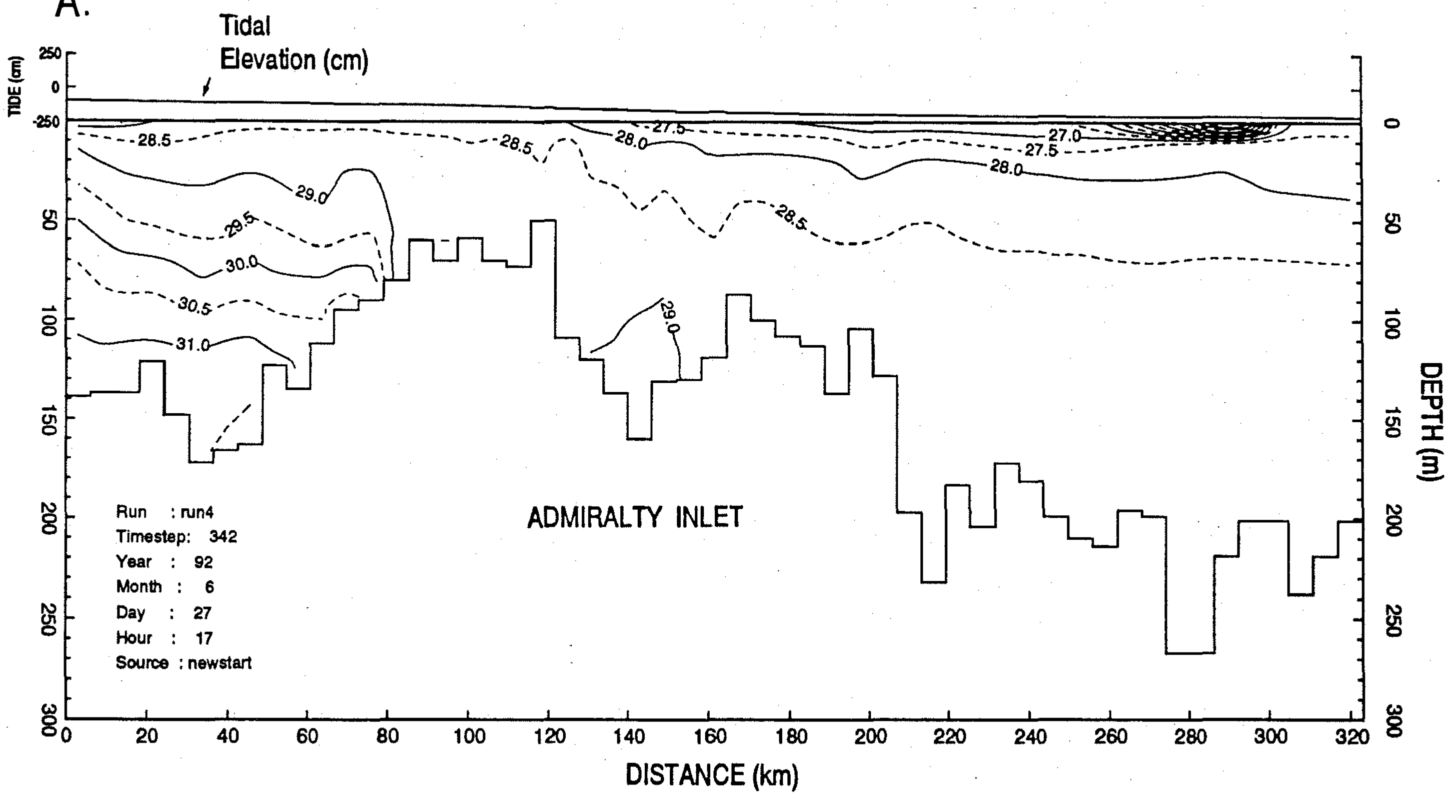


Figure 22. Cross-sections through Admiralty Inlet showing alternate states of salinity distribution at two representative stages of the tidal cycle. The 29‰ contour is migrating into Puget Sound on the flood while the 28‰ is retreating. The shallow surface plume on the right is from the Duwamish River. (Courtesy Jim Stronach, Seaconsult Marine Research)

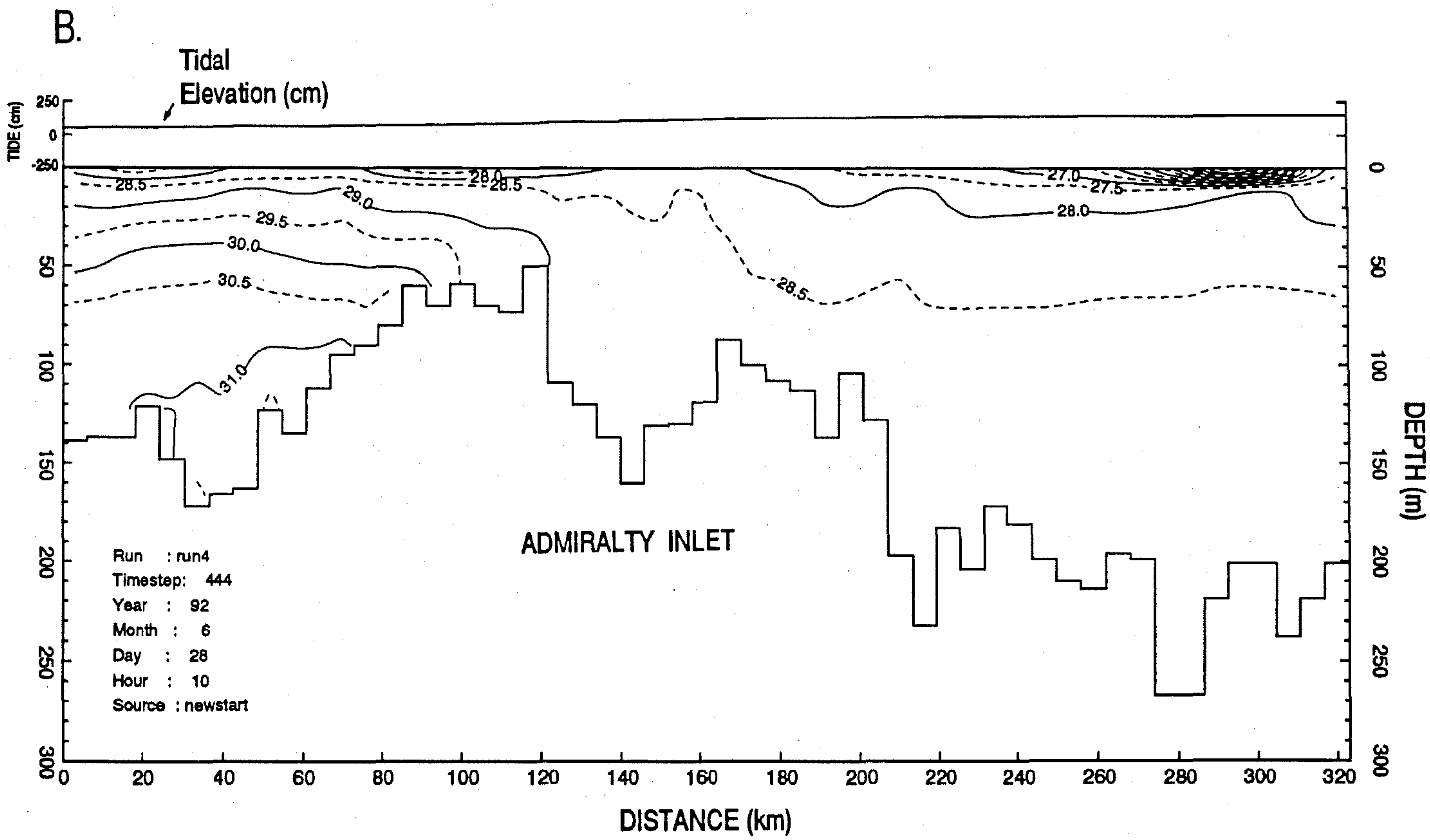


Figure 22. *Continued*

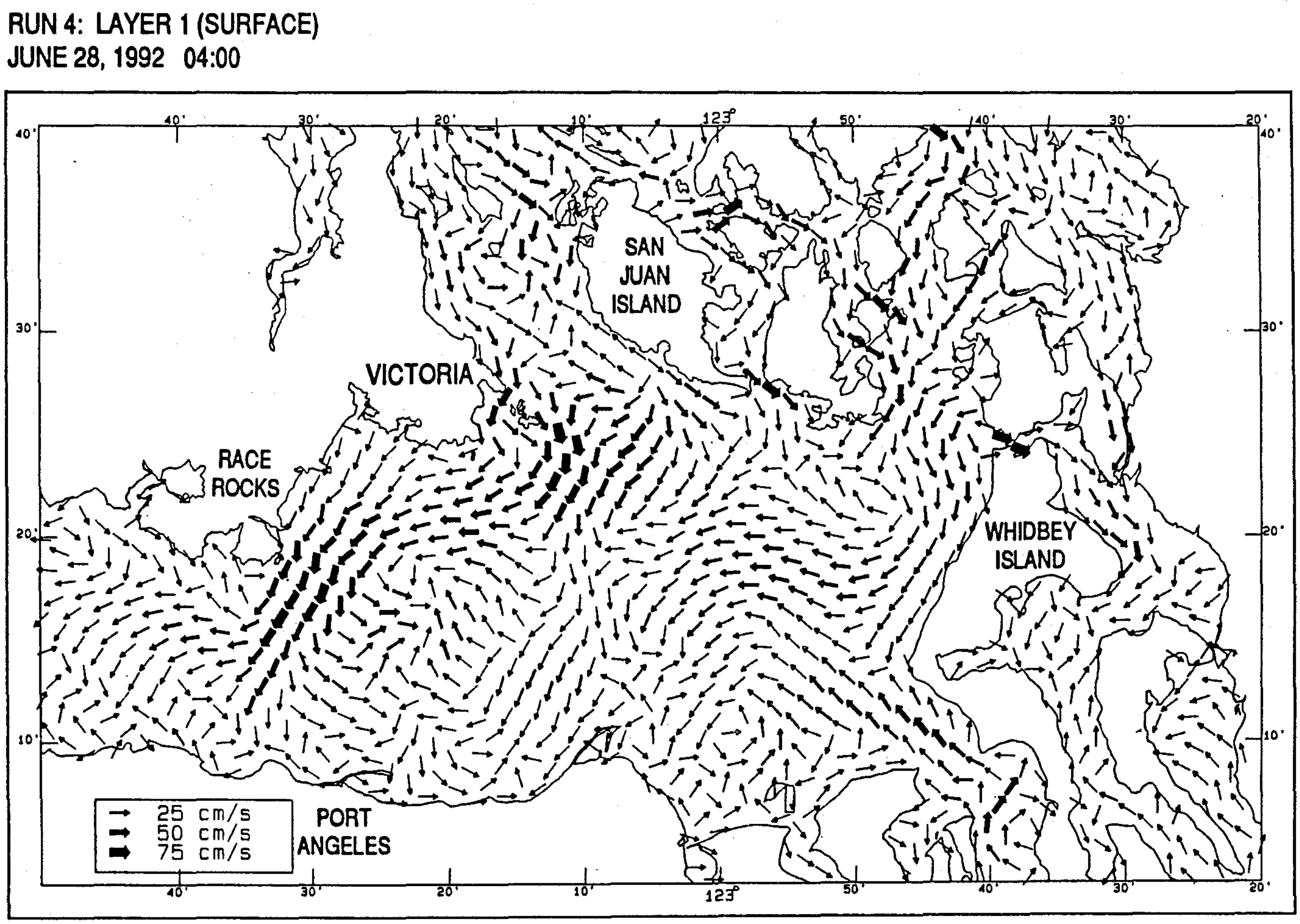


Figure 23. Surface currents in Juan de Fuca Strait midway between the two cross-sectional plots of Figure 22. Strong cross-strait currents are seen to the south of Race Rocks to the west of Victoria. (Courtesy Jim Stronach, Seaconsult Marine Research.)

Fraser River plume and the underlying ocean. This buoyant-spreading model is the preferred model for examining surface temperature variability in the Georgia-Fuca basin. An interfacial stress is used to couple the upper river water with the underlying oceanic model through the velocity shear and density difference. A second-order flux-corrected transport algorithm can be added to these models for studying transport and diffusion of passive scalars such as phytoplankton, sewage, pulp mill effluent or specific contaminants such as dioxin. External non-conservative processes such as sunlight, which increases the rate of decay of coliform bacteria while warming of the water column, also can be included. This module can be used for the density-advection equation to ensure the low numerical dispersion required for multi-year simulations.

Tidal currents for the Juan de Fuca Strait-Strait of Georgia region derived from the GF6 model have been published as a series of flood and ebb maps in the *Current Atlas* (Bolton et al. 1983). These tidal current charts enable the user to determine the flow structure at about 4-km resolution in the Georgia-Fuca System for different stages of a typical mixed tide in the Strait of Georgia. Except for the entrance to Admiralty Inlet, Puget Sound has not yet been included adequately in the baroclinic model.

Finite Element Models

Although three-dimensional finite difference, regional-scale models provide important insight into the physical mechanisms affecting circulation in the inland waters, the resolution of the models is too coarse to adequately model flow in the vicinity of the large number of islands and small channels. The limitations in resolution arise from limitations in computer technology. The GF-series of models, for example, typically has only one or two grid cells in the smaller channels and much of the coastline is poorly resolved. A similar 3-dimensional finite difference model developed for Puget Sound (Chu et al. 1988) could not adequately describe the tidal propagation in these small channels because of the step-like geometry in the numerical grid. Another approach is to develop a two-dimensional longitudinal-vertical model and neglect the lateral dimension. With such a model, Lavelle et al. (1991) were able to attain 20-m vertical and 3-km horizontal resolution for the main basin of Puget Sound. Noteworthy features of the model included reproduction of the density flow over Admiralty Inlet and the generation of internal tides between Admiralty Inlet and The Narrows. The internal tide waxed and waned over long time scales because of changes in stratification.

In an attempt to better resolve the small scale features of the Georgia-Fuca system associated with the numerous small islands and rugged coastline, two-dimensional finite element models are now under development. The problem of improved spatial resolution has been addressed in a series of 2- and 3-dimensional models developed by Walters (1987, 1991) and Foreman et al. (1994). Present models are essentially barotropic but can impose a fixed, measurement-based baroclinic (density) structure. These models use a finite element approximation in space and a harmonic approximation in time, and include all the non-linearities from the shallow water equations. The finite element approach allows for a variable resolution that is dependent on the local water depth, and thus provides better resolution near the coast and topographic rises. The harmonic approximations in time leads to the required computational efficiency. The models allow for as many tidal constituents as one wants to build into the model, steady state winds and an imposed density structure. Time steps are limited by the Courant-Friedrichs-Lewy criterion for barotropic (surface) wave speed. For baroclinic models, time-stepping is limited by the internal gravity wave speed.

Foreman et al. (1993) have developed a three-dimensional finite element model to calculate the tidal, estuarine, and wind-driven flows in the eastern Juan de Fuca Strait and the southern Strait of Georgia. The model is especially useful for the Gulf and San Juan islands where the geometry, bathymetry and currents are highly irregular. The present grid for the model (Figure 24) has approximately 20,000 triangles and sides vary in length from 80 m in one of the side channels to 3.7 km in the Strait of Georgia. The vertical structure of the model is presently discretized using a total of 21 layers. Test calculations have been made with a refinement of the two-dimensional grid to 80,000 elements. Tides in the model are approximated using eight constituents that account for 85% of the daily current variance. Additional constituents can be added. The estuarine component of the flow is computed diagnostically from historical salinity and

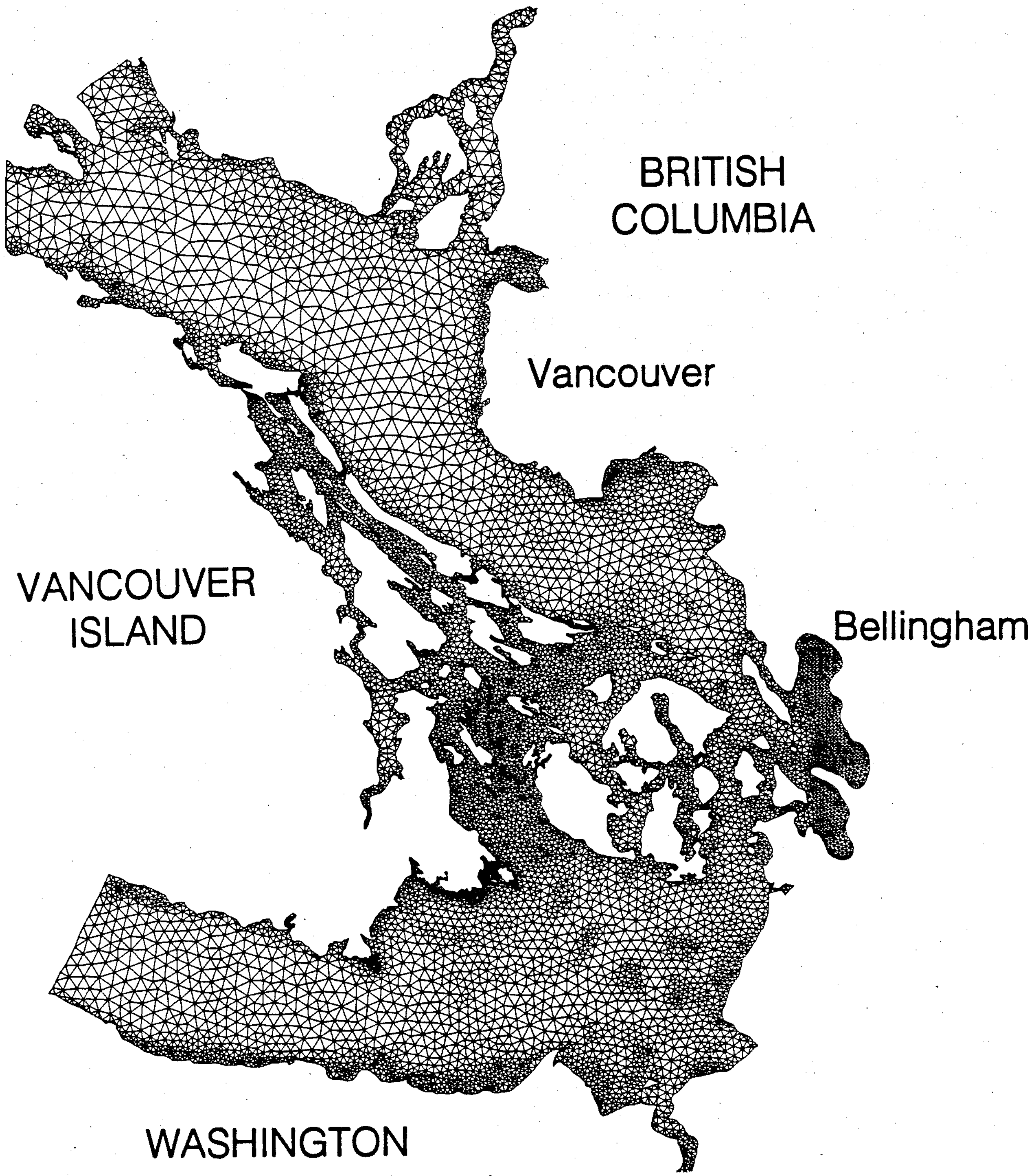


Figure 24. The finite element grid presently being used to model the circulation in the Georgia-Fuca system. Physical parameters are calculated at the "nodes" of the triangles. (Courtesy Mike Foreman, Institute of Ocean Sciences.)

temperature data collected by Crean and Ages in 1968. These fields are not permitted to evolve in time but a continuous evolution of the estuarine flow is permitted by interpolation between monthly responses. Wind-driven currents also can be simulated although only the steady response to the winds is permitted. However, periodic winds on diurnal and storm scales can be simulated. The static nature of the estuarine and wind responses is seen as a major limitation of the model and extension to a fully prognostic model is underway. Extensions to Puget Sound and the northern Strait of Georgia are in progress.

Puget Sound Numerical Models

The *Tidal Current Atlas* (Bolton et al. 1983) published for the Georgia-Fuca system based on the GF6 model included only the outer portion of Puget Sound (Admiralty Inlet) as part of the boundary condition for the broader model. The only existing atlas of the surface tidal currents for Puget Sound was prepared by McGary and Lincoln (1977) based on photographs of polystyrene particles placed in the Puget Sound oceanographic model operated at the University of Washington. As with any physical model, the flow estimates are limited by frictional effects and the ability of the model to scale correctly to real geophysical flow. Winds and rotational effects are not included in the model. Currents are referenced to eight stages of a mixed tide at Seattle.

A time-dependent baroclinic model of Puget Sound has been presented by Lavelle (1988) and Lavelle et al. (1991). It focuses on the circulation of Admiralty Inlet and the main basin using two-dimensional coordinates in the along-channel and vertical directions with one-dimensional models for the adjoining basins. The model has 20-m resolution vertically and 3-km resolution horizontally. It is driven by time series of winds, runoff, surface elevation and salinity profiles taken from Admiralty Inlet entrance. The idea behind the model was to create a tool to study intrusions across the shoals of Admiralty Inlet and their propagation down the main basin. The model identifies the following factors as controls on the occurrence and strength of intrusions: (1) The trans-sill salinity gradient; (2) the intensity of tidal stirring and mixing over the sills; (3) the supply of fresher surface water through runoff; and (4) the winds. The model further shows that maxima in the basin salinities are coupled to maxima in the trans-sill salinity difference and that vertical transport at all frequencies is dominated by advection rather than by diffusion. Substantial freshening of the main basin takes place during the winter months because river discharges are large and freshwater becomes mixed downward in the sill region to be entrained in the landward bottom flows. Extraordinarily large river runoff can suppress the effect of large trans-sill salinity differences with the effect of weakening potential intrusions. Winds also can directly influence intrusions by determining the position of freshwater lenses relative to the sills. Winds can directly influence intrusions via bottom compensation flows in Admiralty Inlet. Northward winds encourage intrusions by enhancing the salinity differences across the sill. Figure 25 shows the mean salinity and velocity obtained from the high-resolution, two-dimensional numerical model of Lavelle et al. (1991).

Tideview

Channel Consulting Ltd. has developed a visualization system specifically designed for viewing tide height and tidal current predictions derived from numerical simulation models. Known as *Tideview*, the system is able to reconstruct and display tidal current predictions and tide height predictions for specified times. The user can have either a map of the currents for a given time or can display graphs of the tide height current velocity at a single site over a period of time. Although originally designed for recreational applications of the IOS finite element model, the system's ability to display all types of numerical model results makes it a useful tool for engineering and scientific applications. Additional functionality found in the program includes: (1) display of water depths and numerical model grids; (2) display of currents and tide heights; (3) calculation and display of particle tracks for pollutant and oil spill dispersal studies. Incorporation of three-dimensional fields and display is now underway.

EVIDENCE FOR TRANSBOUNDARY TRANSPORT

In this section, we present some of the existing evidence for along- and cross-channel transboundary transport within the Georgia-Fuca System. The conclusion is that transboundary transport is an everyday occurrence, a

fact that is readily apparent in the movement of the Fraser River plume which regularly passes unchallenged between Canadian and United States waters.

Satellite Imagery

Some of the most direct evidence for transboundary transport can be found in satellite and airborne images of surface water movement. Airborne mapping provides detailed visual information on oceanic features while satellite imagery provides larger scale information of the similar features (LANDSAT satellite imagery has a pixel size of about 10 m while NOAA satellite imagery has a pixel size of 1.1 km). LANDSAT visual imagery and NOAA satellite Advanced Very High Infrared (AVHRR) imagery obtained in summer during periods of clear skies and moderate to strong northwesterly winds clearly show the tendency for the warm brackish particle-laden waters of the plume to cross the international boundary separating Canada and the United States in the southern sector of the Strait of Georgia (Figure 4). Although most prominent in summer when runoff is greatest and conditions most favorable to satellite imagery, the movement of the plume across the international boundary is a year-round process. Tidal mixing in the narrow passes normally blocks the seaward passage of the plume waters but during times of weak mixing the surface waters of the strait leak out of the Strait of Georgia into Juan de Fuca Strait.

Drift Card Deployments

Ebbesmeyer et al. (1979) report on the recoveries of 240 of 700 drift cards deployed from Port Angeles harbor on the southeastern shore of Juan de Fuca Strait in the late 1970s (Figure 26). A large number (66%) grounded in the immediate vicinity of Port Angeles with another 22% grounding east and northeast of the city. The single drift card that reached Victoria may have taken a circuitous route rather than the direct

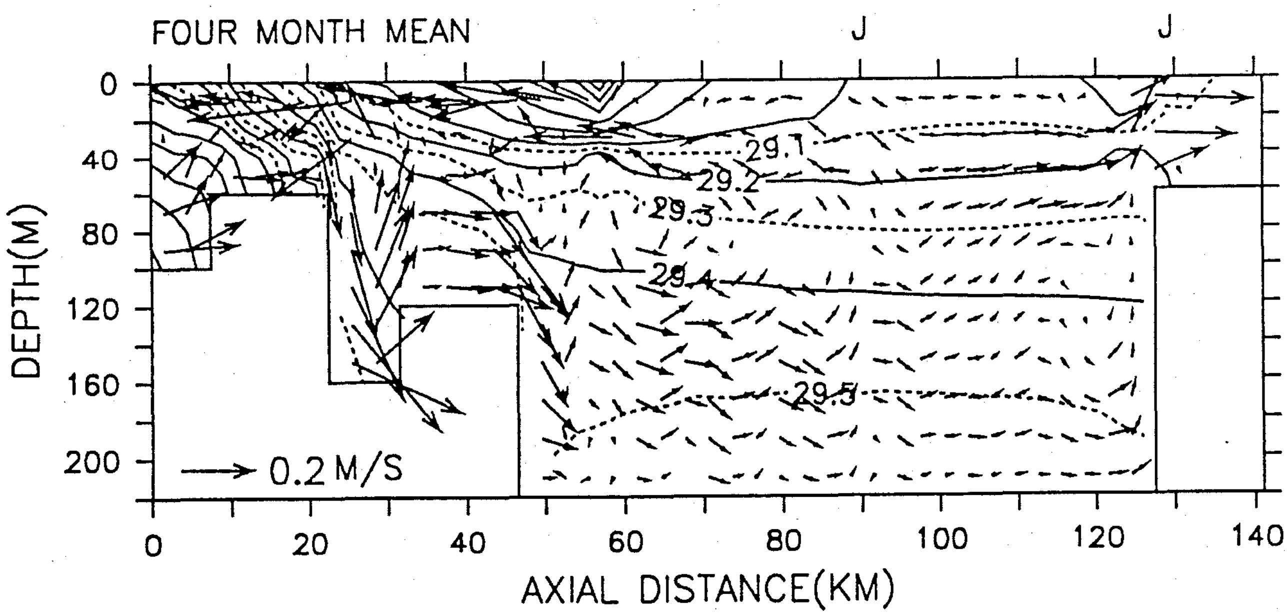


Figure 25. Four-month mean of two-dimensional time-dependent model of subtidal velocities (m/s) and salinities (‰) in Admiralty Inlet and the main basin of Puget Sound. Scale represents horizontal velocities; vertical velocities are magnified by a factor of 150. The line J - J denotes the junction of Colvos Passage with the main basin. (From Lavelle et al. 1991)

course suggested by the drift card recovery map (Wolferstan 1981). Drift card studies in the Strait of Georgia have been summarized by Waldichuk (1957).

Floatable Wreckage

Ebbesmeyer et al. (1991) have examined the distribution of shipwreck material that followed the collision between the steamship SS *Pacific* and the clipper ship *Orpheus* about 15 to 20 miles off Cape Flattery on the Washington coast on 4 November 1875. The SS *Pacific* sank within one hour of the collision and debris was scattered into the ocean at the time of strong southeast winds and a heavy sea. Only 6% of the 250 to 300 passengers on the ship were recovered, including two survivors who drifted into Juan de Fuca Strait with the ensuing current. Information used in the report suggests that the collision was followed by a protracted reversal of the surface estuarine flow in the strait due to a series of five major storms in November. Commentaries by the two *Pacific* survivors as they drifted into the strait over the next few days indicated that they had significant cross-channel trajectories. As indicated by Figure 27, the greatest amount of debris over an 11-day period after the collision was reported in three places: (1) off Neah Bay three days after the collision; (2) north of Port Angeles on 10 November; and (3) in the vicinity of Victoria during 11–14 November.

Although windage on the debris was not taken into account, the study clearly shows the ability of combined wind and current transport to move materials across the international boundary. The observation of debris off Victoria on 8 November suggests a combined wind-current transport up-strait at a speed of about 20 miles per day with an obvious cross-border component from the vicinity of Neah Bay to Victoria. Overall statistics indicate that the debris traveled up-strait at rates of

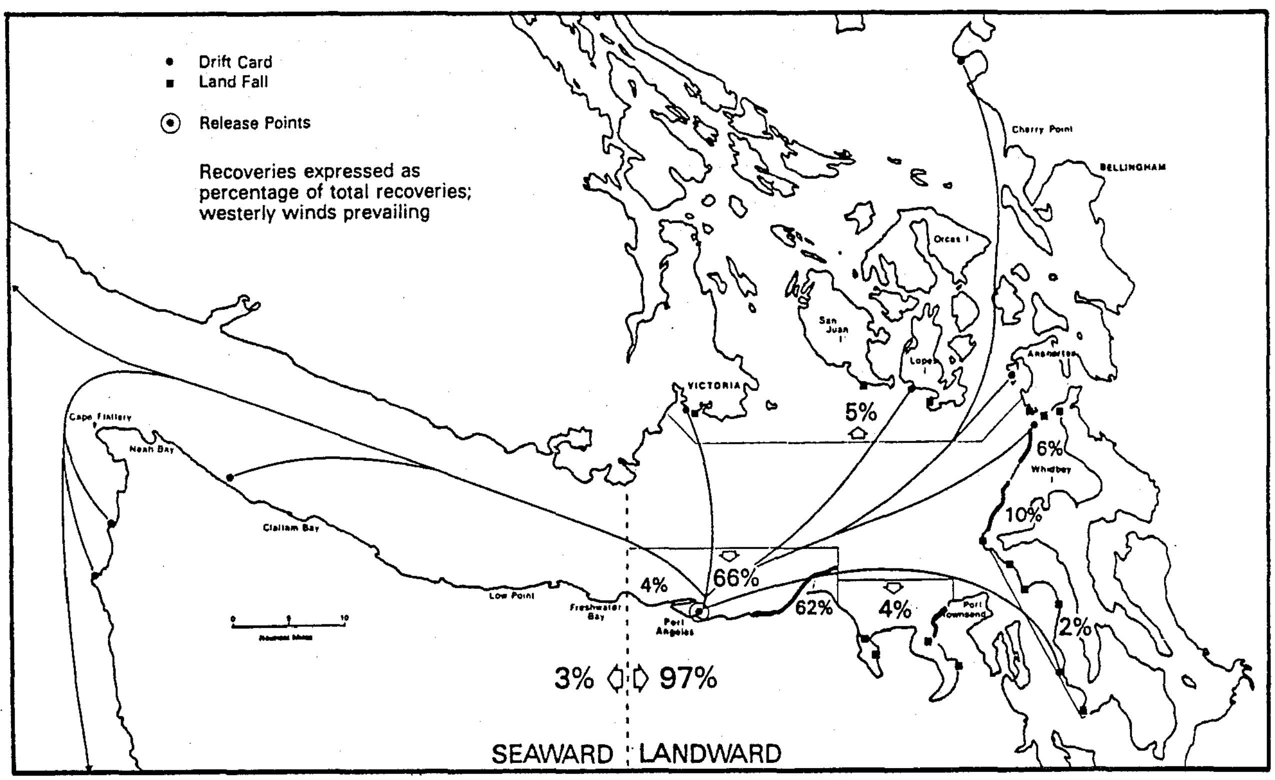


Figure 26. Summary of drift card recoveries in Juan de Fuca Strait for cards released from Port Angeles Harbor. (From Wolferstan 1981.)

9 to 20 miles per day (19–43 cm/s) and was able to penetrate as far as 100 miles inland.

Nestucca Oil Spill

During the stormy night of 22 December 1988, the barge *Nestucca* and its tug *Ocean Service* collided off Grays Harbor Washington while operators were attempting to replace a snapped tow cable. A two-meter gash in the hull of the barge resulted in the rapid escape of 231,000 gallons of Number 6 (heavy bunker C) fuel oil that began to drift with the prevailing northward winds and currents. Soon after, oil began to wash up on the beaches of northern Washington. By 31 December, oil had reached the entrance to Juan de Fuca Strait, and by 15 January 1989, some oil had washed up on the Canadian side of the strait. The oil from the spill continued to come ashore along the west coast of Vancouver Island and by 15 January had reached Cape Scott on the northwest coast of Vancouver Island. Ebbesmeyer et al. (1991) estimate the speed of the drift to be 18 nm/day (39 cm/s) from the spill site to Cape Flattery, 12 nm/day (26 cm/s) along the west coast of Vancouver Island and 9 nm/day (19 cm/s) into the strait. Although conditions for flow reversal existed, evidence that remnants of the spill reached Sooke on the inner coast of Juan de Fuca Strait has not been substantiated.

Tenyo Maru Oil Spill

The fishing vessel *Tenyo Maru* sank near Finger Bank on the west coast of Vancouver Island on 22 July 1991. At this time of year, the coastal flow over the outer shelf is dominated by a wind-driven equatorward flowing shelf break current. Oil from this spill was observed to move toward the United States coast with the prevailing southward flow (Venkatesh and Crawford 1993).

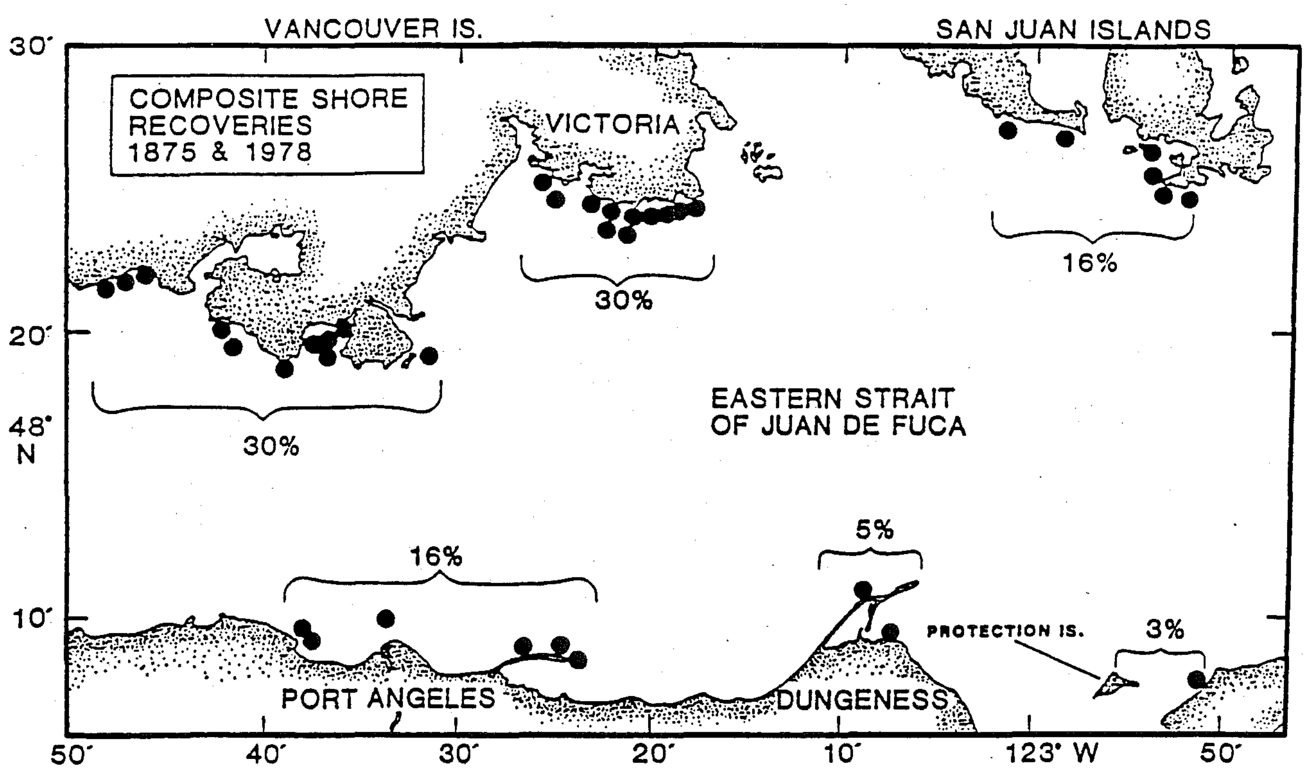


Figure 27. Composite of shore reports of the SS *Pacific* wreckage (1875) and drifters for 1978 in the eastern portion of Juan de Fuca Strait. (From Ebbesmeyer et al. 1991).

The important aspect of this spill is that it emphasizes the fact that the direction of transboundary transport can be expected to vary with prevailing wind conditions and season. Winds are mainly from the north in summer and from the south in winter.

Anacortes Oil Spill

At 0130 on 26 April 1971, approximately 230,000 gallons (880 m^3) of Number 2 diesel oil was spilled at the Texaco refinery near Anacortes in the eastern portion of the San Juan Islands (Ebbesmeyer et al. 1979). Aerial surveillance supported by waterborne observations and beachcombing revealed that the slick from the spill traveled southward through Rosario Strait and had reached Smith Island 24 statute miles (38 km) downstream in eastern Juan de Fuca Strait by 1800 on 26 April. A portion of the slick moved eastward to Guemes Island and a branch of the slick that entered the strait moved into San Juan Channel that separates Lopez Island from San Juan Island. In general the response to the spill by government agencies was rather feeble and there was no attempt to document the long-term movement of the slick as it moved into the central Juan de Fuca Strait.

Drifter Studies

Frisch et al. (1981) report aircraft-tracked drifters in the outer Juan de Fuca Strait which had seaward excursions of 25 km/day prior to a summer storm and then up to 60 km/day up-strait during a storm-induced flow reversal (Figure 15). Landward excursions of 55–60 km were observed which were about half that implied from winter current-meter observations. Drifter studies from drift cards released at mid-channel in the inner and outer strait under various conditions were recovered on the beaches of the strait (Pashinski and Charnell, 1979).

A recent drifter and water property study was undertaken during a two week period from the 25 June to 8 July 1993 by W. Crawford, M. Woodward and M. Foreman in eastern Juan de Fuca Strait south of Victoria. Trajectories from a total of 47 drifter deployments were obtained onboard the CSS *Vector* using 10 m-drogued Loran-C surface drifters built for the Tides and Currents Section of the Institute of Ocean Sciences. These drifters have absolute positioning accuracy of about 200 m and are little affected by windage. Light to moderate westerly winds prevailed throughout the field program and were not considered a major factor in the overall drift. Launch locations and recovery locations for all 47 deployments are presented in Figure 28. Trajectories for eight of the drifter tracks, including start and end times, are presented in Figure 29. Several aspects of the surface drift are immediately clear from these tracks: (1) The motions were dominated by semi-diurnal tidal currents and seaward flowing estuarine currents. The estuarine currents were persistently strong despite the moderate westerly winds; (2) The flow reversals that accompanied the change in the tide were fairly abrupt; and (3) There was considerable cross-strait drift, although none of the drifters launched on the Canadian side actually made it to the shores of Washington State. Drifters that neared the Canadian shore often became trapped in backeddies, especially in the vicinity of Race Passage to the west of Victoria. This tendency for nearshore drifters to land on the beach seems to be characteristic of floating objects, as experience with satellite-tracked drifters in the North Pacific has shown.

Numerical Model Studies

The three-dimensional diffusion of a pollutant cloud has been modeled using the three-dimensional density-dependent GF8 model (Stronach, 1990). In this model, velocity calculated from the hydrodynamic model is augmented by random velocities generated by Monte Carlo simulation. The pollutant is "released" on a given isopycnal surface but changes depth as the depth of the density surface changes with time and space. Four simulations were carried out using a horizontal diffusion coefficient of 200 m^2/s and a time step of 10 minutes. The analyses were for winter stratification conditions, observed winds for the period 7–11 November 1987 and a single tidal constituent (M_2). Two simulations were done for the central Strait of Georgia and two for Juan de Fuca Strait south of Race Rocks. In the latter case, particles were deployed at a density surface of sigma-t = 23.9 (depth ≈ 55 m) and in the second case at the surface. Results from these two simulations are shown in Figures 30 and 31, respectively. Winds were from the north at about 10 m/s for the first two days and then weak and variable for the rest of the record (Figure 30A). The grid box scale for the model is 1.95 km × 1.95 km and a total of 10,000 particles were originally released. Concentrations are measured as the number of particles per grid area of 3.80 km^2.

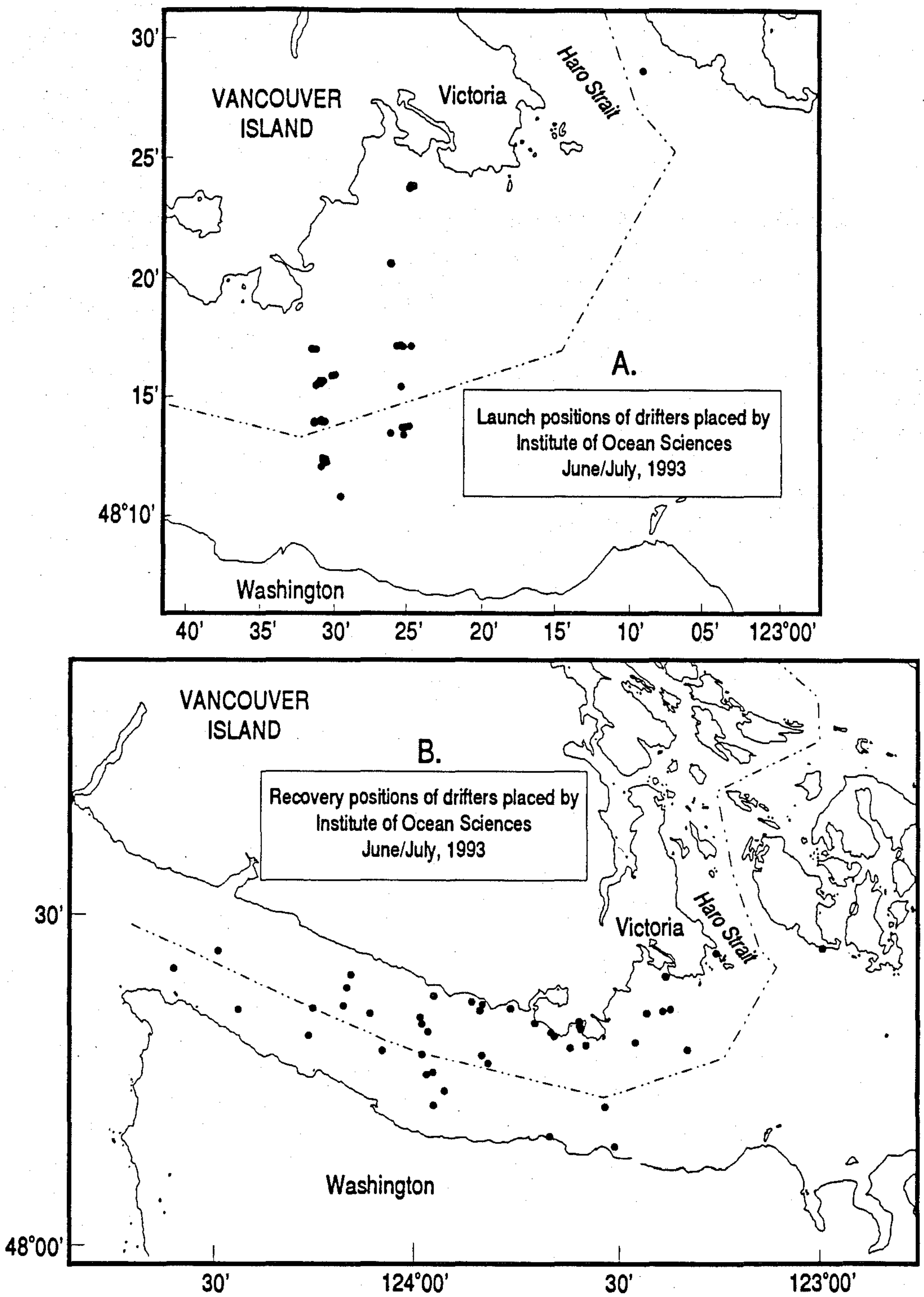


Figure 28. Launch and recovery sites of Loran-C surface drifters launched in the eastern portion of Juan de Fuca Strait in June/July 1993. Drifters were tracked on-site from the C.S.S. *Vector*. (Courtesy Bill Crawford, Institute of Ocean Sciences)

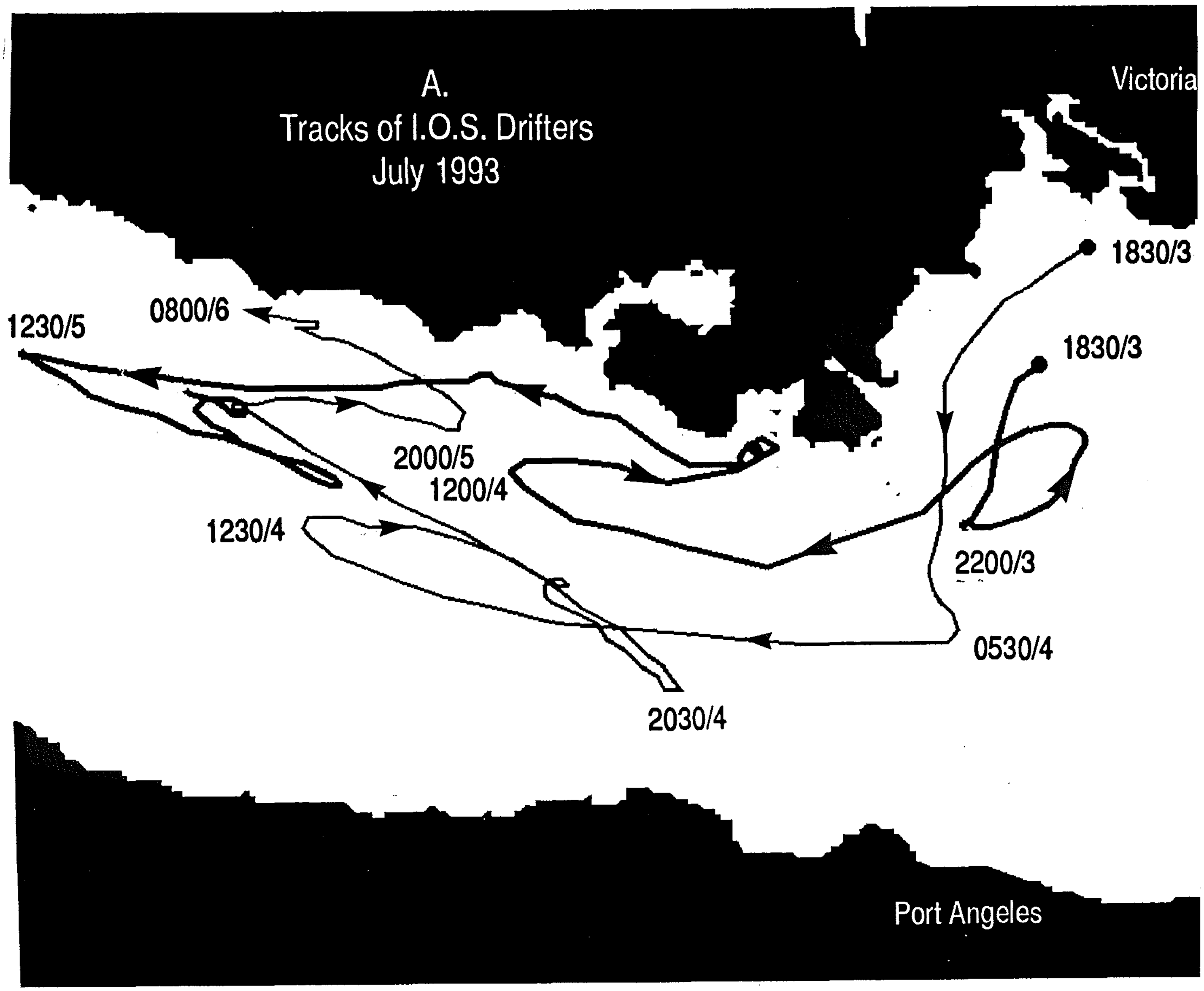


Figure 29. Trajectories for eight of the 47 Loran-C surface drifters launched in July, 1993. Solid dots give launch sites; times are hour (PDT) followed by day. (Courtesy Bill Crawford, Institute of Ocean Sciences)

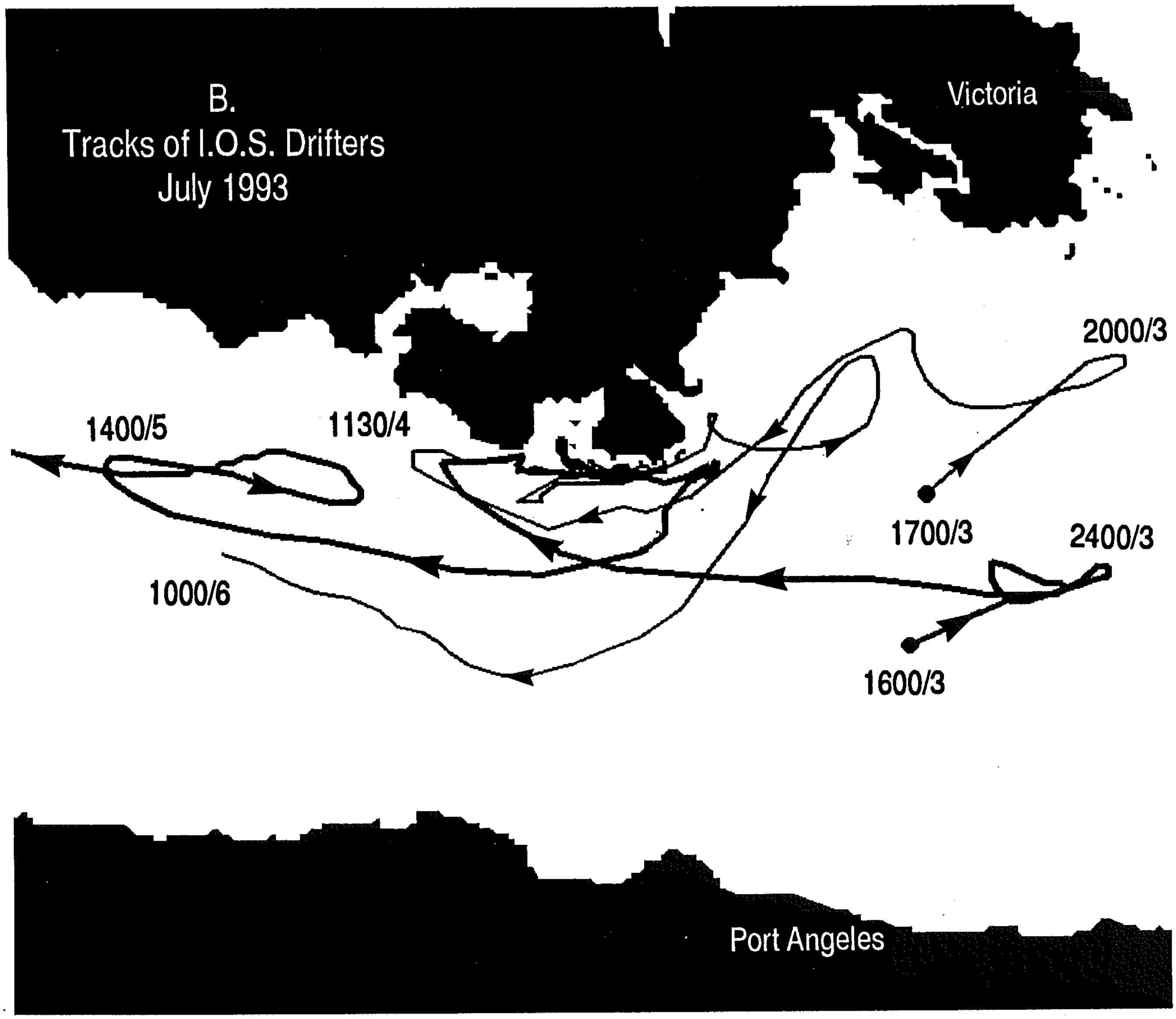
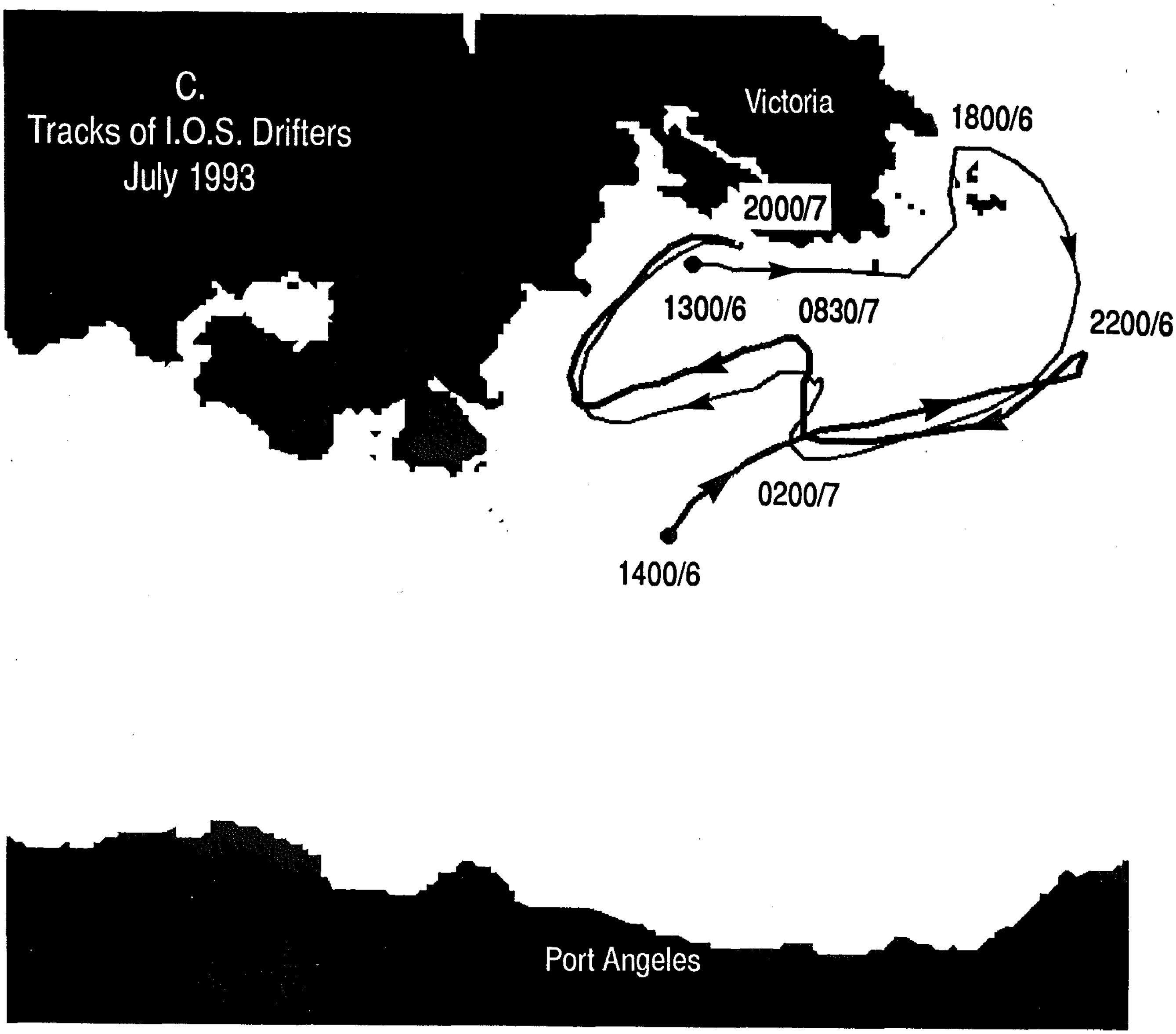


Figure 29. *Continued*



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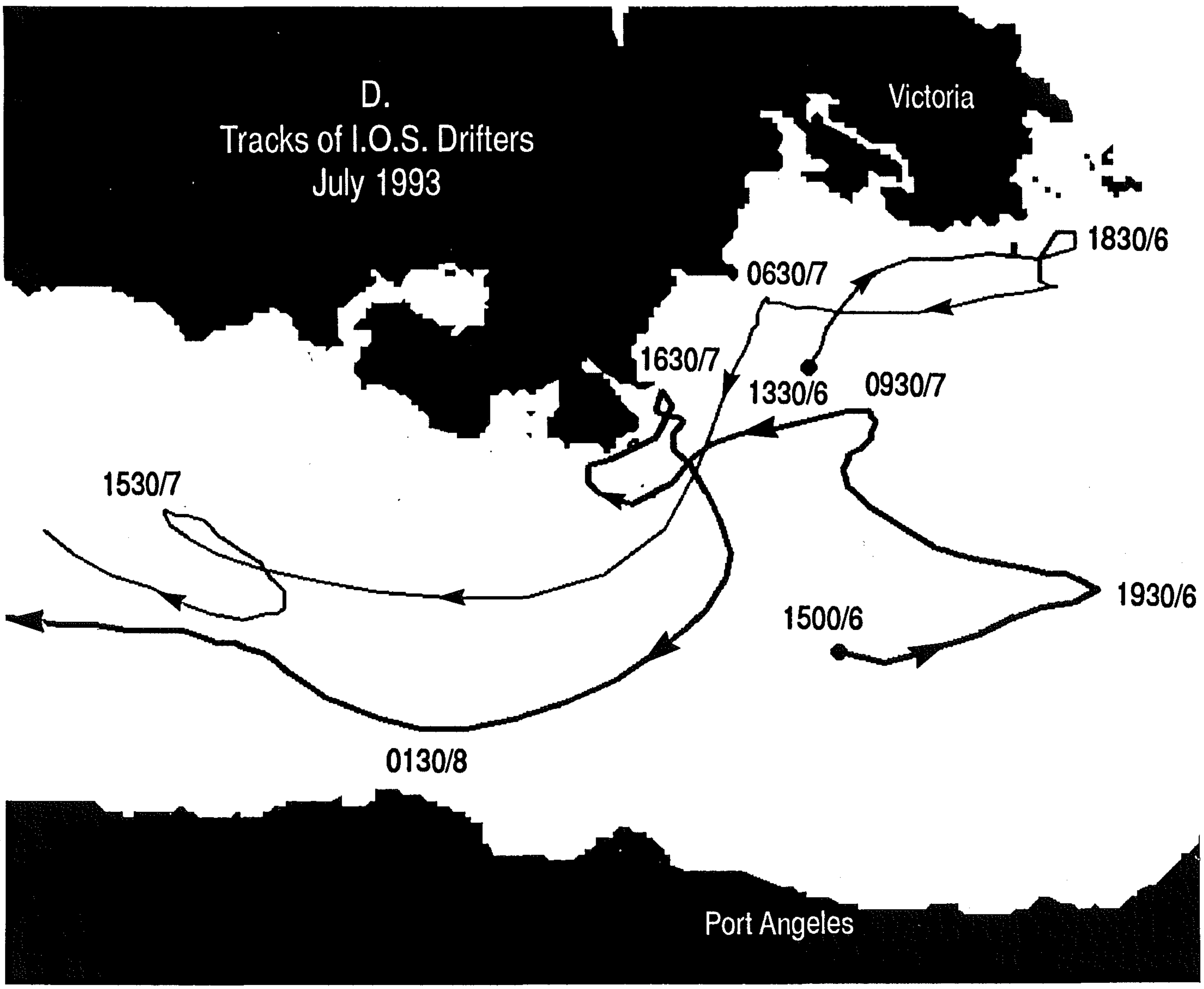

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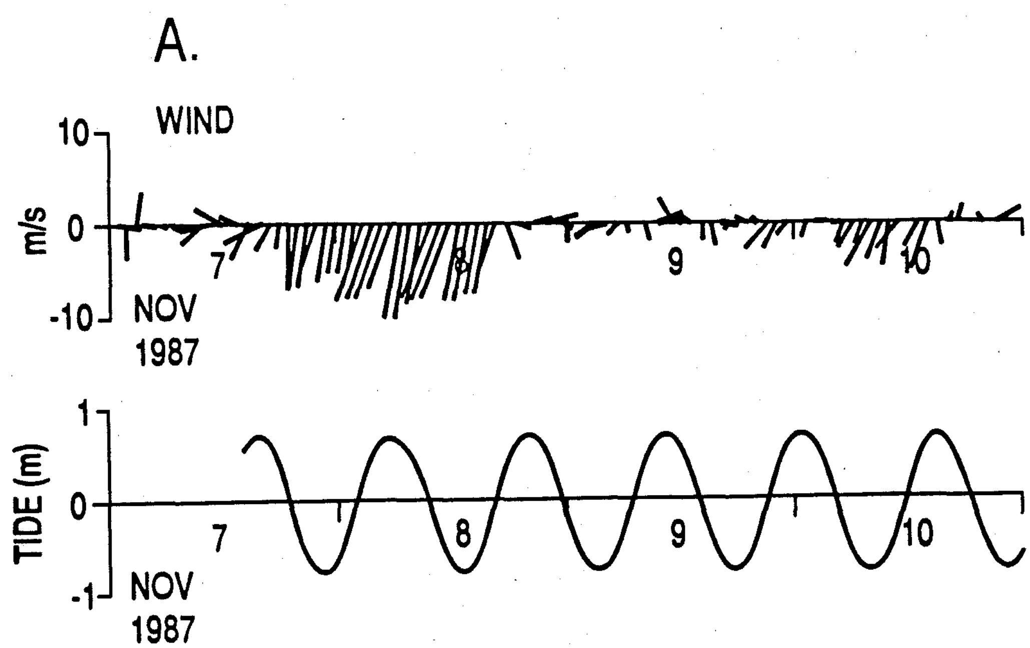

Figure 30. Particle concentrations (particles per 1.95 km-square grid cell) starting with 10,000 particles deployed at ≈ 55m depth in a Gaussian distribution near mid-strait (■) for winter estuarine flow conditions and observed winds in the Seaconsult Research Ltd. GF-8 baroclinic model. (A) Tide and wind conditions for the model run; (B) Particle distribution one day into the start of the run (Day 8). Particle depths ranged from 50m on the western side of the distribution to about 70 m on the eastern side; (C) Particle distribution near the end of the model run (Day 11). Particle distributions ranged from 45 m in the west to over 100 m in the east. (Adapted from Stronach 1990.)

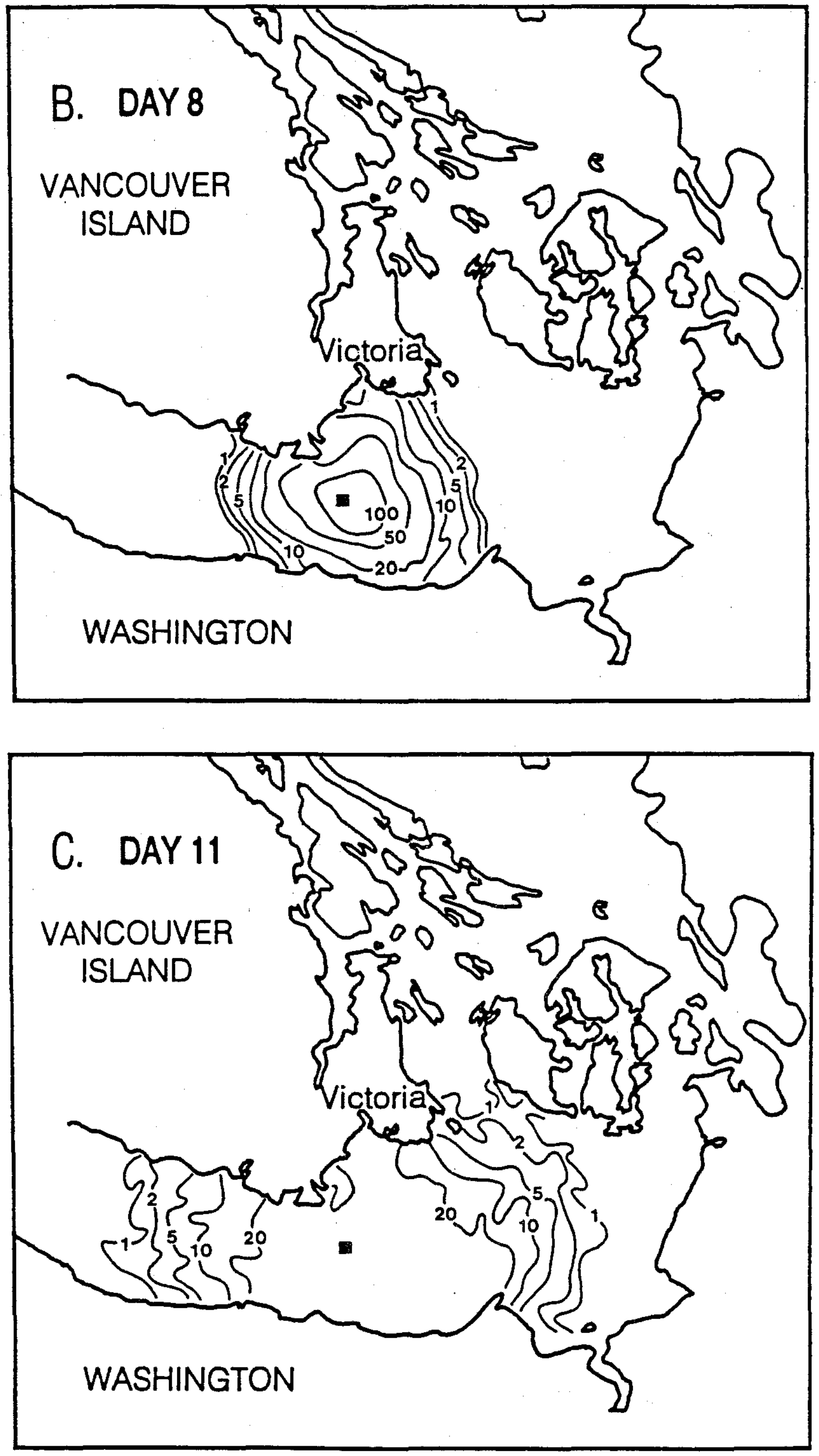

Figure 30. *Continued*

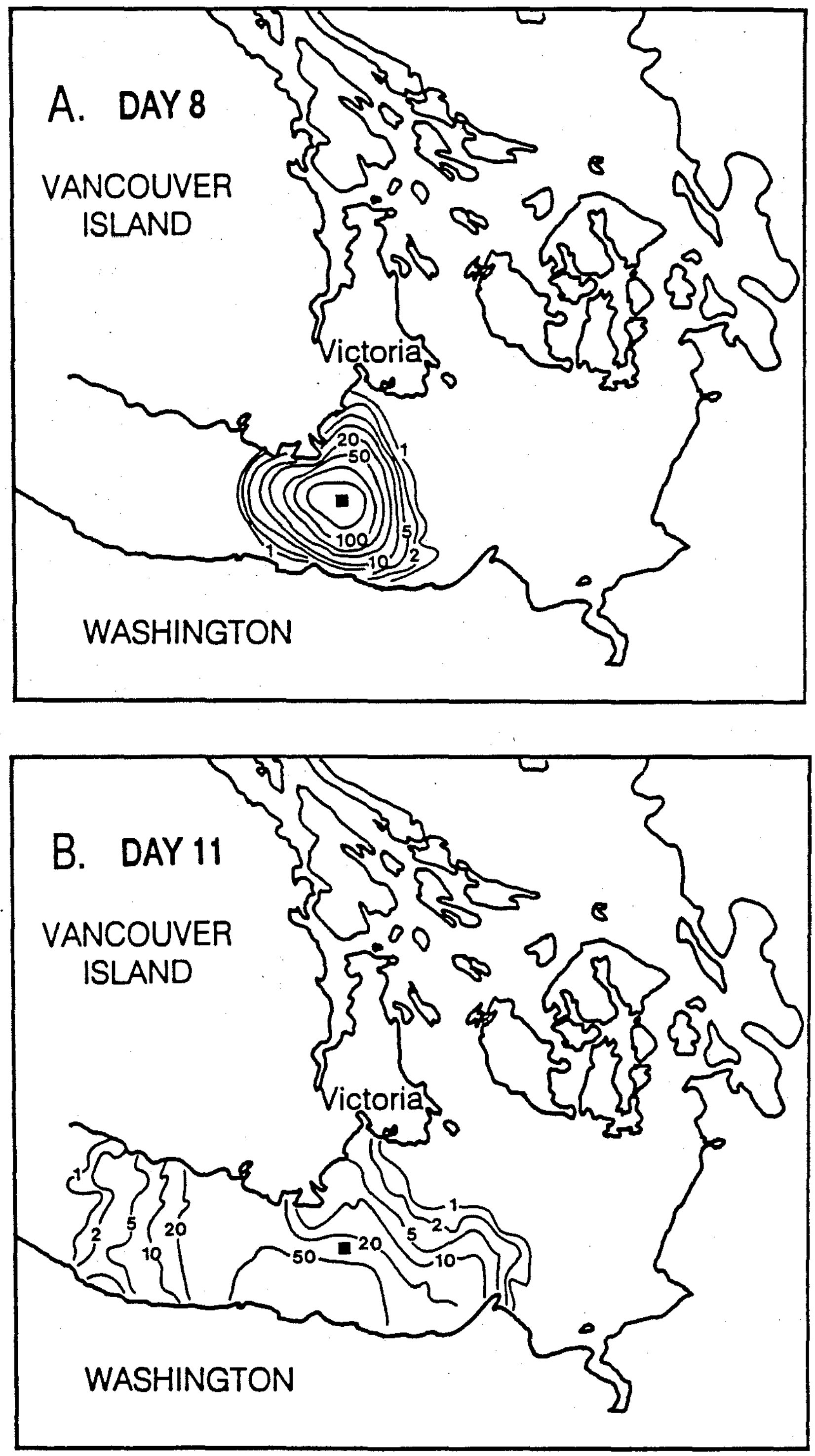

Figure 31. As with Figure 30 except for surface (depth = 0m) deployment of particles. (A) Particle distribution one day into the start of the run (Day 8). The model retains particles at surface; and (B) Particle distributions near the end of the model run (Day 11). (Adapted from Stronach 1990.)

Although the situation is highly idealized, the results of the model imply the spread of passive "pollutants" into Canadian and United States waters. Three days after the particles were released, the combination of wind and currents had resulted in relatively high concentrations of particles along the eastern shores of Juan de Fuca Strait for both the surface and intermediate depth levels. At the surface, particles tended to move seaward with the prevailing estuarine circulation.

Victoria Sewage

No discussion would be complete without some remarks about the possibility of transboundary transport from the two Victoria sewage outfalls located at Macaulay and Clover Points in 60 to 65 m of water a few kilometers southward of Victoria. Initial entrainment by the buoyant freshwater plume leads to hundred- to thousand-fold dilution of the rising effluent. Under normal conditions, the plume rises to a level of neutral buoyancy several tens of meters below the surface. However, in late winter, when near-uniform stratification prevails in the eastern sector of Juan de Fuca Strait, the plume may reach the surface. Current meter observations and numerical modeling results indicate that the mean flow is weakly to the east and southeast within a few kilometers of the Victoria shoreline and that mixing is vigorous throughout the region because of the strong tidal currents. As indicated by Figure 21, the eastward drift merges with a strong southward mean flow from Haro Strait and subsequent advection is seaward into Juan de Fuca Strait. A report by EVS Consultants (1992) summarizes all available data and finds that greatest contamination of the sediments and modification to benthic organisms is confined mainly to an east-west distance of about 100 m from the outfall but can extend up to about 400 m or more for certain metals and chemical compounds. North-south distributions have not been adequately determined. Surface water contamination is low except immediately over the outfalls. Greases rise to the surface but appear to be rapidly dispersed by the surface flow. The discharge rate for the combined outfalls is roughly a factor of $1/10^5$ smaller than that for the upper layer of Juan de Fuca Strait.

Seaconsult Marine Research has developed a PC-based EDIS (Effluent Dispersion) model, which incorporates an embedded buoyant plume model (the United States Environmental Protection Agency distributed initial dilution model), to generate barotropic flow at 333 m grid resolution off Victoria for examination of effluent dispersal from the Victoria sewage outfalls. The model includes tidal currents derived from the two-dimensional hydrodynamic model, winter and summer estuarine simulations from the GF8 model, and historical or manually-input surface winds. A Monte Carlo simulation of contaminant dispersal also includes the effects of particle sinking. The model has been applied to studies of pulp mill effluent in coastal waters.

CONSEQUENCES OF LONG-TERM CHANGE

Having established the primary transport mechanisms for the Georgia-Fuca system, we can now begin to think about the kinds of changes that might occur as a result of natural or anthropogenic modifications to the physical system. Factors that could conceivably alter the circulation of the Georgia-Fuca system are: Global climate change; construction of hydro-dams across tidal narrows; and diversion of runoff from the major rivers. The British Columbia government at one time considered building a floating bridge across the Strait of Georgia which would have altered significantly the movement of brackish water in the strait.

Global Climate Change

There is much concern lately concerning the possibility of long-term changes in the global climate due to the continued emission of "greenhouse" — infrared-absorbing — gases (carbon dioxide, methane, and certain chlorofluorocarbons) into the atmosphere. Mean annual surface air temperature records for the Northern Hemisphere assembled by Jones et al. (1986) and Hansen and Lebedeff (1987) imply a gradual warming of the surface air temperatures over the past 100 years that appears to be related to increased retention of long-wave radiation from the sun. If this is indeed related to a secular warming of the atmosphere, rather than to some natural long-term cyclic variability, there may be several significant consequences to the oceanography of the Georgia-Fuca system.

Sea Level Rise

Mixing of heat from the atmosphere into the upper ocean is one possible explanation for the observed eustatic (global) sea level rise of about 1 mm/year (Thomson and Tabata 1989; Douglas 1991). Assuming it remains

at about the same trend, such a rise in mean sea level will not have a major impact on the coastline over the next few hundred years although the effect of rise will clearly be more strongly felt in the low lying areas of the Fraser and Skagit river deltas. Sea level rise would also affect sediment discharge from the rivers and might have an impact on slumping of the deltaic foreshores.

As suggested by the map of "absolute" land movement in Figure 32, the contribution of sea level rise from global change is overshadowed in the Pacific Northwest by long-term changes in the elevation of the land due to tectonic activity along the continental margin. Crustal subduction and underthrusting associated with the relative movements of the oceanic and continental plates off our coast are equal in importance to long-term sea level changes in the ocean. (Local glacio-isostatic rebound is no longer considered important to sea level changes in this region.) For example, near Seattle, the crust is subsiding as much as 2 mm/yr while on Vancouver Island the land is emerging at a rate of 1 to 3 mm/yr. If we add this rate to the mean oceanic change of 1 mm/yr, then land around the southern end of Puget Sound is sinking at an annual mean rate of 2 to 3 mm/yr while that on much of Vancouver Island is rising at an annual mean rate of 1 to 2 mm/yr. Over a period of a few hundreds of years, such changes will begin to have a significant impact on the infrastructure of some of the major coastal cities. Sewage systems and shoreline stability are two structures that might be affected by the changing sea levels.

There is another important geophysical process hidden in Figure 32 — the build up of crustal stresses between the continental and oceanic plates that is causing the western boundary of Vancouver Island and northern Washington State to uplift. Under normal circumstances, the frictional stresses produced by the underthrusting of the oceanic plate along the continental margin are released through small-scale slippages. Unfortunately for those of us living in the Pacific Northwest, the overriding plate appears to be stuck, causing it to buckle under the lateral pressures of continental drift (Draggart, pers. comm. 1994). Predictions are that the stresses now being stored in the crustal rocks may be released through a major earthquake of magnitude 8 or greater on the open-ended Richter scale. Tremors from earthquakes of this magnitude can last for several minutes and cause massive destruction (cf. Thomson 1981). The return period for earthquakes of this magnitude is about 200 to 500 years. From the geological record, we know that the last earthquake of this magnitude to affect the Georgia-Fuca region was 300 years ago. We are therefore "due". But are we prepared?

Wind and Precipitation

Two of the attributes of the Georgia-Fuca system that may be affected by a change in climate are the basin scale winds and the amount of precipitation entering the system as rain and snow. Any long-term changes would, of course, be superimposed on existing seasonal changes. Since these seasonal changes are quite large, the long-term changes initially will be hidden in the seasonal signal.

As a possible scenario, suppose that global warming leads to protracted winter winds along the outer coast and decreased regional precipitation. Protracted offshore southerly winds (perhaps, in the form of more frequent southerly gales) would increase the frequency and duration of estuarine-flow reversals in Juan de Fuca Strait. The existing positive estuarine flow pattern, consisting of surface outflow and deep inflow, would be less persistent and there would be increased likelihood of extensive up-strait flow reversals. This, in turn, would affect the vertical structure of the estuarine circulation. Weakening of the landward flow at depth would reduce the cross-sill density gradient which drives intrusive deep-water replacement in the Strait of Georgia and Puget Sound. A change in the precipitation pattern accompanying any change in the wind systems would need to be taken into account. Greater precipitation might help offset the effect of increased offshore southerly winds but reduced precipitation would augment the effect of the winds. Reduced intrusive flow would lengthen the flushing times for the major basins and lead to possible acceleration of pollutant retention. Diametrically opposite changes, involving a combination of decreased southerly winds and increased regional precipitation in the Pacific Northwest, would enhance the positive estuarine flow and reduce the flushing times for the major basins.

A change in the prevailing coastal winds also would effect changes in the upwelling of high salinity, high density, low oxygen water along the outer coast and therefore influence the deep and intermediate water replacement in the Georgia-Fuca system. The situation

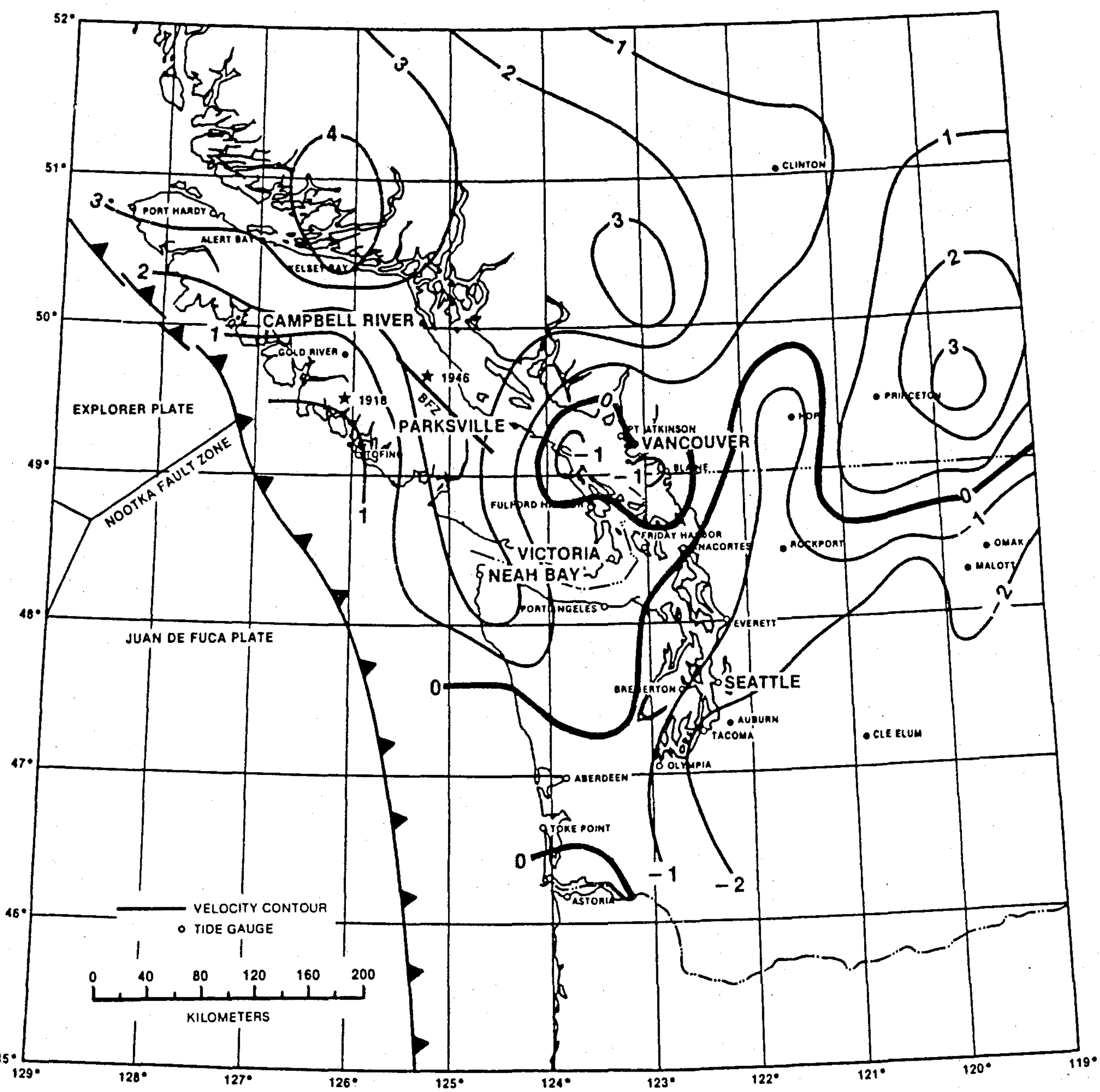

Figure 32. Smoothed contours of vertical velocity of the land (mm/year) computed from an adjustment model. An eustatic sea level rise of 1 mm/year was removed from the sea level records. The epicenters for two large on-shore earthquakes in central Vancouver Island are shown by stars annotated with the year of occurrence. (From Holdahl, Faucher and Dragert 1989).

might resemble a protracted version of the persistent El-Niño-Southern Oscillation (ENSO) type conditions that prevailed along the west coast of North America during 1982/83 and 1991/92. During major ENSO-type events on the coast, there is a reduction in the summer duration and intensity of upwelling. Since this upwelled deep water makes its way inland with the estuarine flow, this situation leads to temperatures, salinities, and densities that are lower than normal in Juan de Fuca Strait. The reduced density of the inflow will affect the density of the water spilling into the major basins adjoining Juan de Fuca Strait, leading to a slow modification of the water properties throughout the various basins.

Hydraulic Control

Returning to our climate change scenario of increased precipitation, we would find a change in the hydraulic control over the sills as follows. First, the increased runoff would lead to greater stratification of the upper portion of the water column in the Strait of Georgia and northern Puget Sound where most of the runoff occurs. Increased upper layer stratification would reduce the ability of tidal currents to mechanically mix the water column in the vicinity of the sill and therefore improve the ability of the layers to slide over one another (Griffin and LeBlond 1990). In the southern Strait of Georgia, this would facilitate the escape of brackish water at the surface and enhance the ventilation of denser water at depth. Reduced cold weather in winter would reduce vertical convection in the southern Strait of Georgia and reduce the depth of penetration of intermediate depth intrusive events.

Man-Induced Change

One day, someone may decide that building dams on a few of the tidal passages in the Georgia-Fuca system would be a way to generate "clean" hydroelectric power for the burgeoning populations of British Columbia and Washington State. Aside from the fact that the very construction of such a constriction might alter the flow pattern that is being harnessed (the flow might go elsewhere), it is likely that dams would modify the overall tidal regime of the system. Tidal elevations and currents might lead to adverse effects that would need to be addressed before construction could proceed. This calls for reliable numerical simulation models which can be physically altered to simulate the insertion of constrictions at the selected sites.

Modifications to the timing or volume of river runoff for either hydroelectric needs or for diversion of freshwater as a commercial resource could result in severe modifications to the existing estuarine circulation. Any reduction in the volume outflow from the major rivers such as the Fraser River or Skagit River would weaken the existing two-layer estuarine flow and reduce the upper layer stratification. The latter would stimulate vertical mixing within the tidal passes thereby increasing basin-scale flushing times and reducing deep water ventilation. The ability of brackish water to escape seaward would be curtailed. The reduced runoff would reduce upper layer sediment load which then might affect the stability of the major deltas. Erosion and retreat of these deltas would occur, similar to the present retreat of the Nile delta in Egypt. Salt water intrusion and increased up-river penetration of oceanic salt wedges (cf. Ages 1979) would destroy agricultural soil and adversely affect man-made infrastructure such as drainage systems and irrigation channels.

CLOSING REMARKS

The findings of this report point to a clear need for oceanographers from the United States and Canada to conduct cooperative field programs on all aspects of marine science. We require simultaneous work on both sides of the border and in shared waters including the southern Strait of Georgia and eastern Juan de Fuca Strait. We need to repeat the monthly surveys of Crean and Ages (1971) but this time in conjunction with chemical, biological and physical programs. We need to encourage numerical simulations that incorporate all three major basins of the Georgia-Fuca system and which begin to account for biological and chemical variability through processes such as particle scavenging and aggregation, as discussed by Lavelle et al. (1991) and Lavelle (1993) for Puget Sound. Numerical investigators could begin to anticipate the impacts of mega-projects on the oceanography of the Georgia-Fuca system, including the long-range effects of dams or river diversion. This work should be conducted in advance of any proposals so that there is adequate time for thoughtful research and informative discussion. The studies of decadal scale variability in Puget Sound conducted by Ebbesmeyer et al. (1989) need to be extended to other regions and to include long-term secular changes that might accompany global climate change. Since there is a strong coupling between variability within the inland waterway and the

open Pacific Ocean, oceanic research within the Georgia-Fuca system cannot be conducted in isolation of research on the outer continental margins of Washington State and British Columbia. This work would be facilitated by cooperative programs by agencies on both sides of the international border.

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DISCUSSION

Curtis Ebbesmeyer *(Panel)*: Thank you Rick. I want to personally thank you for putting all this together. I am not a modeler, but I do like to push data around and I've noticed that a lot of the models stop at Cape Flattery. It's been very hard to get what the ocean does into the models. Is there a model on the horizon that we can actually use to couple what is going on in the Strait of Georgia with what happens, say, at the Columbia River? Or on the coast when an El Niño comes along?

Rick Thomson: The problem that we've had is that we don't have long-term reliable data right at the entrances to the basins. We need to collect that on an annual basis so that we know a bit better about the density, temperature, salinity structure, current structure of those basins. That really has to be done, I certainly agree with you on that.

Richard Beamish *(Panel)*: Rick, in your opinion are there any anthropogenic effects on the oceanography now, and do you think there could be some in the future?

Rick Thomson: Right now I would say, no, there are no significant man-made effects, but lets go to the future. I think that's a more interesting question. Chris Garrett phoned me up when I was trying to put this talk and paper together, and he said, 'Well of course you've included that, you are going to mention that'. I hadn't even thought about it.

The future is important because there is always going to be somebody to say, 'Gee we can get really clean hydroelectric power by just putting the dam somewhere across one of the tidal passes, we've got these really strong tidal currents, let's dam it and see what happens.' I think this is where numerical models come in, that we can close off a few of these channels and see what impact they have on the response of this whole basin to those changes. And we care about what happens locally to the people who can't go back and forth anymore, and have to portage their 50-foot boat.

As far as the modelling is concerned, we can do that. I always go back to this interesting work that Roger Flather did. He had a model of the circulation in the strait, and he got things so that they look like they are now, and then he closed the entrance off and looked at the response. He learned that the flux in and out of Juan de Fuca Strait strongly influences the tidal signal on the west coast of Vancouver Island.

I looked into sea level rise. The global sea level rise is about 1 mm per year. Some people say it's due to global warming, but whatever it is, there's approximately 1 mm per year global sea level rise. If you take that away, Seattle is still sinking about 2 mm per year, so if you add on top of that the eustatic effect, sea level is rising in Seattle. Vancouver is staying about neutral, but Vancouver Island is uplifting 2 or 3 or 4 mm per year.

Bill Austin *(Khoyatan Marine Lab, Cowichan Bay)*: Just to follow up on Dick's question, at a smaller level, say at some of the fjords, could clearcutting have changed the estuarine circulation pattern? And just as another example, could major removal of water to ship to California or somewhere change estuarine circulation patterns?

Rick Thomson: Yes, for the first question. To answer your second question, you know the smaller tributaries don't contribute very much compared to the Fraser River and the Skagit, but there is always the possibility that somebody is going to divert one of these major rivers. If you do that you're going to have a major impact on the circulation of the system. The smaller rivers and the tributaries probably have a local impact.

Chris Prescott *(Puget Sound Water Quality Authority)*: I wanted to follow up on a tangent to Dr. Ebbesmeyer's question. The water that goes 'out of the system', does much of that come back in; is there any significant return?

Rick Thomson: The water coming back is a mixture of the outgoing water and the incoming water. Depending on how much mixing takes place, and during those times when there is vigorous mixing by the tidal currents, for example during spring tides, the water that is coming back is a composite of the water coming in and the water that's trying to go out in the surface layer.

Chris Garrett *(Panel)*: In your collaborations with these people you're supposed to be serving in other disciplines, what part of the physical behaviour of the

system has emerged as critical? Do we really need a 3-D numerical model, or, given the uncertainties of the other disciplines, to the extent that we need an answer, can we actually get away with box models, or at least use the box models first of all to guide us in what really matters about the physics?

Rick Thomson: People in academia can get away with box models. People in government service who have to provide answers to people like Dick Beamish, for example, who wants to know whether there is any impact on the fisheries, have to provide what they consider the best technology available. Box models work fine when you're trying to conceptualize things, but if you really want to get down into the detail that Dick wants for particular basins, I really think we do need those kind of numerical models. For example, if the wind changed off the coast because of global warming we would get a lot more southerly winds. What's that going to do to the estuarine circulation? If runoff changes, if it rains a lot more?

Chris Garrett *(Panel)*: But I want to see a hierarchy of models, I want to see the rough estimates today so that you can convince us that you need the more accurate models tomorrow.

Rick Thomson: I think that you're fighting a losing battle, because I think that they are going to go ahead with these numerical models anyway. I know the bureaucrats like numerical models, they have great faith in them. As scientists we're a bit more skeptical, but I think it's a battle we're going to lose.

Marine Sediments in the Strait of Georgia, Juan de Fuca Strait and Puget Sound: What can They Tell us About Contamination?

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ABSTRACT

We examine the role that sediments play in chemical contamination of our common inland sea. Most of the inorganic sediments that are accumulating within either the Strait of Georgia or Puget Sound come from direct inputs to the respective basins and there is little opportunity for particles to exchange between the basins. Juan de Fuca Strait, through which the inland seas communicate with the open shelf, receives little inorganic particulate matter and, due to strong currents, tends not to accumulate new sediments at the bottom. Therefore, contaminants that are strongly bound to particles are for the most part accumulated within the basins they enter and we can account for a large fraction of the input. Once they enter the water, these contaminants — which include lead, highly chlorinated organic compounds, some of the polynuclear hydrocarbons and some of the atmospheric weapons-testing products like plutonium — tend not to transport across boundaries. Other contaminants are bound only partially to particles and a substantial portion of these can therefore migrate out of the basin they enter. This category of contaminant includes elements like copper and zinc for which perhaps 50% or more of the input passes from Puget Sound or the Strait of Georgia into Juan de Fuca Strait. Since Juan de Fuca Strait is not accumulating sediments, these contaminants get flushed to the outer shelf or are potentially returned with inflow into the coastal basin through tidal mixing at the passes. Some contaminants like cadmium, nutrients and soluble organics tend to remain dissolved in seawater and therefore escape the system during water exchange; sediments tend not to record the history of input of these contaminants or play a strong role in the contaminant budget, with the possible exception of local industrial or municipal "hot spots" in harbours. Atmospheric contaminants have the potential to travel long distances across boundaries. For our coast, contaminants transported by air are probably more a global than a British Columbia — Washington issue; in this context, volatile organochlorines are the leading contaminants of concern. We examine the sources and fate of chemical contaminants from sediment data and suggest how sediments affect contaminant transport, whether there is harm to the system and how sediment data may be applied to the questions posed for the panel.

INTRODUCTION

During the past two centuries the coastal sea comprising the Strait of Georgia, Puget Sound and Juan de Fuca Strait (the Georgia-Puget-Fuca or GPF System; Figure 1) has been subject to escalating contaminant burdens. This is a direct consequence of a rapidly increasing population in the surrounding drainage basins (increasing from perhaps hundreds of thousands to about five million) and an evolution from traditional hunting and gathering to agriculture, resource extrac-

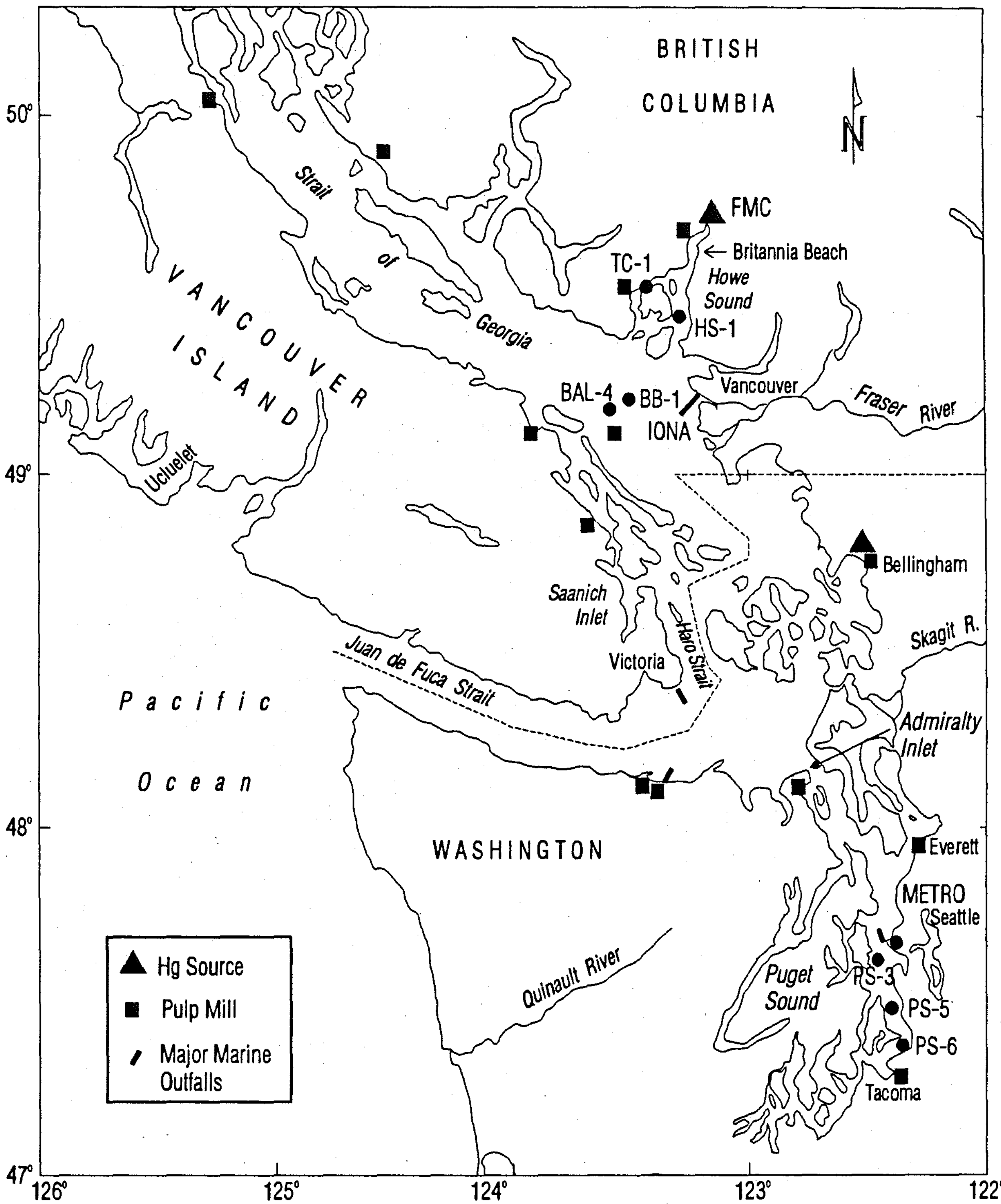


Figure 1. Major population centres and industries, and location of sediment sample cores in the Strait of Georgia, Puget Sound and Juan de Fuca Strait. The inner boundary for Juan de Fuca is taken to be Haro Strait and Admiralty Inlet.

tion and industry. Because marine discharge has been convenient and cheap, waste products have been disposed into this coastal sea directly through municipal and industrial outfalls and by ocean dumping. A further contaminant burden, which is more difficult to quantify than direct discharges, derives from municipal and agricultural runoff, from a variety of atmospheric sources including incineration, automobile emissions and aerial application of chemicals, and from dispersive uses of chemicals in the ocean itself such as marine antifoulant usage, accidental spills, and applications in aquaculture. The Fraser River, the Skagit River and the other multiple small rivers contribute a further contaminant burden to the coastal sea along with large amounts of suspended inorganic sediment. In summary, a broad spectrum of contaminants from a variety of sources impinges on the GPF system; some contaminants degrade, some are advected to the open sea, but a significant portion of many of these contaminants end up in the local sediments. Contaminant increases in our coastal environment are not unique; rather they parallel the global human assault on marginal seas (cf. Goudie 1986; IGBP 1993). The United Nations Joint Group of Experts on the Scientific Aspects of Marine Pollution (GESAMP) differentiate between *contamination*, which is an artificial increase of a chemical above background, and *pollution*, which implies harm to living resources or hazards to human health. This distinction leads to the concept of "assimilative capacity" (Preston 1989). In this paper we will follow the GESAMP terminology, using the term pollution only where there has been some measured harm.

Site- or source-specific contamination has been and continues to be encountered in the GPF system, particularly in shallow harbours and in the intertidal zones of places like Vancouver Harbour, Elliott Bay, Everett Harbor and Victoria Harbour (e.g., see Dexter et al. 1981; Waldichuk 1983; Malins et al. 1984; Kay 1989; Crecelius et al. 1989; Goyette and Boyd 1989). Where pollution has been demonstrated, various actions have been taken such as processing waste before disposal (e.g., going to secondary treatment as at Seattle's METRO sewage treatment facility at Westpoint or Iona at Vancouver), changing a chemical process (switching from chlorine to chlorine dioxide bleaching of pulp) collecting smaller storm and municipal sewage systems into a larger one and extending an outfall into deeper water (e.g., Iona or Victoria), or adopting an alternate disposal activity (e.g., landfill, recycling). The treatments are often successful at mitigating the identified pollution, but unless the quantities of contaminants are actually reduced, these strategies do not alter the large-scale effect of contaminant burdens on the coastal sea taken as a whole. Pollution of the Strait of Georgia and Puget Sound has previously been reviewed (Parsons 1972; Dexter et al. 1981; Waldichuk 1983; Puget Sound Water Quality Authority 1986, 1991; Kay 1989; Wells and Rolston 1991). One kind of pollution, coastal eutrophication from sewage and agricultural discharge (see e.g., Rosenberg 1985), has generated heated debate (Stockner et al. 1979; Parsons et al. 1980; Clarke and Drinnan 1980; Stockner et al. 1980). Perhaps the most important revelation of this debate is that we do not presently have a set of measurements that could be used with confidence to evaluate long-term eutrophication of the Strait of Georgia (e.g., enhanced productivity accompanied by oxygen depletion in deep waters). Sediments have proved extremely useful in deriving historical trends for many contaminants. Unfortunately, other than the catastrophic change from oxic to anoxic conditions in deep basin waters, a way has not yet been found to apply sediment records directly to the determination of more subtle, long-term trends in eutrophication of our coastal seas (see for example, Sancetta and Calvert, 1988; Furlong and Carpenter 1988).

The overall health of our coastal sea is a critical issue which must be considered in a "systems" context; this implies a joint, cross-boundary, systematic approach in responding to pollution issues, collecting data on sources of contaminants and monitoring the basin-scale consequences of our activities. The sediments, which provide both an important source or sink for contaminants including nutrients, must be an integral part of any "systems" study.

In this paper we focus on the sediments within the GPF system; sediments on the outer continental shelves, which have been reviewed elsewhere (Carpenter and Peterson 1989; Macdonald and Pedersen 1991), are considered only briefly in the context of transboundary transport. To interpret contaminant records in sediments requires a knowledge of the sources of particles and the contaminants that are likely to end up in the sediments. Therefore, we first review what we know about the supply of sediments to the system. Then we review briefly the known sources of contaminants to the GPF

system. Finally, we review contaminant measurements in sediment to see what we can learn about scales of transport and the overall trends with time. We provide references to recent work, especially from the open literature, that apply to contaminants in sediments. We do not attempt to provide a comprehensive survey of sediment measurements; rather we have used the questions posed to the British Columbia/Washington Marine Science Panel as a way to focus our discussion.

Contaminant trends from sediments

Sediments tend to integrate contaminants from all sources and thereby provide a way to estimate both point and distributed source loadings to the system. Since the deposits accumulate over long time periods they tend not to be prone to the short-term variations seen in the water column. In this context, sediments can be used to identify contaminants not accounted for in known sources including clandestine dumping. Often, since they tend to concentrate contaminants, sediments are the first (only) place a contaminant is detected (Mackay 1986) or provide the site(s) where the effects of a contaminant on biota can be unequivocally demonstrated (e.g., Malins et al. 1984; Goyette et al. 1988). Because sediments tend to remain in place, they provide the opportunity to conduct repeated, comparative aerial mapping of contaminants. Since sediments are the final sink for many contaminants, understanding how much contaminant they sequester, where the contaminants are accumulating, and the rate at which they accumulate is critical to estimating a basin-scale contaminant budget and the distance of transport. Lastly, basin sediments tend to accumulate vertically with time thereby potentially preserving an historical record of contaminant trends. Such a record may not be available elsewhere because trend monitoring has not been in place, archives do not contain appropriate samples, or because sensitive chemical techniques of measurement for particular contaminants were previously unavailable.

Despite the information we can extract from them, sediments do not yield complete descriptions of the depositional histories for all contaminants and their records must be interpreted with caution. Some "particle active" contaminants tend to stick to organic or inorganic material and thus become entrained into and immobilized in the sediments; examples include lead, highly chlorinated organochlorines, many of the polynuclear aromatic hydrocarbons (PAHs) and some of the nuclear weapons-testing products like plutonium. For these kinds of contaminants the sediments may produce unequivocal records which in turn account for a major portion of the contaminant added to the system. For the particle-active contaminants we can say much about their potential for transport by learning how effectively the various zones within the system trap particles produced in or supplied to the system. The question becomes one of comparing the residence time of particles to the residence or flushing time of the water (e.g., see Paulson et al. 1988; Macdonald et al. 1991; Crecelius and Bloom 1988). Other contaminants tend to remain in the dissolved phase (nitrate, light hydrocarbons, some volatile organochlorines, As, Cd) or become remineralized in the water or within the sediment surface (organic carbon and nitrogen compounds, manganese) and therefore leave no record, a partial record, or an altered record in sediments. These kinds of contaminants may be transparent to sediments. Under the right circumstances, some contaminants are cycled between the sediments and the water column; in this case the contaminated sediments may provide a continuing source of contamination to the water column (e.g., Flegal and Sañudo-Wilhelmy 1993). Biota living in or feeding on sediments alter the contaminant record by mixing surface sediments, and also by taking up the contaminants and reintroducing them to the biosphere. This mixing process produces a lag in the response of surface sediments to changes in the contaminant burden of newly sedimenting particles (Carpenter et al. 1985; Macdonald et al. 1992). In regions like our coastal sea where rivers supply copious amounts of inorganic particles, we must account for slumps or rapid sedimentation events that may disturb the sedimentary record (e.g., Carpenter et al. 1985; Bloom and Crecelius 1987; Macdonald et al. 1991). The key point is that to understand and extract the greatest benefit from sediment contaminant data we need to understand both the general bio-geochemistry of the sediments and the specific properties of the contaminant.

SOURCES AND SINKS OF SEDIMENTS IN THE GPF SYSTEM

The GPF system can be thought of in simplest terms as two inner basins (Strait of Georgia and Puget Sound) connected via restricted passages to the head of Juan de

Fuca Strait (Figure 2). Almost all of the freshwater runoff and associated inorganic particle loadings enter the two inner basins. Juan de Fuca Strait forms a channel with relatively large volume through which "imports to" and "exports from" the inner basins must pass. Johnstone Strait at the north end of the Strait of Georgia undoubtedly accounts for a small proportion of the imports and exports of water; however, it does not impinge on international borders.

STRAIT OF GEORGIA

The predominant source of particulates and freshwater to this basin is the Fraser River (Pharo and Barnes 1976). Its particle loads, which are given in Table 1, have been estimated by Luternauer and Murray (1973), Milliman (1980) and Milliman and Meade (1983). The Fraser River is sand-dominated; sediment transport occurs predominantly during freshet in late spring, and

TABLE 1

Strait of Georgia, Puget Sound, and Juan de Fuca Statistics

	Strait of Georgia	*Puget Sound*	*Juan de Fuca Strait*
Basin dimensions			
Surface area	6900 km^2 [a]	2633 km^2 [b]	3700 km^2 [v]
Volume	1100 km^3 [c]	168 km^3 [b]	740 km^3 [v]
Average depth	155 m [a]	64 m [b]	200 m [v]
Maximum depth	420 m [b]	283 m [b]	280 m
Tidal volume	23.1 km^3 [c]	8 km^3 [b]	
Deposition area	~40% [d]	~30% [c]	nil [w]
Population 1991	1.7 million [p]	3.2 million [p]	0.3 million [p]
Water residence time	0.8 yr [g] (top 50 m:0.3 yr [h])	120–140 day [i]	10–20 day [v]
Primary productivity	120–345 gC m^{-2} yr^{-1} [f,j]	465 gC m^{-2} yr [k]	≈300 gC m^{-2} yr^{-1} [x]
River inputs			
Particulates	(12–30) × 10^6 ton yr^{-1} [l]	2.6 × 10^6 ton yr^{-1} [e]	
Freshwater	140 km^3 yr^{-1} [m]	30 km^3 yr^{-1} [n]	
Sedimentation rate	0.6–2.7 cm yr^{-1} [d]		
	0.12–0.4 g cm^2 yr^{-1} [e]	0.1–1.2 g cm^{-2} yr^{-1} [c,o]	
Municipal discharge	0.37 km^3 yr^{-1} [p]	0.23 km^3 yr^{-1} [q]	0.05 km^3 yr^{-1}
	9.5 × 10^4 ton yr^{-1}	3 × 10^4 ton yr^{-1} [q]	0.9 × 10^4 ton yr^{-1}
Pulp Mills	0.51 km^3 yr^{-1} [p]	0.18 km^3 yr^{-1} [t]	0.09 km^3 yr^{-1} [t]
	4.7 × 10^4 ton yr^{-1} [p]		
Other Industry	0.1 km^3 yr^{-1} [p]		
Ocean Dumping	1.2 × 10^6 m^3 yr^{-1} [s]		1.8 × 10^4 m^3 yr^{-1} [u]
	6 × 10^5 ton yr^{-1} [s]	7.5 × 10^5 ton yr^{-1} [t]	1 × 10^4 ton yr^{-1} [u]

[a] Parsons (1972).
[b] McLellan (1954).
[c] Waldichuk (1957).
[d] Luternauer et al. (1983).
[e] Carpenter et al. (1985).
[f] Stockner et al. (1979).
[g] Waldichuk (1983).
[h] LeBlond (1983).
[i] Schell and Nevissi (1977).
[j] Parsons et al. (1980).
[k] Winter et al. (1975).
[l] Milliman (1980).
[m] Milliman and Meade (1980) (Fraser River accounts for approx. 75% of total: Thomson (1981).
[n] Dexter et al. (1981).
[o] Lavelle et al. (1986).
[p] West et al. (this volume).
[q] Barrick (1982) (METRO (Westpoint) at 380,000 m^3 day^{-1} accounts for 60%).
[r] Luternauer and Murray (1973).
[s] Kim & Sullivan (1993).
[t] Romberg et al. (1984).
[u] PSDDA (1988).
[v] R. Thomson, Pers. Comm.
[w] Carpenter and Peterson (1989).
[x] D. Mackas, Pers. Comm.

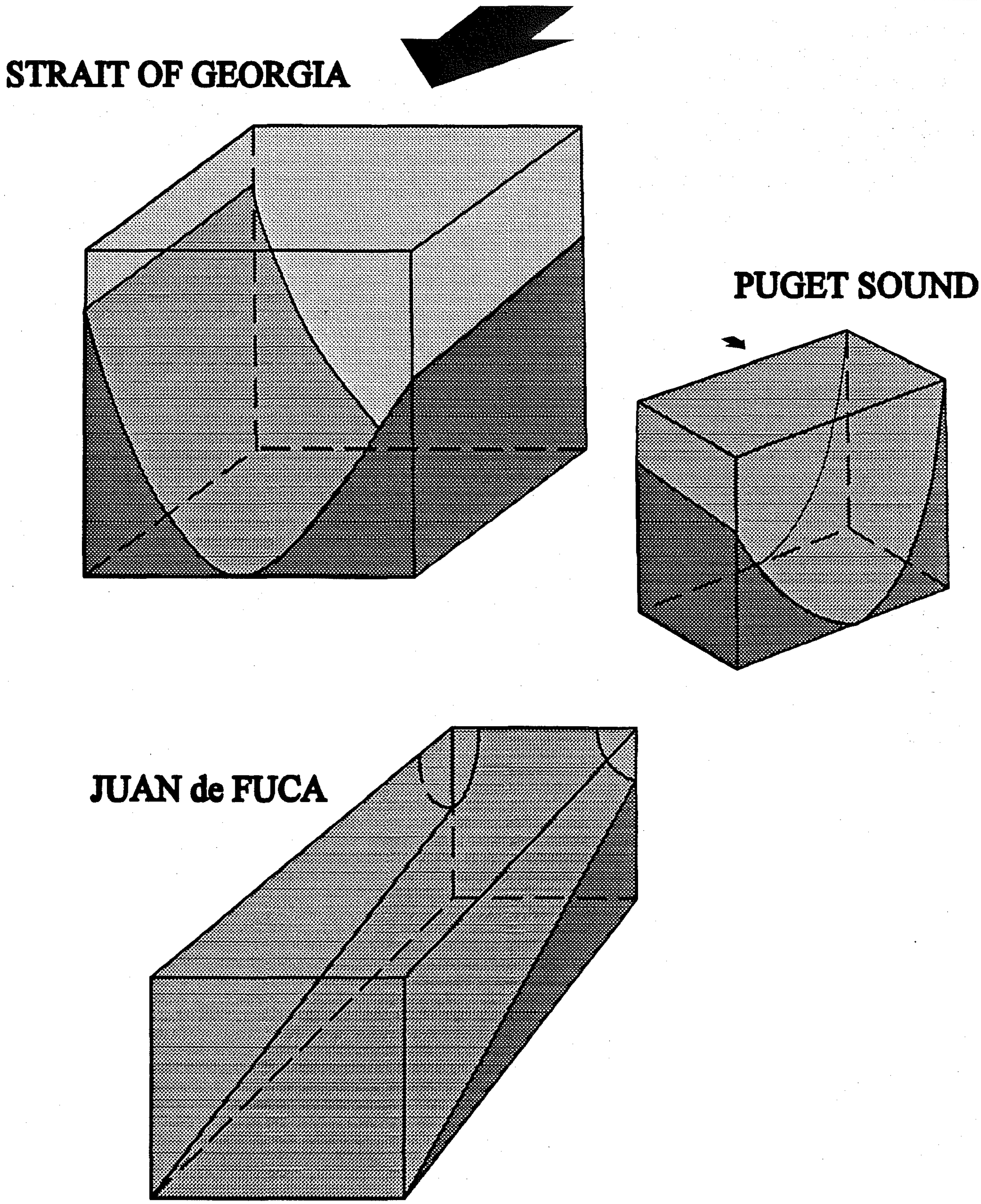


Figure 2. The Strait of Georgia, Puget Sound and Juan de Fuca Strait shown schematically in proportion to their volume and how they are connected. Major river inputs of sediment are shown as width-scaled arrows.

most of the sediment derives from Pleistocene deposits from the interior of British Columbia. Silt and clay have accumulated more thickly in the basins of the Strait than on its ridges (Luternauer et al. 1983), and most of the sediment appears to have settled either in the delta or in the basins of the northern two-thirds of the strait (Pharo and Barnes 1976; Syvitski and Macdonald 1982; Hart et al. 1993; T. Hamilton, pers. comm.). The dispersal of sediments away from the boundary (to the north) is influenced first by the circulation of surface waters (e.g., see Feeley and Lamb 1979) and subsequently by deeper currents. Persistent southeastward movement of Fraser River water does occur during freshet (Pharo and Barnes 1976); however, the area to the southeast of Sand Heads is an area of little deposition or net erosion (T. Hamilton, pers. comm). The Fraser River, along with minor inputs from smaller rivers and coastal erosion, provides a large source of particles with the potential to scavenge particle-active contaminants and transport them to burial predominantly within the basin sediments on the Canadian side of the border. It appears that little of the inorganic load escapes the Strait of Georgia. The annual sediment load from the Fraser River spread over the depositional area (Table 1) implies an average sedimentation rate of about 0.4–1.1 g/cm^2 per year. This range is certainly compatible with the limited observations based on dated sediment cores (Carpenter et al. 1985; Macdonald et al. 1991; Macdonald et al. 1992) and on seismic records of post-glacial sedimentation (cf. Pharo and Barnes 1976; Luternauer et al. 1983). However, the data base cannot be considered sufficient to render an accurate accounting of the modern particle budget for the Strait of Georgia.

Puget Sound

Puget Sound receives sediment particles both from numerous rivers that drain the Cascade and Olympic mountains, and from shoreline erosion. Biogenic particles composed of silica, carbonate, and organic carbon comprise only a minor component of the bedded sediment; nevertheless they are often a major component of the suspended particles. Anthropogenic particles from combustion and waste-water treatment plants are insignificant sources of particles in sediment, but contribute significant quantities of chemical contaminants.

Sediment mass balances for Puget Sound have been calculated by comparing sediment input rates with sedimentation rates (Crecelius et al. 1983; Romberg et al. 1984; Carpenter et al. 1985; Lavelle et al. 1986). The estimated sediment flux for rivers entering Puget Sound is 3×10^{12} g/year with the Skagit contributing approximately one-third to one-half of the load (Dexter et al. 1981; Downing 1983; Carpenter et al. 1985). Shoreline erosion contributes perhaps another 0.4×10^{12} g/year (Lavelle et al. 1986). Puget Sound is an efficient sediment trap (Baker 1984) with most of the sediment accumulating as fine-grained sediment in the central basin. Mean particle residence times are about 15 days and about 30% of Puget Sound is depositional (Roberts 1979; Carpenter and Peterson 1989).

Sedimentation rates in the range of 0.05 to 1.2 g/cm^2 per year have been calculated from excess ^{210}Pb (Carpenter et al. 1985 and Lavelle et al. 1986). Mass-balance calculations point out the need for better resolution of depositional patterns and more accurate characterization of the volume of sediment supplied by different sources.

Juan de Fuca Strait

The sediments in Juan de Fuca Strait tend to be relatively coarse-grained due to winnowing by strong currents (Anderson 1967; Roberts 1979). Carpenter and Peterson (1989) conclude that fine-grained sediments and any scavenged chemicals probably remain in suspension and are carried elsewhere; little if any accumulation occurs at the sea floor. This general picture is corroborated by seismic profiles which show a widespread glaciomarine unit recognizable to the entrance of the strait, with the upper part of this unit dating at approximately 10,000 radiocarbon years BP (Linden and Schurer 1988). Juan de Fuca Strait, therefore, provides a short residence-time corridor for contaminants to be carried out to the open sea in the surface waters (dissolved or attached to fine particles) or back into the strait with near-bottom drift along the south side. Records of contamination that can be interpreted in an historical context are not likely to be found within these sediments, nor are the sediments in this region likely to provide an important sink for contaminants except locally in confined harbours. However, sediments (containing associated contaminant records) may be accumulating at the entrance to Juan de Fuca Strait either in the cut-and-fill basins to the southwest of Barkley Sound (Macdonald and Pedersen 1991) or in

coastal embayments on the northern side of the strait, some of which are accumulating organic-rich sediments (Pedersen et al. 1989).

At the entrance to Juan de Fuca Strait there is a potential for suspended sediments (and associated contaminant burdens) migrating northward from the Columbia River and Washington shelf to cross the boundary into British Columbia waters. Macdonald and Pedersen (1991) concluded that Quinalt and Juan de Fuca Canyons provide formidable barriers to the northward transport of resuspended bottom sediments. The mid-shelf silt deposit, which is a predominant feature of the outer Washington shelf, has no counterpart on the British Columbia shelf.

SOURCES OF CONTAMINANTS TO THE GPF SYSTEM AND ITS SEDIMENTS

Major sources of contaminants to the GPF system and the quantities delivered have been compiled by Dexter et al. (1981), Kay (1989) and West et al. (this volume). Here, we give only the estimated loadings from major sources or from sources relevant to the sediment contaminant trends to be discussed later (Table 1).

Pulp Mills

Based on B.C. provincial permits, the cumulative effluent from six pulp mills in the immediate area contribute the largest loading to the Strait of Georgia, both by volume of effluent and mass of suspended solids. In addition to the six mills located on the strait, several pulp mills (and sawmills) upstream of the Fraser Estuary also discharge effluent and associated chemical contaminants into the Fraser River (Carey and Hart 1988; Rogers et al. 1992). Puget Sound has five pulp mills located on it and there are a further two mills on Juan de Fuca Strait at Port Angeles (Table 1; Romberg et al. 1984). Pulp mill effluent contains wood fibre and waste wood plus the chemical products of pulping and bleaching. The historical use of chlorine to bleach pulp has produced a broad suite of chlorinated compounds, not all of which have been identified. These compounds, some of which are fairly soluble, include chlorinated lignins and resin acids, chlorinated phenolics (phenols, guaiacols, catechols, and vanillins) and chlorinated dioxins and furans (e.g., see Voss and Yunker 1983; Macdonald et al 1992; Cretney et al. 1992). Since the discovery of chlorinated dioxins and furans in pulp mill effluent and in sediments near pulp mills (Trudel 1991), the industry has converted the bleaching process from pure chlorine to mixtures containing chlorine dioxide, and have ceased using wood-chips and shavings known to be contaminated with pentachlorophenol which contains traces of dioxins.

The pulp and paper industry in British Columbia historically used mercury as a slimicide (discontinued in the early 1960s) and zinc dithionite as a brightener (discontinued in the early 1970s).

Sewage

Municipal sewage contributes the second largest loading to the Strait of Georgia following closely behind the pulp mills (Table 1). However, for the whole GPF system, municipal effluent is the single, largest anthropogenic loading (Table 1). Sewage potentially contributes several types of pollution problems (Waldichuk 1983; Kay 1989): Pathogenic microorganisms; nutrients; biochemical oxygen demand; organic solids; and chemical contaminants. Included in the chemical contaminants category are heavy metals (Paulson et al. 1988), hydrocarbons (Barrick 1982; Barrick and Prahl 1987), fecal sterols (Venkatesan and Kaplan 1990), and organochlorine compounds (Rogers et al. 1986), all of which potentially contaminate sediments in the receiving environment.

Ocean Dumping

There are eleven active dump sites in the Strait of Georgia, the major ones being at Point Grey and Sand Heads off Vancouver. There are a further two dump sites in Juan de Fuca Strait (Kay 1989). Most of the material dumped in Canadian waters is inorganic dredge spoil consisting of gravel, sand and silt although waste dredged near forest operations contain wood debris (Waldichuk 1983; Kay 1989). Average loadings of ocean-dumped material for the period from 1987 to 1992 are given in Table 1. Contaminant burdens of dredgeate and the dumpsites themselves are monitored under the Canadian Environmental Protection Act (CEPA) to prevent the dumping of substances like mercury, cadmium, organohalogen compounds, oils and persistent plastics when they exceed certain concentrations. Most types of material dumped in B.C. waters do not appear to have an adverse affect on the marine community with the exception of smothering at

the dump site itself (Kay 1989). The dump sites closest to the boundary are in Juan de Fuca Strait; amounts dumped at these sites are not large (only 2% of Canadian ocean dumping (Table 1)).

For Puget Sound, detailed records are available on the status of dredging and disposal activities since the 1980s following the development of the Puget Sound Dredged Disposal Analysis program (PSDDA). During the period of 1970-1985, the total volume of sediment dredged in the central basin of Puget Sound (Tacoma to Everett) was 13×10^6 m^3. Approximately half of this sediment was disposed to unconfined open-water sites in the central basin (PSDDA 1988). A similar volume of sediment is projected to be dredged from 1985 to 2000. During 1970 to 1975 the total volume dredged in the Southern and Northern Sounds was 6×10^6 m^3 with 2×10^6 m^3 disposed to unconfined open-water sites adjoining the boundary waters (PSDDA 1989). Projected dredging volume for the Northern Sound (1985–2000) estimated to be 5×10^6 m^3 could be disposed to unconfined open-water sites in or near transboundary waters. Extensive testing of dredged materials ensures that open-water disposal does not chemically degrade the marine environment; smothering at the dump site itself probably occurs.

Atmospheric Transport

Contaminants can move long distances through the atmosphere, not only across the United States/Canada boundary but also from distant countries. The leading atmospheric contaminants are:

1. Volatile organochlorine compounds like the hexachlorocyclohexanes (HCHs) including Lindane (γ-HCH), pesticides and polychlorinated biphenyls (PCBs) (Eisenreich et al. 1989; Strachan 1990; Iwata et al. 1993) and other organochlorines produced through incomplete incineration of plastics (Hites 1990; Macdonald et al. 1992) or by automobiles (Benfenati et al. 1992).
2. Hydrocarbons produced by incomplete combustion of wood, coal and oil (Wakeham et al. 1980; Gschwend and Hites 1981; Barrick 1982; Bates et al. 1984; Barrick and Prahl 1987).
3. Aerosol lead from automobile exhaust (Bloom and Crecelius 1987; Macdonald et al. 1991), and volatile metals like mercury.
4. Radionuclides from atmospheric weapons-testing in the 1950s and 60s (Carpenter and Beasley 1981) and from Chernobyl in 1986 (Joshi 1987; Taylor et al. 1988).

The atmospherically transported contaminants can enter directly into coastal waters or indirectly by first depositing within the drainage basin and thence via runoff into the coastal sea. For the volatile organochlorine compounds, part of the global redistribution is driven by temperature differences between tropical and temperate regions where many of these compounds first enter the environment, and cold regions such as the poles (cf. Iwata et al. 1993). From this perspective, the North Cascades which drain into Puget Sound, and the coastal and interior ranges of British Columbia which drain into the Strait of Georgia, could provide a mechanism to enhance the delivery of volatile contaminants to the GPF system.

Several studies have estimated the atmospheric deposition rate of particulate metals and polynuclear aromatic hydrocarbons (PAHs) to Puget Sound and the Washington coast. Aerosol and deposition samples collected at Seattle, Sequim and Quillayute, Washington, were used to predict deposition in the Pacific Northwest (Crecelius 1981; Prahl et al. 1984; Romberg et al. 1984). These studies indicated that lead was the only contaminant that had a significant input via the atmosphere. The concentration of mercury and methyl mercury in precipitation has also been determined on the North Olympia Peninsula (Bloom and Watras 1989).

A study of the atmospheric deposition of metals and PAHs to Commencement Bay, an urban industrial bay, concluded that direct atmospheric deposition appeared to be a small contribution in terms of mass loading relative to other sources of inputs to the bay (US EPA 1991). The total input from atmospheric deposition could not be assessed from the results of this study because of uncertainty in the estimates of atmospheric deposition on land and its subsequent runoff to the bay.

Wind back-trajectories indicate that during periods of offshore winds, the concentration of airborne lead can be similar on the Washington coast to that in the Puget Sound area (Fox and Ludwick 1976). This suggests that urban air is frequently transported to the GPF system.

Other Specific Sources of Contaminants

Copper (Cu) Zinc (Zn), Lead (Pb), Antimony (Sb) and Arsenic (As) From Britannia Mine and ASARCO

The Britannia Mining and Smelting Company (1905–1963) and subsequently the Anaconda Mine (1963–1974) discharged thousands of tons of Cu- and Zn-rich tailings directly into Howe Sound from 1905 to 1974 (McDonald 1990; Broughton 1992). Slumping and winnowing has subsequently transported much of this material into deeper parts of the inner basin of Howe Sound and perhaps across the sill into the outer basin. Acid rock drainage presently continues to enter the surface waters of Howe Sound (Dunn et al. 1992).

The ASARCO Pb-Cu smelter located near Tacoma, Washington, contributed a significant quantity of As, Pb, and Sb to Puget Sound between the years 1889 and 1980 (Crecelius et al. 1975).

Mercury (Hg) From Chlor-alkali Production

From 1965 until 1970 the FMC plant at the head of Howe Sound was losing perhaps as much as 20 kg/day of Hg in its effluent water, while Bellingham Bay similarly received an estimated 4.5–9 kg/day from another chlor-alkali plant. After 1970 the discharge at both plants was reduced to about 0.1 kg/day (Crecelius et al. 1975; Thompson et al. 1980). Surface sediments from regions near both plants were contaminated; mercury concentrations of 2 to 20 µg/g were measured compared to naturally occurring concentrations of about 0.1 µg/g (Bothner 1973; Macdonald and Wong 1977; Thompson et al 1980). This Hg is a clear example of pollution, since local benthic fauna were found to contain up to 13 µg/g Hg in their tissue and crab fisheries were closed (Thompson et al. 1980).

Chlorophenols From Lumber Yards

The leaching of chlorophenol from surface-treated lumber (antisapstain/preservative) has introduced significant quantities of this chemical to the waters of the Strait of Georgia. For the years 1986–1987, Krahn et al. (1987) estimated the total loading to the lower Fraser River to be 916 kg/year, to Burrard Inlet, 523 kg/year, and to Howe Sound, 85 kg/year. It is important to note that this chlorophenol contains trace quantities of other organochlorine contaminants including the dioxins (approximately 200 µg/g). The use of PCP in the Canadian lumber industry was discontinued by 1989 (Rogers et al. 1992).

Organotins From Antifouling Applications

Tributyltin (TBT) was first used as a broad-spectrum agricultural fungicide, miticide, insecticide and marine antifoulant. From the mid-1960s onwards, TBT was used as an antifoulant for salmon-farm pens and boat bottoms (Ellis 1991). After it was recognized in the 1970s that very low concentrations of TBT could harm bivalve molluscs, particularly oysters and mussels, and bioaccumulate in salmon, TBT was partially banned in the United States and Canada in the 1980s. Low-release TBT paints are still permitted on boats larger than 25 m and on aluminum structures. Antifoulants have the potential to be transported across boundaries following dissolution into the water or directly with the boat if it crosses the boundary. To be effective, regulations would have to be the same on both sides of the boundary.

PCB Spill

In 1974, 720 kg of Arochlor 1242 was accidentally spilled into the Duwamish River estuary (Carpenter and Peterson 1989). Surficial sediments from this region contain the highest PCB concentrations observed in Puget Sound sediments (Pavlou and Dexter 1979).

Coal

Coal is a potential source of many organic compounds to sediments including hydrocarbons such as alkanes, naphthalenes, and phenanthrenes. Since these compounds are also found in petroleum, source-identification is important to discriminate between contamination from oil or coal whose substantially different physical matrices likely influence transport, fate and biological effects. Barrick et al. (1984) studied the hydrocarbon and azaarene distributions in 16 western Washington coals ranging in rank from soft coals to anthracite. They demonstrated that specific geochemical marker-compounds and compositional patterns characteristic of select groups of these coals give rise to an identifiable chemical signal in marine sediments of Puget Sound. Studies by Furlong and Carpenter (1982) and Barrick et al. (1984) identified coal particles and coal marker-compounds in subsurface sections of a sediment core taken near Tacoma. Coal particles may have been intro-

duced into Puget Sound from both erosion of coal-bearing strata in the Puyallup River drainage basin or during trans-shipment from the Port of Tacoma. Azaarene and other marker compounds provide the means to distinguish significant natural and anthropogenic coal input from other regional fossil sources such as street runoff and fuel oils discharged in municipal waste water.

For Juan de Fuca Strait, coal particles thought to derive from a coal barge wrecked off Victoria (Brotchie Ledge) in 1891 appear to interfere with sediment hydrocarbon measurements made around Victoria's municipal outfalls (Warman 1992; L. Taylor, pers. comm.). Due to the strong currents which do not allow fine, light particles to settle, coal fragments may by exclusion become an important recent sedimentary input for PAH in Juan de Fuca Strait.

Pesticides

The 1989–1990 Pesticide Reconnaissance Survey was conducted to assess the extent and toxicological significance of water-soluble and sediment-bound pesticide residues present in Puget Sound drainages (PTI 1991). Water and sediments were collected from five drainage areas that empty into Puget Sound; these were analyzed for 33 different pesticide residues. Five pesticides were detected in a least one water sample: diazinon, 2,4,-D, dicamba, bromacil, and diuron. The most commonly detected pesticide in water samples was 2,4-D (0.077 to 0.70 µg/L). Four pesticides, or their degradation products, were detected in at least one sediment sample: dichlobenil, pentachlorophenol, DDT/DDE/DDD, and endosulfan I and II. Pentachlorophenol was detected in all six sediment samples at concentrations up to 33 µg/kg.

The water and sediment data were compared to toxicological values; pesticide concentrations were below or did not exceed published acute or chronic toxicological values; two pesticides, diazinon and endosulfan I, were detected in at least one sediment sample at concentrations potentially hazardous to aquatic life that may contact contaminated sediments.

SEDIMENT TOXICITY

Puget Sound

In general, sediments in the nearshore areas of urban bays are more contaminated than those in open water or less developed areas. Intensive surveys of sediment quality have been conducted near Seattle, Tacoma, Everett, Bremerton, Port Angeles, Olympia and several non-urban bays. These surveys demonstrated that the more contaminated sediments were toxic to marine organisms, pollution-tolerant organisms were the dominant organisms at some urban sites, and fish tissue contained elevated concentrations of some chemicals compared to fish from non-urban bays. Surveys in some parts of Puget Sound showed that histopathological disorders in bottom fish were most prevalent in the urban bays where the sediments were most contaminated.

The results of sediment toxicity surveys in southern, central and northern Puget Sound suggest sediment toxicity in most areas sampled outside urban harbours was not elevated above Puget Sound reference levels (PTI 1991; Crecelius et al. 1989; Strand et al. 1986). The limited amount of fish disease observed suggests that fish were not affected by chemical contamination except in urban waterways. Studies have shown that most sole living in the rural and open areas of Puget Sound rarely suffer from liver diseases (Malins et al. 1985; Crecelius et al. 1989; Strand et al. 1986). The observed concentrations of chemical contaminants in tissue samples from fish and mussels did not appear to pose an unacceptable health risk to consumers of these organisms (Crecelius et al. 1989; PTI 1991; NOAA 1989).

The National Oceanic and Atmospheric Administration (NOAA) annually collects and chemically analyzes sediment samples from sites located in Puget Sound, as well as coastal and estuarine sites throughout the United States as part of the National Status and Trends Program (NS&T). Long and Morgan (1990) computed the "Effects Range-Median" (ER-M) using data from a wide variety of methods that included biological effects and sediment chemistry. When the NS&T Puget Sound sediment chemistry data are compared to the ER-M concentrations, only three sites exceeded the threshold: Bellingham Bay exceeds the ER-M for chromium and nickel; Whidbey Island Possession Point exceeds for nickel, and Elliott Bay exceeds for PCBs. That chromium and nickel exceed the threshold is most likely due to natural mineralogy of the sediments, not pollution. Based on the Long and Morgan (1990) ranking of potential for biological effects at the NS&T sediment sites, Puget Sound is less affected than most of the major urban bays and harbours in the United States.

Two long-term monitoring programs are measuring sediment contamination in Puget Sound. The Washington State Department of Ecology periodically samples 50 Puget Sound Ambient Monitoring Program (PSAMP) sites for sediment chemistry and toxicity (Tetra Tech 1990; Striplin et al. 1994). The NOAA NS&T program samples sediment at 11 sites (NOAA 1989; Long and Morgan 1990). The sites for both programs are located outside the more contaminated bays and away from major pollution sources. The levels of metals were, for the most part, below the state's sediment quality standards. Sediments at several PSAMP sites exceeded the state sediment standards for PAHs and other organics.

Strait of Georgia

Only limited work has been done linking sediments to toxic effects in biota on the Canadian side of the border. In particular, sediments from Vancouver Harbour have been found both to be contaminated (Goyette and Boyd 1989) and to exhibit effects on the benthic animals (Goyette et al. 1988; Goyette and Boyd 1989; Burd and Brinkhurst 1990; Cross and Brinkhurst 1991). Effects in Vancouver Harbour were similar to those observed by Malins et al. (1984) for contaminated harbours in Puget Sound; English sole exhibited lesions, especially specimens from Port Moody and the north and south shore of the inner harbour (Burrard Narrows and Coal Harbour). Elevated concentrations of PAH and various metals are associated with these sites. A more complete survey of harbours around the Strait of Georgia would probably identify other restricted, urbanized locations as having abnormal benthic populations or effects on species.

In Canadian waters, fishery problems have been identified around specific known sources of contamination. Noteworthy was the shellfish and groundfish closure for eight years at the head of Howe Sound due to mercury pollution in the early 1970s. More recently, in 1988, prawn, shrimp and crab fisheries near pulp mills on the Strait of Georgia were and continue to be closed due to pollution from chlorinated dioxins and furans. These episodes of pollution have affected primarily the edibility of animals living on or in sediments in close proximity to a known source of contaminants.

HISTORICAL TRENDS FROM DATED SEDIMENT CORES

Table 2 provides a summary of literature concerning dated sediment cores collected from the GPF system specifically to investigate contaminants. What have we learned from these cores? Figure 3 shows the sedimentary concentrations of contaminants over time; data were selected from among the cores listed in Table 2. Estimated residence times for metals in water are shown on Table 3.

Heavy Metals

Lead (Figure 3a)

There is a consistent picture of contamination during the past century for sediments in the Strait of Georgia and Puget Sound. Contaminant Pb in sediments is first seen in Puget Sound around the turn of the century, probably originating at that time from the ASARCO smelter which started production in 1889. Sediments from the Strait of Georgia begin to record Pb contamination about 25 years later coincident with the introduction of leaded gasoline. The lag between the two basins is probably due partly to differences in population growth and source function, and due partly to differences in the sizes of the basins and amounts of inorganic sediment supply (sink). Clearly the Puget Sound sediments have been more heavily contaminated than those of the Strait of Georgia and for a longer time period. In the Strait of Georgia, Britannia Mines (Howe Sound) has probably been a source for some of the Pb as evidenced by the higher burdens in sediment cores from Howe Sound. There is evidence that Pb concentrations started to decrease in the GP sediments perhaps as early as 1970. The major source of modern Pb to deep basin sediments is leaded automobile gasoline; since this has been phased out of use beginning in the late 1970s, we can expect the Pb concentrations to continue to decrease in surface sediments. Macdonald et al. (1991) estimated the flux of Pb into the Strait of Georgia to be about 180 tonne/year (in 1981) which accounted for about 20% of Pb emitted from gasoline consumption around the basin. Paulson et al. 1988, estimate the flux of Pb into Puget Sound to be 41 tonne/year, much of it coming from municipal and industrial sources. Bloom and Crecelius (1987) and Paulson et al. (1988) conclude that most of the Pb input to Puget Sound becomes trapped there in the

TABLE 2

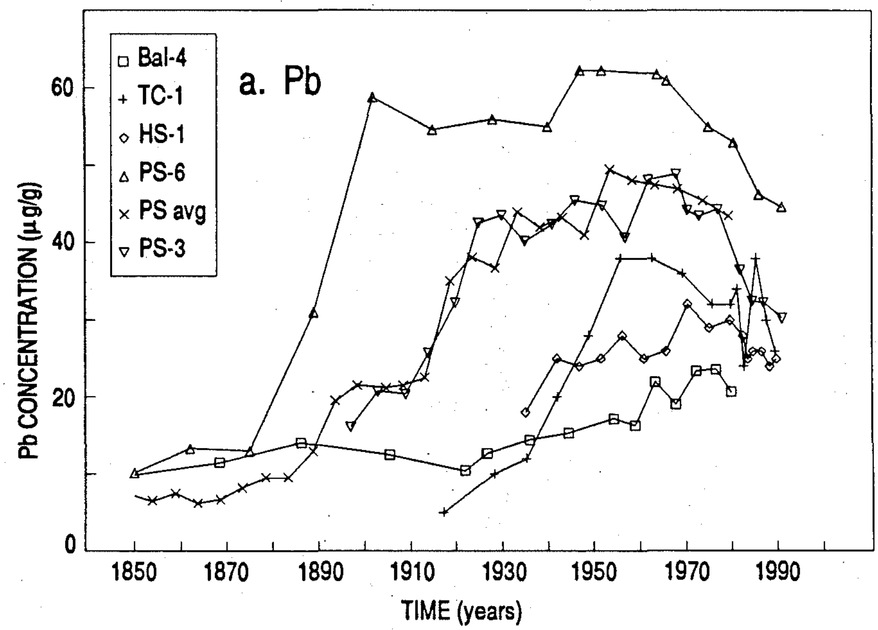
Summary of contaminant data from dated sediment cores

Location	*Date Collected*	*Contaminants Measured*	*Reference*
Puget Sound	1970–72	As, Sb, Hg, Cr, Co, C	Crecelius et al. 1975
Saanich Inlet	1975	Pb, Cu, Cd, Hg	Matsumoto and Wong 1977
Puget Sound	1975	PAH	Barrick and Prahl 1987
Howe Sound	1976	Hg	Thompson et al. 1980
Central Puget Sound	1976	Pb, Cd, Zn, Hg, Cu, Ni	Schell and Nevissi 1977
Central Puget Sound	1977–82	EPA Priority Pollutants	Romberg et al. 1984
Puget Sound	1978–79	^{241}Am, ^{239,240}Pu ^{137}Cs	Carpenter and Beasley 1981
Central Puget Sound	1982	Ag, Hg, Pb, Cu, Cd	Bloom and Crecelius 1987
Ucluelet Inlet	1986	C, N, Cd, Mo	Pedersen et al. 1989
Ballenas Basin (SofG)	1980	Pb, Zn, Cu, Cd, C, N, δ^{13}C	Macdonald et al. 1991
Strait of Georgia	1990	Dioxins, Furans, PCB-77	Macdonald et al. 1992
Puget Sound	1975–76	Acyclic Hydrocarbons	Barrick et al. 1980
Central Puget Sound	1983	Aliphatics and PAH	Bates et al. 1984
Commencement Bay	1981	PAH, PCB, metals chlorinated butadienes	Crecelius et al. 1985
Puget Sound	1978	Azaarenes	Furlong and Carpenter 1982
Everett Harbour	1983	PAH, PCB, 13 metals	Crecelius et al. 1984
Central Puget Sound	1991	PAH, 16 metals, C,N,P Pesticides, PCB	Crecelius, unpublished
Puget Sound	1975–76	Organo-sulfur compounds	Bates and Carpenter 1979

TABLE 3

Estimated residence times for metal in water

Metal	*Residence Time (years)*	*Location*	*Reference*
Pb	0.7–0.8	Saanich Inlet	Matsumoto and Wong 1977
Pb	0.1–0.4	Strait of Georgia	Macdonald et al. 1991
Pb	0.12	Puget Sound	Boehm et al. 1985
Cu	0.33	Saanich Inlet	Matsumoto and Wong 1977
Cu	0.5–1.7	Strait of Georgia	Macdonald et al. 1991
Cu	0.21	Puget Sound	Boehm et al. 1985
Zn	0.2–0.7	Strait of Georgia	Macdonald et al. 1991
Cd	2.2	Saanich Inlet	Matsumoto and Wong 1977
Cd	10–40	Strait of Georgia	Macdonald et al. 1991
Cd	0.32	Puget Sound	Boehm et al. 1985
Hg	0.19	Puget Sound	Boehm et al. 1985
Ag	0.04–0.11	Puget Sound	Boehm et al. 1985
As	0.29	Puget Sound	Boehm et al. 1985



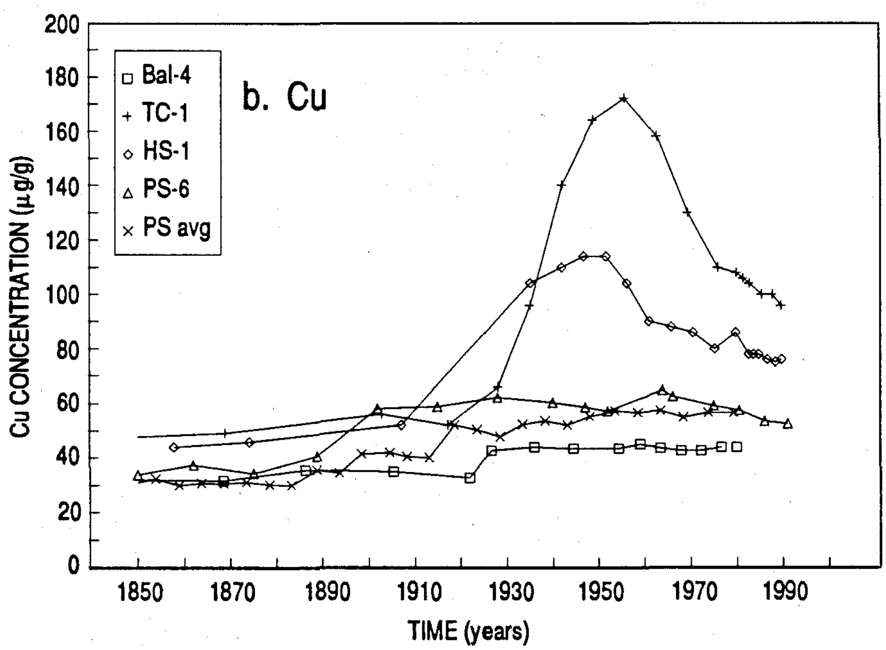
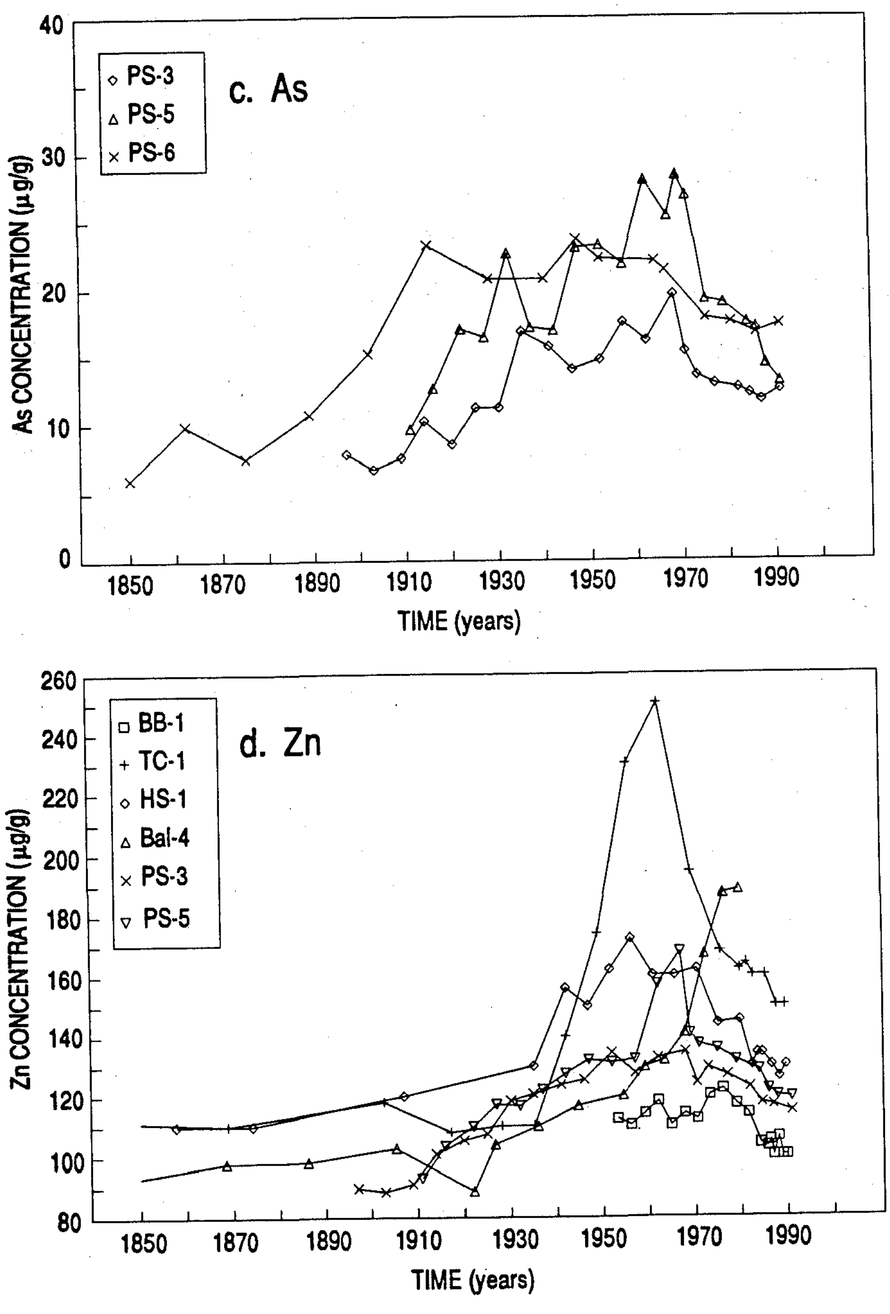


Figure 3. Sedimentary concentration as a function of time for Puget Sound and Strait of Georgia: (a) lead; (b) copper; (c) arsenic (d) zinc; (e) mercury; (f) tin; (g) silver; (h) Total PAH; (i) PCB; (j) OCDD; (k) 2,3,7,8, TCDF; and (l) Total DDT (DDT+DDE+DDD). Data were selected from among the dated sediment cores listed in Table 2. See Figure 1 for locations.

Data sources include Crecelius and Bloom 1988 (PS-avg); Crecelius unpublished (PS-3, PS-5, and PS-6); Macdonald et al. 1991 (Bal-2, Bal-4); Macdonald et al. 1992, and Cretney unpublished (BB-1, TC-1, HS-1).

For PCB (Fig 3i), the data at BB-1, TC-1 and HS-1 refer only to the PCB-77 congener which has been multiplied by 100 to scale it with the total PCB (sum of congeners) reported for the Puget Sound stations. Some of these cores have been subject to surface mixing (e.g., TC-1 and probably the PS-6 core). This has not been considered in the dating scale for the figures.



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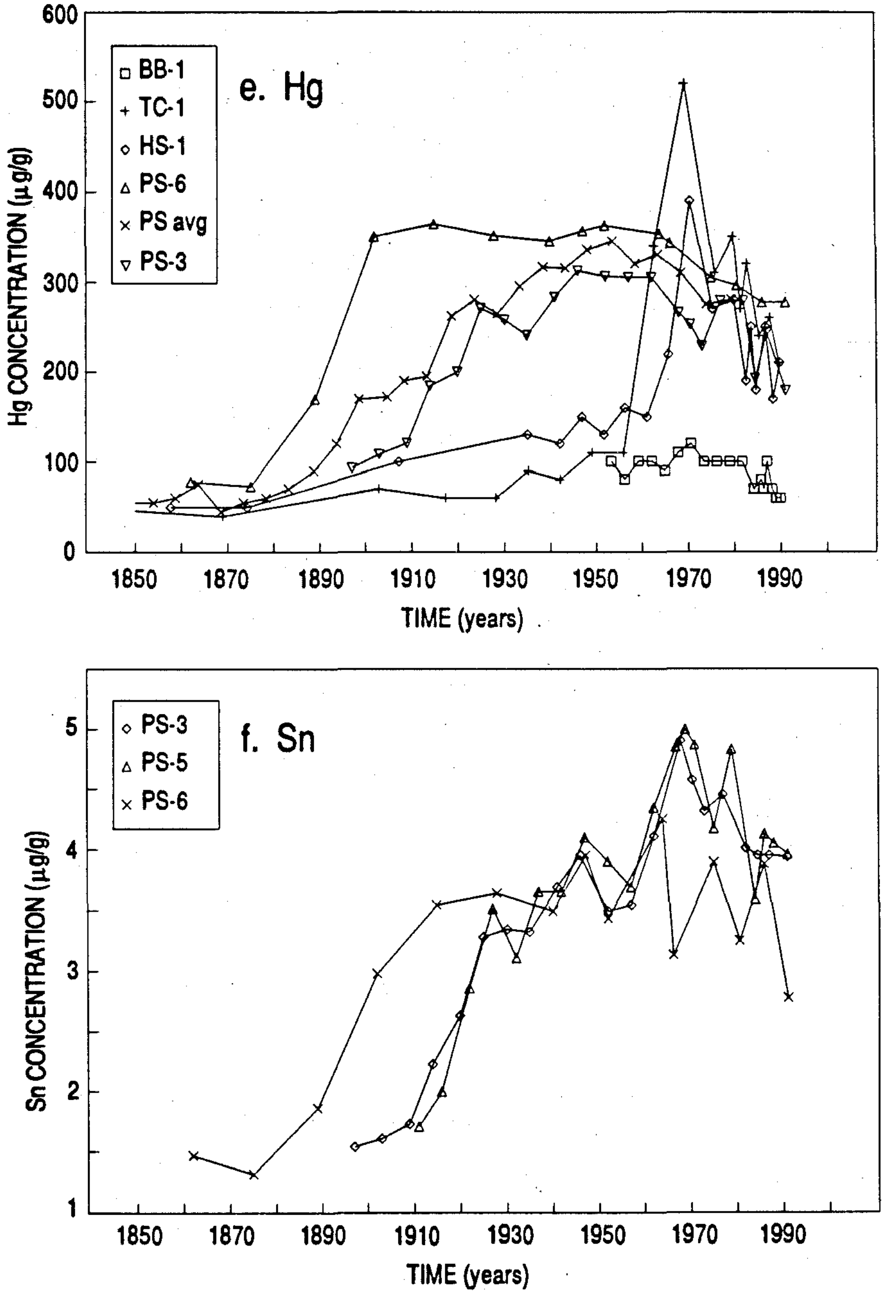

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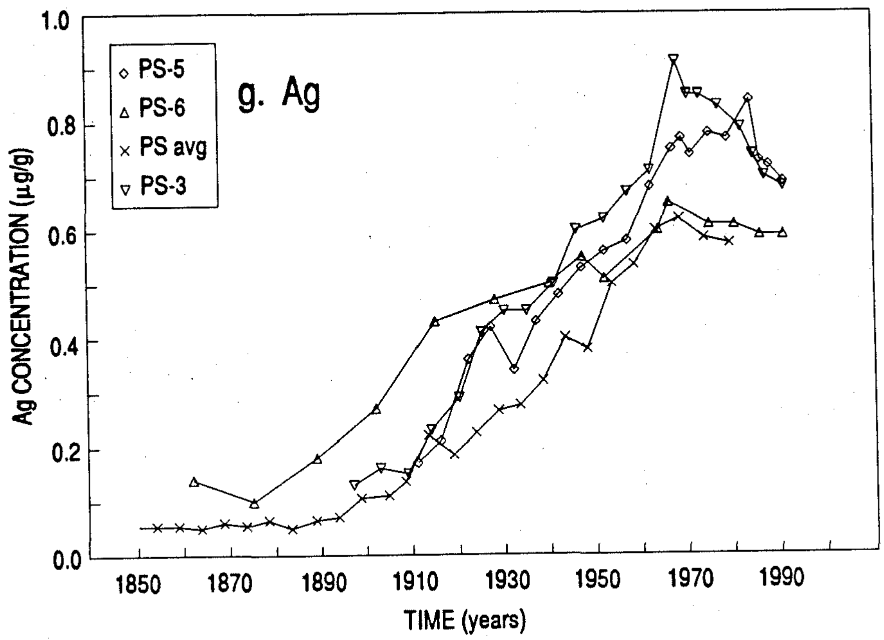

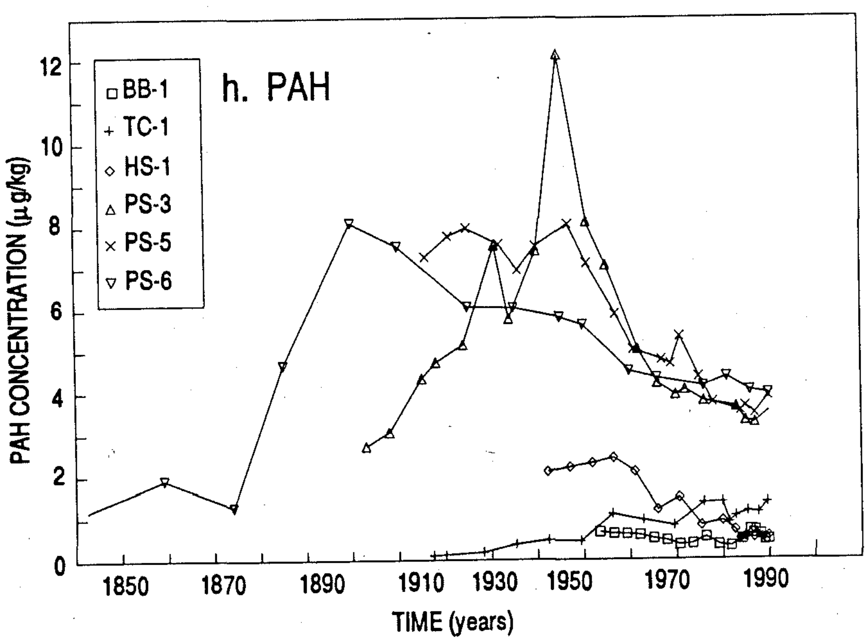

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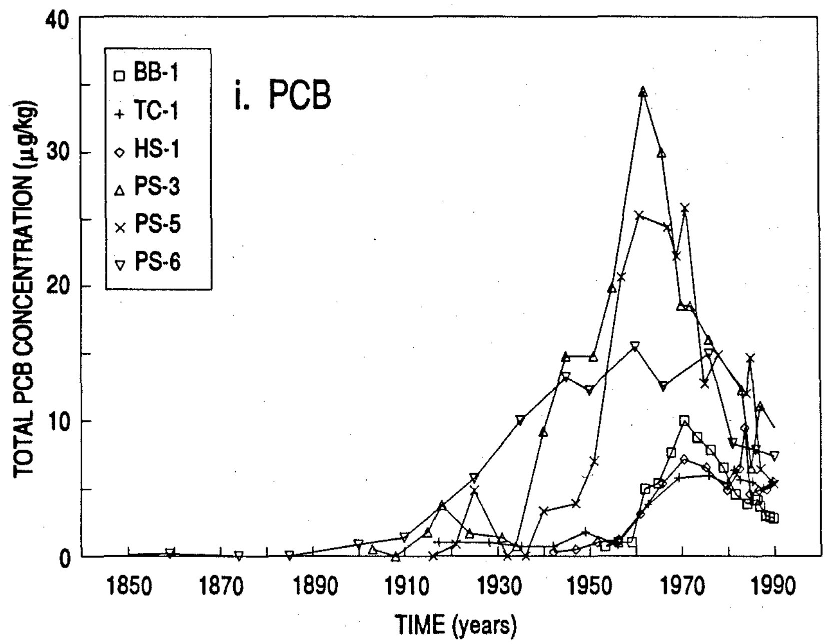

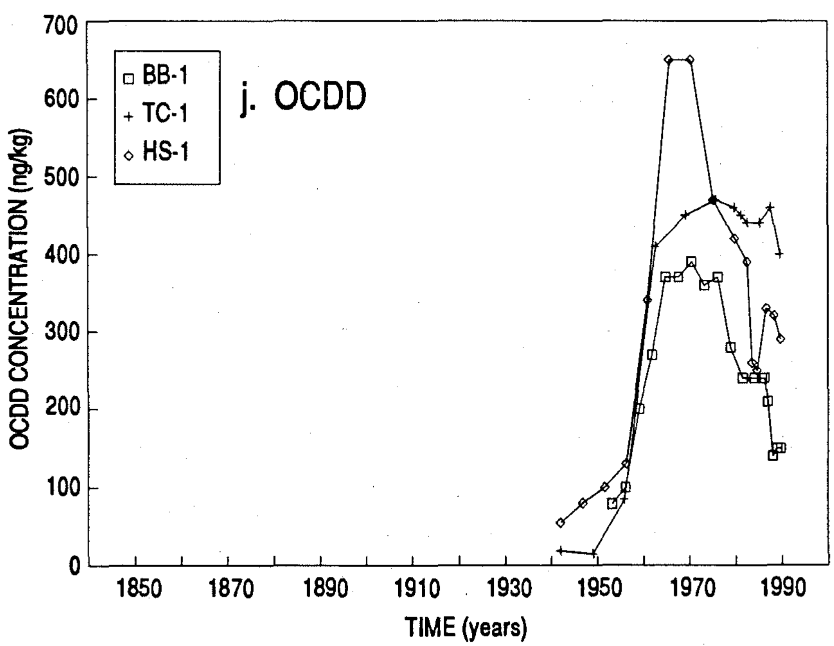

Figure 3 *Continued*

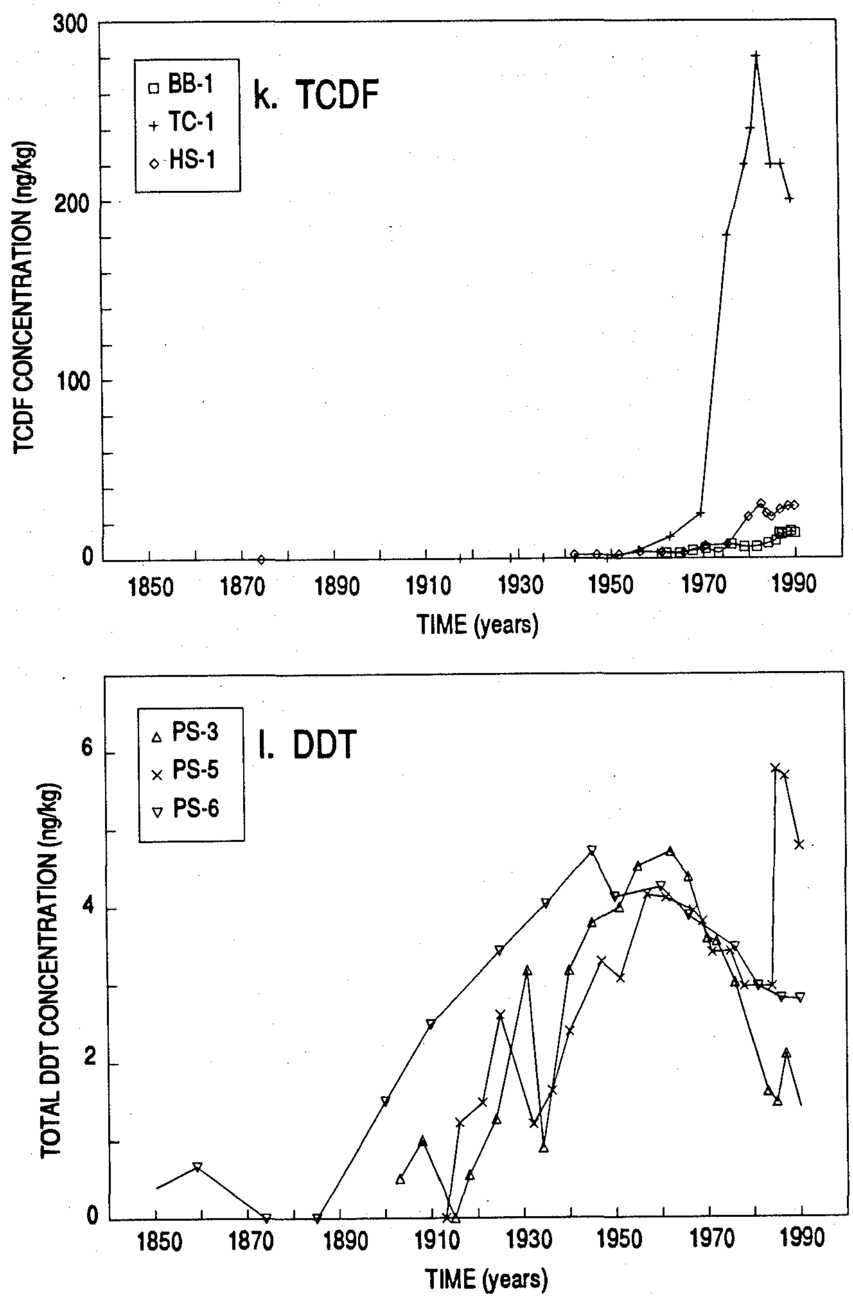

Figure 3 *Continued*

sediments. From the point of view of transboundary contaminant transport it appears from Figure 3a that Puget Sound and the Strait of Georgia have had independent, locally-supplied Pb contamination histories. This is supported by the isotopic signature of Pb in the Strait of Georgia which shows Canadian gasoline to be the predominant source both for sediments and for the water column (Macdonald et al. 1991; Stukas and Wong 1981).

Copper (Figure 3b)

Like Pb, contaminant Cu is first seen at about the year 1900 horizon in Puget Sound sediments. Contaminant Cu increases in sediments until the present where it accounts for about half the total Cu burden in sediments. The two predominant historical sources of Cu to Puget Sound have been ASARCO and municipal effluent (Paulson et al. 1988). Recently Paulson et al. (1993) have constructed a box model to predict dissolved Cu concentrations in Puget Sound; they identify the main marine sources of contaminant Cu in 1986 to be municipal, marinas and shipbuilding, and other industries. Paulson et al. (1993) suggest that loadings have significantly decreased during the 1980s due to pollution abatement programs at the three main sources, which may explain the downward trend seen at PS-6 (Figure 3b). The Strait of Georgia shows detectable Cu contamination after about 1930, but Howe Sound, into which Britannia Mines disposed their tailings since 1905, shows much heavier contamination since about 1930. Cores collected at the entrance to Howe Sound, well away from any direct tailings impact, suggest that Cu input fluxes were greatest between 1940 to 1965 and have since significantly decreased. Dissolved Cu from Howe Sound has probably been an important source for the Strait of Georgia proper, explaining at least part of the sedimentary Cu-enrichment seen there in the sediments since 1930.

Only part of the cultural enhancement of Cu is captured and recorded in GP sediments, and undoubtedly part has remained in the dissolved phase to escape the GPF system. The estimated residence time in the water for Cu is longer than for Pb (Table 3) and therefore it is expected to be transported beyond the basin it enters. Crecelius and Bloom (1988) and Paulson et al. (1988) suggest that 55–60% of the Cu loading into Puget Sound escapes into Juan de Fuca Strait. For Howe Sound there is evidence of enhanced Cu (and Zn) concentrations in the deep water (Thompson and Paton 1978; van Aggelen and Moore 1986). Recent cores from the deep basins in Howe Sound show the tailings as a layer buried under 10–15 cm of natural sediment that has accumulated during the interim 14 years (Drysdale and Pedersen 1992). Based on pore-water data, these authors suggest that remobilization of Cu and Zn from the tailings in the deep basin is inhibited by the reducing conditions that are found at shallow depths in these sediments. A reduction in Cu flux to sediments at the entrance to Howe Sound since about 1960 (Figure 3b) is suggested, but the sediments have by no means returned to their pre-mining Cu concentrations. Contaminant Cu in dissolved form is still entering the water within Howe Sound via discharge of acid rock drainage from the old Britannia Mine workings.

Arsenic (Figure 3c)

Figure 3c shows that the contaminant record for As in Puget Sound sediments follows that of Cu. Since about 1970 the sedimentary levels have been decreasing. The contamination of sediments with As (and Sb) is greatest near the smelter where slag, containing 1% As and Sb, was dumped for many years into Puget Sound (Crecelius et al. 1975). The slag is inert in seawater and does not contribute a significant quantity of dissolved metals to Puget Sound by leaching (Crecelius 1986), which implies that most of these bound metals will remain in place to be buried. There are no data for As in dated cores from the Strait of Georgia.

Zinc (Figure 3d)

Much of what has been said of Cu can simply be repeated for Zn. The sediments, which capture perhaps half of the Zn flux to the basin (Paulson et al. 1988), show the same general features as for Cu, with recent sediment concentrations decreasing. It is noteworthy that the Zn maximum for cores TC-1 and HS-1 in the Strait of Georgia is not synchronous with the Cu maximum; rather it is displaced 10 to 20 years later. This is most likely due to differences between the source functions for Cu and Zn, Zn having peaked later in the production history at Britannia Mines.

Cadmium

Basin sediments from GP show a constant background concentration (0.2–0.4 μg/g) with no apparent

increases of anthropogenic Cd accumulating near the surface (Bloom and Crecelius 1987; Macdonald et al. 1991). In contrast to this, excess Cd has been found in shallow locations near identifiable sources such as boat yards or industries where it has probably been introduced in particulate form (Crecelius et al. 1984; Crecelius et al. 1985; Goyette and Boyd 1989). Dissolved Cd has a long residence time in the water (Table 3) and therefore tends to escape both the Strait of Georgia and Puget Sound into Juan de Fuca Strait whence it eventually escapes to coastal waters. Bloom and Crecelius (1987) estimate that less than 3% of the Cd entering Puget Sound is captured in its sediments. Cd can possibly be enriched by scavenging to anoxic sediments where it is co-precipitated as the sulfide with FeS (Pedersen et al. 1989). This process may provide a sink for excess anthropogenic Cd, but trends in anoxic sediments from Ucluelet Inlet do not show surface enrichments.

Mercury (Figure 3e)

The records for basin sediments of Puget Sound and the Strait of Georgia clearly differ from one another. Since as early as 1900, Puget Sound has been receiving contaminant Hg with the general trends following the population increase and mirroring the Pb contamination. Apparently, Hg contamination of the Puget Basin sediments reached its maximum in the 1950s even though, as noted earlier, there was heavy Hg contamination in Bellingham Bay from 1965 to 1970. The Hg concentrations in Puget Sound basin sediments have continued to drop since 1950. For the Strait of Georgia only one core from the basin has been measured for Hg (BB-1) and it shows no significant trend.

In Howe Sound, data from sediment cores collected subsequent to the reduction in 1970 of Hg discharges accounted for an estimated 1000 kg of contaminant Hg buried under natural sediments (Thompson et al. 1980 and Figure 3e). Most of the Hg released at the head of Howe Sound by the FMC chlor-alkali plant has not been accounted for and may either have been scavenged by particulates over a wide area or advected out of Howe Sound. The Hg pollution in Howe Sound appears to have been confined to the shallow waters at the head of the inlet where crab fisheries were closed from 1970 to 1982; contamination was spread considerably further reaching the inner basin sediments and probably as far as sediments at the mouth of Howe Sound. The production of CH_3Hg in Hg-contaminated sediments from Howe Sound appears not to have been a significant source of Hg to the water (Thompson et al. 1980).

Following the reduction in the discharge of Hg to Bellingham Bay, surface sediment contamination was found to decrease with a half-life of about 1.3 years (Bothner et al. 1980). This study suggested that the removal of Hg was associated with sediment particles transported out of the study area. Surface-sediment samples collected in 1983 indicate that recovery from Hg contamination in Bellingham Bay was still continuing (Strand et al. 1986). It appears that both Puget Sound and the Strait of Georgia have had parallel, but unconnected, incidences of Hg contamination and pollution. Since about 1970, the Hg concentrations in both regions have been decreasing in surface sediments.

Tin (Figure 3f)

Cores collected in Puget Sound show clear evidence of Sn contamination starting at about the turn of the century. The source(s) of this contaminant Sn remain undefined. Unlike the other metals discussed so far, contaminant Sn concentrations have decreased little, if at all, in sediments that have accumulated since about 1940. These data suggest that further work is needed to determine the source of contaminant Sn. There appear to be no Sn measurements for dated cores from the Strait of Georgia.

Silver (Figure 3g)

Silver begins to contaminate sediments in cores collected from Puget Sound at about the turn of the century. Ag contamination has increased almost linearly since that time in sediments until about 1970 where there is evidence in a number of cores that it is holding constant or perhaps decreasing slightly. Ag is thought to be a good indicator of sewage (e.g., Sañudo-Wilhelmy and Flegal 1992). Therefore, the flattening of the Ag profiles may simply reflect sewage treatment which commenced at METRO in 1965. With surface-sediment concentrations about 10 times the background, Ag can be viewed as one of the most contaminating metals. There are no parallel data for the Strait of Georgia.

Organic Compounds

Carbon (C), Nitrogen (N)

Organic carbon plays a predominant role in the geochemistry of sediments since it controls the availability of oxygen, and with it the redox conditions that subsequently control the cycling of metals and of nutrients. Coastal marine sediments receive their organic carbon and nitrogen from terrestrial and marine sources; both C/N ratio and stable isotope composition of C ($\delta^{13}C$) can be sensitive indicators of the source of the organic matter. C/N ratios usually increase with age (or depth) in sediments because during diagenesis nitrogen-containing compounds tend to be less stable.

Marine organic carbon predominates in northern Strait of Georgia sediments as shown by the C/N ratio of about 5–6 (Bornhold 1978). In contrast, the sediments in Howe Sound, a coastal fjord freely connecting to the Strait of Georgia, appear to receive large amounts of terrestrial carbon (C/N ratios of 10 to greater than 30; Drysdale and Pedersen 1992). In Ballenas Basin, which occupies the central portion of the Strait of Georgia, the sediments receive much of their inorganic load from the Fraser River. Consequently these sediments fall between the above two extremes; the C/N ratio (9-10) and $\delta^{13}C$ values (−20 to −22‰) indicate that terrestrial sources contribute perhaps 30–40% of the total organic carbon (Macdonald et al. 1991). What is interesting about the Ballenas Basin sediments is that terrestrial carbon appears to become more important toward the surface (young) sediments. This trend opposes that expected from diagenetic processes which suggests that recent terrestrial carbon inputs have increased. The most likely source of terrestrial C is pulp mill effluent which is apparently augmenting the basin carbon fluxes by about 25%.

Puget Sound, despite high planktonic productivity, has sediments that exhibit the properties of terrestrial carbon (Carpenter and Peterson 1989).

PAH and Other Hydrocarbons (Figure 3h)

Aliphatic, aromatic, sulphur and nitrogen-containing hydrocarbons have been studied systematically in ^{210}Pb-dated sediments from Puget Sound since 1975, making this one of the most thoroughly studied coastal regions. Of these compounds, the PAHs are known to have polluted harbour sediments both from Puget Sound and from the Strait of Georgia (cf. Malins et al. 1984; Malins et al. 1985; Goyette et al. 1988). The suite of publications ensuing from the Puget Sound work (Prahl and Carpenter 1979; Bates and Carpenter 1979; Barrick et al. 1980; Prahl et al. 1981; Barrick and Hedges 1981; Barrick 1982; Furlong and Carpenter 1982; Bates et al. 1984; Barrick et al. 1984; Barrick and Prahl 1987) has been recently reviewed by Carpenter and Peterson (1989). Equivalent studies do not exist for the Strait of Georgia.

The Puget Sound sediment studies show that PAH tend neither to be degraded nor produced within the sediments, at least within the roughly 100-year time span represented by the sediment cores. Many, but not all, Puget Sound coring sites show a maximum in PAH concentration around 1945 to 1960 (e.g., Figure 3h — core PS-3). Preliminary data for total PAH in dated cores from the Strait of Georgia (W. Cretney, unpublished), also shown in Figure 3h (BB-1, TC-1, HS-1), suggest that PAH distributions there may have some similarities with Puget Sound although the sedimentary concentrations appear to be much lower. The PAH sub-surface maximum in sediments has been attributed to domestic coal burning which increased until about 1950 and then was gradually replaced by other fuels which are thought to produce less PAH (Gschwend and Hites 1981). Counter to this is the increase in use of other fuels as a result of increasing population. For Puget Sound, the burning of fossil fuels is a major source of PAH, particularly for nonalkylated 3–6 ring compounds. However, it is important to note that modern anthropogenic increases are set against a measurable background of naturally-produced combustion PAH, augmenting it by perhaps a factor of 5 to 10 (Figure 3h). The geographic distribution of combustion PAH in Puget Sound sediments suggests that the major sources are municipalities and industries at the northern end of the sound (aluminum smelting and oil refining). One core collected near a pulp mill in the Strait of Georgia (Figure 3h — core TC-1) shows slightly enhanced total PAH concentrations near the surface; the origin of this total PAH has not yet been unequivocally determined. Generally, total PAH appears to have been decreasing in surface sediments for the past 20–30 years, although concentrations in Puget Sound appear still to be well above background.

Contaminant aliphatic hydrocarbons are found in the central basin of Puget Sound. Aliphatic hydrocarbons

are not of much environmental concern but they can be a useful bioindicator for determining the geochemistry and sources of other contaminants. Based on the aliphatic composition, Barrick (1982) determined that the origin of aliphatic hydrocarbon was primarily chronic inputs from municipal runoff and sewage discharge. These contaminants appear to have increased by a factor of about 10 since the turn of the century (Barrick et al. 1980; Barrick and Hedges 1981). Sewage treatment since 1973 may have reduced the hydrocarbon (lipid) input somewhat, but according to Barrick (1982) METRO's discharges are still sufficient to account for virtually all of the hydrocarbon inputs to the Puget basin sediments. Conversely, the Puget Sound sediments can therefore account for much of METRO's discharges. It is likely that the municipal runoff and outfalls entering other parts of the GPF system introduce similar types and quantities of hydrocarbons.

Organochlorines (Figure 3 i, j, k, l)

PCB

PCB has been measured in cores from Puget Sound (as a sum of PCB congeners) and in cores from the Strait of Georgia (the PCB-77 congener (3,3′,4,4′-tetrachlorobiphenyl)). In Figure 3i the PCBs show similar trends in the two basins. (Note that the PCB-77 concentration in cores BB-1, TC-1, and HS-1 has been multiplied by 100 to scale it to the Puget Sound PCB data). There is a rapid rise in sediment concentration starting in the 1930-1940 horizons. The concentration of PCBs reaches a maximum in sediments deposited in the 1950s and 1960s. Significant decreases in PCB concentration since about 1970 are evident (Figure 3i) and coincide with the phasing-out of the industrial use of PCB starting in about 1971 (Moore and Walker 1991; Eisenreich et al. 1989). PCBs are detectable in the Puget Sound sediments well before their known production. The apparent presence of these compounds in sediment deposited earlier than their production can probably be explained by a combination of one or more factors: bioturbation; bias in the age dating technique; false positive results caused by other compounds that interfere in the quantification. Because the concentrations of individual PCB congeners is very low in the pre-1940s sediment sections, absolute concentrations are uncertain. Although mixing may alter the shape of the PCB profiles and the location of contaminant horizons, it does not affect the conclusion that PCB concentration in recent sediments has been decreasing. Since PCBs come from a variety of dispersive sources and from spills, the contaminant records shown in Figure 3i are not easily linked to any one source; the likely sources include surface runoff, industrial activity, incineration and municipal effluent. The widespread occurrence of PCBs suggests that sources tend to be widespread and connected by long-range transport possibly mediated by particle scavenging and re-volatilization (e.g., see Iwata et al. 1993). Some of the highest organochlorine contaminant loading rates from rainfall in Canada are observed on the west coast, with Asia being identified as potentially an important source (Strachan 1990). In addition to this global phenomenon, local hot spots are observed in coastal sediments near several industries and in industrialized areas (Pavlou and Dexter 1979; Garrett 1983). The sediment records suggest that sediments act as a permanent sink for most of this contaminant. Pavlou and Dexter (1979) estimate that the majority of PCB contaminants (80%) entering Puget Sound are retained in the sediments there; presumably, the remaining amount is advected into Juan de Fuca Strait.

Dioxins, Furans

Chlorinated dioxins and furans have been measured in cores collected from Howe Sound and the Strait of Georgia (Macdonald et al. 1992; Cretney et al. 1992; W. Cretney, unpublished). As shown in Macdonald et al. (1992) and Figs. 3j and 3k the time-trends and areal distributions of OCDD and 2,3,7,8 TCDF differ. OCDD first appears in sediments in about 1940 coinciding with the shift of the chemical industry from its commodity base to plastics. The OCDD content increases to a maximum in about 1970 and then decreases to about half the maximum in the most recent sediment layers. These trends, like those observed elsewhere (Hites 1990), are attributed to atmospheric transport with a variety of sources including the burning of plastics. The reduction of OCDD after 1970 is coincident with the installation of emission-control devices on incinerators (Furlong et al. 1987).

Pulp mill effluent is a second important source of organochlorine compounds to our coastal sea. One of the contaminants from the chlorine bleaching process, 2,3,7,8, TCDF, first appears in the sediments in the

early 1960s, coincident with the conversion to chlorine bleaching at the two Howe Sound pulp mills (Figure 3k). This contaminant has traveled at least 30 km to accumulate in the basin sediments of the Strait of Georgia; nevertheless, its sediment concentrations have been reduced by about two orders of magnitude over that distance. The flux of this contaminant increased approximately linearly with time until 1989 when the mills incorporated chlorine dioxide into the bleach specifically to eliminate much of the dioxin and furan contaminants (McDonald 1990). Based on modeling the sediment core collected near one of the mills, Macdonald et al. (1992) concluded that the 2,3,7,8 TCDF flux has sharply decreased following the pulp-mill bleaching process change. Mixing of the sediment surface by biota, however, will delay the burial of sediments by clean material with an estimated half-life of about 10 years at the site examined.

DDT Compounds

Temporal trends for DDT from dated cores are available only for Puget Sound sediments (Figure 3 l). The profiles are similar to the PCB data discussed earlier again reflecting the use pattern of this pesticide. Industrial production of DDT began in the 1930s and 1940s and its use in Washington was curtailed due to environmental concerns in the 1970s. DDT can be found in the sediments at dated depths that precede its production. As in the case of PCB, this is probably a direct or indirect effect of biomixing. The core taken at PS-6 appears to have been most affected by mixing.

Radionuclides

Atmospheric weapons-testing generated a global fallout contaminant signal commencing in the early 1950s, which reached a maximum in 1963–64 when the Nuclear Test Ban Treaty (1963) curtailed atmospheric and underwater tests by the signatories (China and France not included). As in most oceans and lakes, sediments from the GPF system contain fallout products such as $^{239+240}Pu$, ^{241}Am and ^{137}Cs (Carpenter and Beasley 1981; Carpenter and Peterson 1989). Plutonium-producing reactors at Hanford injected artificial radionuclides to the Columbia River from 1944 until about 1971 (Robertson et al. 1973). The radionuclides were introduced to the Washington shelf via the river where they could have been transported northward into the mouth of Juan de Fuca Strait. This potential source of radioisotopes appears not to have been important in the inner basins of the GPF system, since data from Saanich Inlet and Dabob Bay show isotope ratios in excellent agreement with ratios in unfractionated midnorthern latitude fallout (Carpenter and Beasley 1981); the inventories of the measured radionuclides are in agreement with the estimated delivery of fallout products to the region. However, peak Pu activities are found in sediment layers dating from 1970–1973 suggesting a lag between fallout delivery and scavenging to sediments; the alternative explanation, errors in sediment dating, is discounted as unlikely by the authors. The Chernobyl nuclear reactor accident injected a pulse of radionuclides into the atmosphere; it has been estimated that ^{137}Cs from this source may account for perhaps 3% of the total inventory released from all previous above-ground nuclear testing (Taylor et al. 1988). There is no evidence to suggest that these fallout products have had any significant impact on the marine biota (Carpenter and Peterson 1989; Preston 1989).

Organotins

Sediments located near marinas or ship-maintenance areas are contaminated with tributyltin (TBT). Concentrations in Puget Sound marinas were in the range of 100 to 1000 μg/kg TBT as tin in the late 1980s (Fortman and Crecelius 1989; Varanasi et al. 1988, and Crecelius et al. 1989; Templeton 1991). In Puget Sound's urban bays, the concentrations ranged up to 300 μg/kg (PTI 1988); in non-urban bays the concentrations ranged from less than 3 to 40 μg/kg (US EPA 1989). The concentration of TBT in surface sediment from the central basin of Puget Sound was less than 5 μg/kg and no historical trend could be detected in a sediment core (Crecelius, unpublished).

Similar to Puget Sound, TBT is found associated with marinas in the Strait of Georgia (Stewart and Thompson 1994), and exceedingly high levels of contamination have been recorded in Vancouver Harbour (up to 10,000 μg/kg; C. Garrett, pers. comm.). Interestingly, there does appear to be a trend for TBT in one sediment core collected in Ballenas Basin (Stewart and Thompson 1994) which suggests that the half-life of TBT in these sediments may be longer than is commonly believed (e.g., Stewart and de Mora 1990). In

view of the evidence that TBT is affecting gastropods in the Strait of Georgia (Saavedra Alvarez and Ellis 1990; Bright and Ellis 1990) and that sediments may be an important sink for TBT (e.g., Yonezawa et al 1993) further research directed at organotins in GPF sediments is warranted.

CONCLUSIONS

The Strait of Georgia and Puget Sound operate almost independently of one another with respect to particle sources and sinks. Both regions have major sources of inorganic particles which tend to be trapped within the basin they enter, and which tend to bury contaminants in long-term sedimentary reservoirs. Contaminants that attach strongly to particles are therefore removed from the possibility of transboundary transport. Contaminants that escape the inner basins to Juan de Fuca Strait tend not to be trapped there, whether or not they become attached to particles, since modern sediments are not accumulating in this region.

The marine sediment quality in the transboundary area is generally excellent because (1) the sources of contaminants are quantitatively small compared to the dilution in this high-energy environment, and (2) the major contaminant sources of chemicals are large urban centers (Seattle and Vancouver) or industries that are physically well-isolated from the boundary. Problem sediments have been found in close association with these sources (e.g., Vancouver Harbour, Howe Sound, Elliott Bay, Commencement Bay, Everett Harbor, Bellingham Bay). Basins near these urban centers are effective traps for contaminants that adsorb onto particles.

One encouraging interpretation from the historical trends derived from basin sediment records is that even though urban populations have increased rapidly during the last two decades, the discharge to the marine environment of most of the chemicals examined has actually decreased. This decrease has been most dramatic for chemicals that were specifically regulated. Future improvements in waste-water treatment and source control should also be reflected in improved sediment quality. Because there is a large supply of new inorganic (allochthonous) sediment, and because the coastal basins are deep, particle-active contaminants tend to become quickly scavenged and buried within the Strait of Georgia and Puget Sound. An important consequence of this burial is that the basin sediments do not tend to behave as an infinite source by injecting contaminants back into the water long after the original sources have been reduced or removed. This contrasts the circumstances observed in San Diego and San Francisco Bays, which are semi-enclosed and have limited freshwater input. There, order-of-magnitude enrichments of trace elements is sustained by the contaminated sediments, even though point-source discharges of wastes to the bay were eliminated two decades ago (Flegal and Sañudo-Wilhelmy 1993).

Because the major direction of flow is parallel to the international boundary in Juan de Fuca Strait, contaminated sediments and dissolved chemicals entering from the sides will tend not to cross this boundary. Due to strong mixing in this region, effluent from existing outfalls will be greatly diluted before crossing the international boundary; the rapid flushing of water in this region ensures that contaminants have no opportunity to concentrate.

The major discharges to transboundary waters include pulp mills, sewage outfalls, oil refineries, and ships. Although contaminants from these sources are detected in the ecosystem (chlorinated organic chemicals, petroleum, butyltins and silver) there is no evidence that sediment toxicity persists in the transboundary region. Even when major petroleum spills have occurred, sediments that were initially oiled recovered within a few years.

Many chemicals have widespread distribution in the environment and are known to cause biological effects at extremely low concentrations (e.g., see list given in Colborn et al. 1993). Included among these chemicals are chlorinated organics, butyltins and, more recently, the alkylphenol ethoxylates (Naylor et al. 1992). Caution dictates the monitoring of our coastal sediments for these compounds and their trends.

Symposium Questions — The Perspective From Sediments

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

   Sediments appear to provide a mechanism to scavenge many contaminants and thereby inhibit their transboundary transport. Almost all of the highly chlorinated organics, PAHs, and Pb remain within

the sediments of the basin they enter. For other contaminants like Cu, Zn, and Hg, some fraction probably escapes in the dissolved phase; nevertheless, for these metals, identified pollution problems have been limited to near the source regions which are generally well-removed from the international border.

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 Juan de Fuca Strait? As compared to five or ten years ago, is the severity of harm greater, less or the same?*

   There is no evidence that transboundary pollution in sediments is causing harm. There are, however, regions on both sides of the boundary where contaminated sediments are a local problem and we have cited examples. The solution to these problems can be managed within the respective countries through environmental action. As shown by basin sediment records, the sedimentary concentrations of almost all of the contaminants we examined have actually been decreasing during the past 5–10 years. This is largely due to regulations specifically aimed at decreasing known contaminant sources.

5. *Given forecasts of human population increases for the lands that drain to the Strait of Georgia, Puget Sound, and Juan de Fuca Strait, 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 . . . be greater, less or the same in 20 years?*

   The decreasing contaminant trends noted above are due mostly to action that has been taken to reduce sources. Without further controls, increasing population can be expected to flatten-out or even reverse the present downward trends in surface sediments. Increasing human pressure on drainage basins may alter the supply of inorganic sediment to the system or its quality, but particle-active contaminants will still tend to be captured and buried within the basin sediments. Particular areas of concern are those sediments that contain a rich fauna. These tend to mix sediments, returning buried contaminant to the surface, and also to provide a direct entry of sedimented contaminant into the food web.

6. *What components of the transboundary marine ecosystem appear to be most sensitive to harm from human activities? What types of harm appear to be most serious and should be the focus of monitoring, research, and management activities over the next ten years? Which type of human activities (i.e. discharges or spills of toxic compounds, nutrient, pathogens, physical land modification) need the most management attention?*

   a. Because it is having an affect on biota, the use of tributyltin and regulations governing such use needs to be re-examined. Sediment records of TBT should be investigated for their applicability to determining kinetic losses of this family of compounds.

   b. An emerging environmental concern is the effect of "endocrine-disrupting chemicals," which have the potential to harm living resources by disrupting their reproduction and development (e.g., Naylor et al. 1992; Colborn et al. 1993; Jobling and Sumpter 1994). These chemicals include many of those discussed earlier such as TBT, chlorophenols, pesticides and herbicides. Among these compounds are included some widely-used industrial and domestic detergent components that enter the ecosystem via sewage effluent (alkylphenol poly-ethoxylates such as nonylphenol). Presently we know nothing about the environmental significance in the GPF system of this class of compounds. Sediments, which are probably an important sink for these compounds, would be the place to determine recent trends and the scale of the problem.

   c. Pulp mills are one of largest sources of effluent to the coastal sea (Table 1). Pulp-mill effluent contains a complex, poorly-determined mixture of chlorinated compounds whose environmental effects are simply not well enough understood; many of these compounds are known endocrine disrupters. Much more work needs to be done to determine the chemical composition, the processes that move these compounds through the ecosystem, and the environmental effects.

   d. The Fraser and other rivers provide a large supply of inorganic sediment which scavenges, buries and dilutes particle-active contaminants. Removal of this silt, suggested as a remedial action by Captain Cousteau about 20 years ago (Waldichuk 1983; Thomas 1992), would severely impact the natural sedimentary processes of the

basin. If for example the suspended load of the Fraser River were to be reduced, we predict that sediment contaminant concentrations in the Strait of Georgia would increase and that contaminants would remain within the biosphere longer because of slower scavenging and slower burial. Any proposal to build a dam on the Fraser River should take account of this effect on the Strait of Georgia.

e. As a strategy, there is a need for British Columbia and Washington to adopt equivalent measurement techniques (protocols, and inter-laboratory comparisons) so that data from both sides of the boundary can be compared. This is important for single component measurements (e.g., Hg, Cd) and crucial for multivariate measurements (PAH, organochlorines) if we are to apply modern statistical approaches to determine sources for contaminants.

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DISCUSSION

Curtis Ebbesmeyer *(Panel)*: Robie, you've shared a lot of data with us. Could you share your top two priority worries. I know scientists have a lot of worries and they very often don't share those.

Robie Macdonald: I'm very glad that you asked that question. A statement of the problem is something like this: there are these whelks out there having imposex, basically that's taking a female whelk and turning it into a male. That's not a big problem for most people, why worry about those? But, it's widespread and it's bona fide pollution, and it's something that concerns me. There's an effect out there and we know that it's caused by TBT. I made a little list of Reproductive and Endocrine Disrupters, taken from a paper by Coleburn et al.

REPRODUCTIVE AND ENDOCRINE DISRUPTERS

Industrial Chemicals
* Cd
* Dioxin (2,3,7,8)
* Pb
* Hg
PBBs
* PCBs
* PCP
x Penta- to nonylphenols
Phtalates
Styrenes

Herbicides
2,4-D
2,4,5-T
Alachlor
Amitrole
Atrazine
Metribuzin
Nitrofen
Trifluralin

Nematocides
Aldicarb
DBCP

Insecticides
β-HCH
Carbaryl
Chlordane
Dicofol
Dieldrin
* DDT and metabolites
Endosulfan
Heptachlor and H-epoxide
Lindane (γ HCH)
Methoxyclor
Mirex
Oxychlordane
Parathion
Synthetic pyrethroids
Texaphene
Transnonachlor

Fungicides
Benomyl
Hexachlorobenzene
Mancozeb
Maneb
Metiram-complex
x*Tributyltin
Zineb
Ziram

From: Colborn et al. *Environmental Health Perspectives,* 101 p.379

You'll see that a lot of the elements that I talked about are on this list. Cadmium I didn't talk much about, it's not actually trapped much in the system. It tends to remain dissolved and gets passed through, although there are local places where particular cadmium does accumulate, but it's in their dioxins. We know that it does other things too, but it also affects populations in an insidious way that's difficult to determine. It's not killing the animal necessarily by poisoning, it's not toxic, but if that animal fails to reproduce or fails to find a partner, then you are doing damage to it and maybe as much damage as if you just plainly smothered it or poisoned it. Lead's in there, mercury is in there. Now I want to get down to the ones with the asterisk. We have data that suggests we ought to worry more about tributyltin. In 1989, regulations were put on the use of tin, you can't just use it anywhere you like. You're supposed to use low-release compounds, and use is restricted to aluminum boats, or boats bigger than 25 meters. In other words, it's not exactly being taken out of the system, it's still being used by a lot of outfits. Pentaphenols are used in a lot of industrial soaps and municipal detergent, so they are widespread, and they also happen to be 'sedophiles', I could call them — they tend to stick onto particles. So I think that if we are going to see a problem, sediments would be the first place to look for them. The reason I like sediments is that quite often you can't come up with water-column evidence because water is too patchy, and concentrations are really low. But sediments concentrate things and it's a first place — sometimes the only place — where you'll see an effect. The other worry I mentioned already is that if somebody proposed to put a dam on the Fraser River and take the silt out as Captain Cousteau said we ought, I think that would have an effect on the contaminants in the system.

Bruce McCain *(Panel)*: My question concerns the build-up of PAHs in some of your cores. PAHs are a little different from PCBs and DDTs because they tend to be metabolized by bacteria and other organisms, so it's really difficult to judge loading levels based on what's in sediment. In some areas of the United States we're finding increases in PAHs in surface sediments, mainly because of automobile use and surface water run-off. Would you say that in areas like Vancouver Harbour or lower Puget Sound that you would expect

the loadings are changing, or do you think they are still decreasing as your cores would show?

Robie Macdonald: I don't know if I can give you an answer to that. My guess is that they would not be decreasing unless specific actions were taken, for example a known source was turned off in some way. You're right about the metabolism, once animals take in PAHs they do have ways of cleaning bottoms of it, but a lot of the material, once it gets into the sediments, is pretty refractory and hangs around for a long time. So the sediments can still provide you a trend even though you know you have lost things on the way to the sediment. In fact, Baker and Roy Carpenter and a host of scientists have made piles of measurements on what gets delivered to sediments, and they were able to account for them from source to sink. That was one of the classes of compounds that Puget Sound was effectively trapping, same with PCBs, the estimate was 80% of PCBs that go into Puget Sound go into the sediments. As for Vancouver Harbour, I think high levels of PAH and other things have been measured there. I don't think those problems are going to go away, because in that particular place you are not getting sediment to bury it. So unless one does a remedial action on it, it's going to sit there.

John Armstrong *(Environmental Protection Agency)*: You've talked mostly about core data from the central parts of our region, our deep waters. What can we say about the shallows? Do we have information from Canada and the US on contaminated sediments around various discharge points? And are those areas that I assume are contaminated, growing or shrinking?

Robie Macdonald: You've asked three or four questions there and I don't think I can answer all of them. In the paper we briefly discuss sediment toxicity. We recognize that there are shallow areas in urban waterways and near industries that are contaminated, and our conclusion is that they're not so much in the transboundary region, but in Vancouver Harbour or Elliott Bay or some place. I think that you will find that some of the places, especially in Puget Sound, would tend to decrease because the sources have been dealt with.

Eric Crecelius: I believe that fairly extensive studies have been done in urban areas in Puget Sound and showed sediment contamination. But I don't think there has been a long enough history in these areas to determine yet whether they are recovering. I think that in the near future it will be an important area to study, to see how rapidly these areas are recovering, and to see if recovery rates parallel what we see in the main basin sediments.

Robie Macdonald: One place that contaminants get back into biota is in sediments in which animals live. They tend to mix the surface sediments up, which gives people who try to date sediments a hard time. They can also bring that contaminant into their bodies and, by being a food item, put it back in the benthic ecosystem. In the areas we measured in the Strait of Georgia, half-lives were in the order of eight to ten years for the turn down of contaminants and surface sediments with bio-mixing, longer for sediments that are mixed deeper or more rapidly. These basins tend to be burying at different rates in different places, and we want to worry about the ones where the burial rate is slow relative to the mixing rate, and where contaminants have gotten into them. When you dump contaminants in you'll see hot spots which tend to be the places where sediments are accumulating but not being mixed. If you turn the contaminants off, the hot spots will turn cool because they get buried and the cool spots will turn hot because material is being mixed from deeper. You need to know a lot about the biogeochemistry of sediments before you can predict how long it will take for these things to turn off.

Laurie MacBride *(Save Georgia Strait Alliance)*: What would you say about the potential impact of dredging along our coastal waters, as we get more and more population, and the resulting increasing demand for things like marina developments and so on?

Robie Macdonald: Dumping the material into the ocean, in a transboundary context, doesn't concern me because in some ways that material is more controlled for contaminants and disposal. Where the problem comes, and I think it's what you're getting to, is what kind of damage are you doing to that near-shore area, and I haven't talked a lot about that. I think that would certainly fall into the category of long-term concerns in global management. I think often as scientists we do all the right things, we make models and we measure, and we say this is fine, and we can put this marina here. While we are doing all that, we are whittling away the estuary, whittling away the shoreline. And that's a prob-

lem that can only be stopped by a large scale plan that says 'No we're not going to whittle away these pieces' and they are saved like that.

Chris Prescott *(Puget Sound Water Quality Authority)*: I agree with you that sediment contaminants do tend to stay localized. We find that as you get further from a source, the concentration drops rapidly. But, I wanted to mention two more exceptions to its staying locally. We've heard about bioturbation and dredging. Dr. McCain's work that says that even salmon that stay for a very short time at urbanized estuaries tend to have effects. There are potential transboundary implications there. The other is that migrating birds, which feed in areas like Commencement Bay even for a short time, have significant increases in contaminants, and those again have a transboundary implication.

Martin Keeley *(Friends of Boundary Bay)*: You mentioned briefly the incineration impact of dioxins, where in fact there was a drop off perhaps from the pulp mills, it was now being picked up from the incineration fall-out. Do you see other contaminants from municipal incineration accumulating in sediments, and do you track that as transboundary? Is it moving through the water ecocycle or is it just coming down the rivers?

Robie Macdonald: That's a good question. The main one that we've measured is octodioxin, and we see it drop because in 1970 incinerator emissions were controlled. In that dataset there are a pile of other compounds that we haven't looked at, and I'm sure that some of those will also show up. PCBs get produced by burning plastics and other things too. In the Strait of Georgia, we see that same signal so I think PCBs are there. We haven't created a lot of data to answer your question well. Those are the other things that we would worry about mostly, I think that if we got a microscope out looked at sediments or used hydrochloric acid on the solids, you would probably see fly ash, and you could identify sources that way. We haven't done that.

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

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ABSTRACT

This review focuses mainly on the issue of natural versus anthropogenic nutrient inputs in Juan de Fuca Strait, the Strait of Georgia and Puget Sound. Metals (lead, copper, zinc, cadmium and mercury) and organics (PAHs, organochlorines and organotins) in the water column are also briefly reviewed along with the potential for transboundary (Canada/US) transport of nutrients, plankton and pollutants.

Sewage discharge has only a minor influence on the eutrophication status of Juan de Fuca Strait, the Strait of Georgia, and most of Puget Sound. Direct sewer inputs of nitrogen are very small compared to natural nitrogen inputs from entrainment of nutrient-rich deep water arising from the Georgia Basin estuarine circulation.

Nitrogen concentrations in Juan de Fuca Strait are always high enough (>10 µM NO_3) to allow maximal growth rates of phytoplankton, and therefore extra nitrogen from the sewage outfall in Victoria would not cause increased phytoplankton blooms in the vicinity because of the rapid seaward flushing in Juan de Fuca Strait.

Natural nitrogen inputs to the Strait of Georgia, which include wind-mixing beyond the Fraser plume, and entrainment and salt wedge breakdown at the mouth of the Fraser River, appear to be several orders of magnitude greater than the anthropogenic nitrogen inputs represented by the river-borne nitrogen concentrations. During July and August, phytoplankton growth may be periodically nitrogen-limited. However during this same period, river-borne nitrogen is only about 3 µM. Consequently, the nitrogen input from the Fraser River would only produce a minor increase in chlorophyll, considering the large amount of dilution that occurs in the plume area.

In Puget Sound, nitrogen concentrations in the central basin are similar to the Strait of Georgia. However in poorly flushed bays and inlets, especially in the south end of the Sound, surface nitrate may be depleted all summer, chlorophyll is very high, and bottom oxygen concentrations may become critically low.

Early warning signs of eutrophication are already evident in some poorly flushed bays and inlets of southern Puget Sound. Consequently, similar bays and inlets in the Strait of Georgia should be monitored (e.g. inner Burrard Inlet, Boundary Bay). It is important to understand the physical oceanography of each inlet and its interannual variability, if one is to predict the consequences of future increases in nutrient inputs.

The highest concentrations of metals and organics are in urban bays with poor flushing, especially in Puget Sound. Rural bays and the deep central basins show much lower levels of contaminants. The worst chemical contaminant problems show up in the bottom sediments, where many contaminants are concentrated by adsorbing to particles which settle out.

INTRODUCTION

The quality of the water column is complex and expensive to assess because of the wide variety of parameters that must be measured over a variety of temporal and spatial scales. Nutrients (mainly nitrogen and phosphorus) from sewage treatment plants and agricultural runoff may contribute to eutrophication (an increase in algal biomass and subsequent deep water oxygen depletion when the algae decompose). Metals (e.g. copper, zinc, mercury, cadmium, lead) from industrial discharge elicit local effects, but mainly in the sediments because of their adsorption to particles. A wide range of organic compounds comes from pulp mills (organochlorines such as dioxins and furans), oil spills (various hydrocarbons such as polyaromatic hydrocarbons), wastewater treatment plants (organic load expressed as biological oxidation demand and PCBs from industry) and harbours (organotins such as tributyltin). This review focuses mainly on the issue of natural vs. anthropogenic nutrient loading in three British Columbia/Washington coastal areas, Juan de Fuca Strait, Strait of Georgia and Puget Sound. Metals and organic compounds are addressed briefly at the end of the review, along with the potential for transboundary transport of nutrients, plankton and pollutants.

Natural nutrient loadings include mixing of nitrate-rich deep water to the surface by wind, tides and entrainment (e.g. the surface water layer moving over a deeper layer). The main anthropogenic sources of nutrients are sewage and agricultural runoff. The nutrient load in rivers is a combination of natural and anthropogenic inputs. The ratio of natural nutrient loading to anthropogenic loading can provide a qualitative assessment of a potential eutrophication problem, but for point source loading from sewage treatment plants, consideration must be given to how much dilution occurs and how long the nutrient stays around (i.e. the physical oceanography of the area).

NATURAL VERSUS ANTHROPOGENIC NUTRIENT LOADING

Eutrophication is a process of ecological change whereby increased nutrient and/or organic loading of an aquatic ecosystem leads to increased biological productivity, increased sedimentation of unutilized particulate organic matter, and changes in community composition (Likens 1972). This sequence can be triggered or accelerated by inputs from domestic and industrial sewage and/or agricultural runoff, and can become an important adverse consequence of anthropogenic waste input into aquatic ecosystems. A well-documented local case history is the sequence of sewage pollution and recovery in Lake Washington (Edmondson 1972). How likely is cultural eutrophication to be a regional problem in the Georgia Basin/Puget Sound areas? Our analysis will focus on sewage discharges into Juan de Fuca Strait because of recent debate about the Greater Victoria sewage system, but our approach is also applicable to the Strait of Georgia and Puget Sound.

We will break the regional eutrophication issue down into three subsidiary questions. These are:

- What are the present nutrient concentrations in the Georgia Basin/Puget Sound regions (i.e. Where does the system presently sit on the nutrient-loading axis?)
- Are these nutrient levels limiting the present rates of biological productivity (i.e. Would a higher input rate lead to changes in productivity?)
- How large are anthropogenic nutrient input rates in comparison to the average level and variability of natural input rates (i.e. Would reducing present

sewage inputs affect existing nutrient and productivity levels?)

We have assumed that nitrogen (N) is the most probable limiting nutrient in British Columbia and Washington marine waters. This is generally accepted as valid for coastal marine ecosystems (e.g. Carpenter and Capone 1983; Hecky and Kilham 1988), but contrasts with freshwater systems which often show phosphorus limitation. Data from Juan de Fuca Strait indicate that about 90% of total dissolved inorganic nitrogen is in the form of nitrate, so we have also assumed that measurements of nitrate concentration provide an adequate estimate of total natural nitrogen load and input rate. For anthropogenic inputs, we estimated total nitrogen loading from data on ammonium, particulate and BOD (biochemical oxygen demand) concentrations in wastewater, and from measured or estimated per capita rates.

Physical Oceanography

Overall, the Georgia Basin and Puget Sound regions have an estuarine circulation modified by the effects of tides and wind (e.g. Thomson 1981; Thomson, this volume; LeBlond 1983; Crean et al. 1988a; Ebbesmeyer et al. 1989). Large freshwater inputs from rivers (the largest are the Fraser and Skagit) move gradually seaward at the surface, mostly (about 80–90%) via Juan de Fuca Strait (Crean et al. 1988a) and the remainder via Johnstone Strait at the north end of the Strait of Georgia. Enroute, the freshwater entrains saltier and nutrient-rich water from beneath. Mass balance is achieved by a shoreward deep flow of offshore oceanic water below about 50–100 m (in Juan de Fuca Strait, shallower on the Olympic Peninsula side and deeper on the Vancouver Island side). Strong tidal currents between inner Juan de Fuca Strait and Boundary Passage vertically mix the water column in these regions. The resulting weakly-stratified water (salinity about 30.5–31.5 and initial nitrate concentration about 24–25 μM), flows either shoreward into the sub-surface layers of the Strait of Georgia and Puget Sound, or seaward in the upper layers of Juan de Fuca Strait depending on the tidal phase (see Figures 3a–d in Thomson, this volume). Within the Strait of Georgia and Puget Sound, the entering deep water eventually reaches the surface layer at locations and times determined by local rates of entrainment, and wind and tidal mixing (Parsons et al. 1981; St. John et al. 1993). For the seaward-flowing component, the direct surface outflow through Juan de Fuca Strait has consistently high nutrient concentrations and provides a major nutrient input mechanism for the continental shelf region off the west coast of Vancouver Island (Mackas et al. 1980; Mackas et al. 1987; Crawford and Dewey 1989).

Strait of Georgia

The Strait of Georgia is a narrow coastal basin that connects to the outer coast via restricted channels at both the northern and southern ends of the basin. The southern channels open into Juan de Fuca Strait (Haro and Rosario Straits and Boundary Passage). They have a large cross-section and are much shorter than the northern channel (Discovery Passage, Johnstone Strait, Queen Charlotte Strait, opening into Queen Charlotte Sound) and therefore strongly dominate the total exchange into and out of the Strait of Georgia.

Nutrient input from the northern channel is relatively localized and is in total only about 10–15% of the southern input. Since this natural nitrate input in the north has little influence on the southern part of the strait, and since there are no large anthropogenic nitrogen inputs in the north, the northern part of the strait will not be considered further.

Stability in the southern part of the Strait of Georgia is more complex than in the northern part because of the seasonal influence of the Fraser River. The discharge from the river contributes up to 80% of the total land runoff, and when the river discharge is highest in June (up to 10,000 m^3/s), its plume of silt-laden, brackish water can cover a large part of the southern strait. The plume generally moves northward along the eastern shore of the strait (and is pushed even further northward by southeast winds in the winter), but it may be blown southward by northwest winds (mainly in the summer). There is also some north-south oscillation due to flood-ebb tides respectively. The stability is high near the mouth of the Fraser River due to the low salinity (<20‰) surface layer. The strong halocline beneath the plume strongly inhibits vertical mixing and therefore nitrate-rich deep water is seldom mixed to the surface during wind events. Hence, during a windy summer, primary productivity may be higher beyond the plume than in the vicinity of the plume. The areal extent and location of the plume is also strongly

affected by the fortnightly alternation between spring and neap tides (Harrison et al. 1991; St. John et al. 1993). At high tide the strait tends to impede the flow of water out of the river, while at low tide the level of the water in the strait drops and the flow increases, forming a daily riverine plume. The plumes formed during a neap tide are smaller than during a spring tide, when the drop in the height of the water in the strait is the greatest (i.e. the height of the lower low water is the smallest). By a unique coincidence the maximum river discharge and the biggest spring tides coincide in June. Hence, during June the biggest plume is formed and can cover the whole southern half of the strait. Southeast winds would drive it further north and northwest winds would push it out through Juan de Fuca Strait.

A salt wedge enters the river, especially during periods of low river discharge in February or March. Some entrainment of nitrate-rich water from the salt wedge occurs during flood tides. (See the section on localized nitrogen inputs for further discussion of the salt wedge.)

The flushing time of the deep water of the strait is about one year, and the residence time of the surface water is less than one year (LeBlond 1983). More information on the physical oceanography of the strait can be found in Waldichuk (1957), Thomson (1981, and this volume), and LeBlond (1983).

Puget Sound

Puget Sound is a complex system of interconnected fjords and channels that connects to Juan de Fuca Strait mainly via one narrow channel, Admiralty Inlet. Most of the deep water entering Juan de Fuca moves into the Strait of Georgia and only a small amount makes it over the shallow (70 m) double sill at the south end of Admiralty Inlet and on into Puget Sound. Puget Sound also shows a characteristic estuarine circulation pattern. Mixing at the sill at Admiralty Inlet is intense and up to two-thirds of the initial outflowing water may mix downward into the inward-flowing deeper layer, thereby flowing back into the Sound instead of exiting into Juan de Fuca. This reduces the effective flushing rate of contaminants, especially those contaminants that bind to sediment particles which then settle out in the Sound (Cokelet and Stewart 1985). Tidal flows across the shallow sills at Admiralty Inlet and Tacoma Narrows are responsible for much of the vertical circulatory action within Puget Sound. Many inlets at the south end of the Sound have poor circulation and hence are vulnerable to anthropogenic inputs. Other aspects of the physical oceanography have been reviewed by Ebbesmeyer et al. (1989) and Thomson (this volume).

Present Nutrient Concentrations

Nutrient concentrations at all of the various seaward entrances to the Georgia Basin (Juan de Fuca Strait, Admiralty Inlet, Haro Strait, Boundary Passage) are, by oceanic standards, very high throughout the year and throughout the water column. Figure 1 shows the approximate extent of the region within which surface nitrate concentrations normally exceed 10 µM. The highest surface concentrations are centered south and east of Victoria. Monthly Capital Regional District (CRD) monitoring data collected near the Victoria sewer outfalls 1973–1979 (Figure 2) show surface nitrate concentrations ranging from autumn-to-spring maxima of 350–400 ppb (25–29 µM) down to brief and rather variable summer minima of 175–275 ppb (14–20 µM). The summer nitrate minima in this time series coincided closely with salinity minima and temperature maxima. They almost certainly resulted from seaward movement of pulses of less well-mixed Strait of Georgia surface water during and immediately following the Fraser River freshet, as described by LeBlond et al. (in press).

The salinity and nutrient content of the deep Juan de Fuca inflow have a strong seasonal cycle that varies in phase with seasonal upwelling on the outer coast. This is particularly clear from a June-December 1973 monthly time series of nutrient profiles across mid-Juan de Fuca Strait (Lewis 1974, 1978; survey line about 55 km west of Victoria as indicated in Figure 1). Figure 3 summarizes nitrate vs depth envelopes for Lewis' winter (December) versus summer (July) transects. For additional details of cross-Strait and tidal cycle variability, consult Lewis (1978; his Figures 8 and 9). At mid-Strait, the highest nitrate concentrations, both surface and deep, were measured in summer. This contrasts with most mid-latitude aquatic ecosystems, which typically show some degree of upper-layer nitrate depletion during the summer. In Juan de Fuca Strait, surface nitrate concentrations range about 8–25 µM. Deep water (>100 m) nitrate concentrations average about 30 µM (range from about 20–35 µM). Nutrients and other variables (T, S, $[O_2]$) can be used to identify the

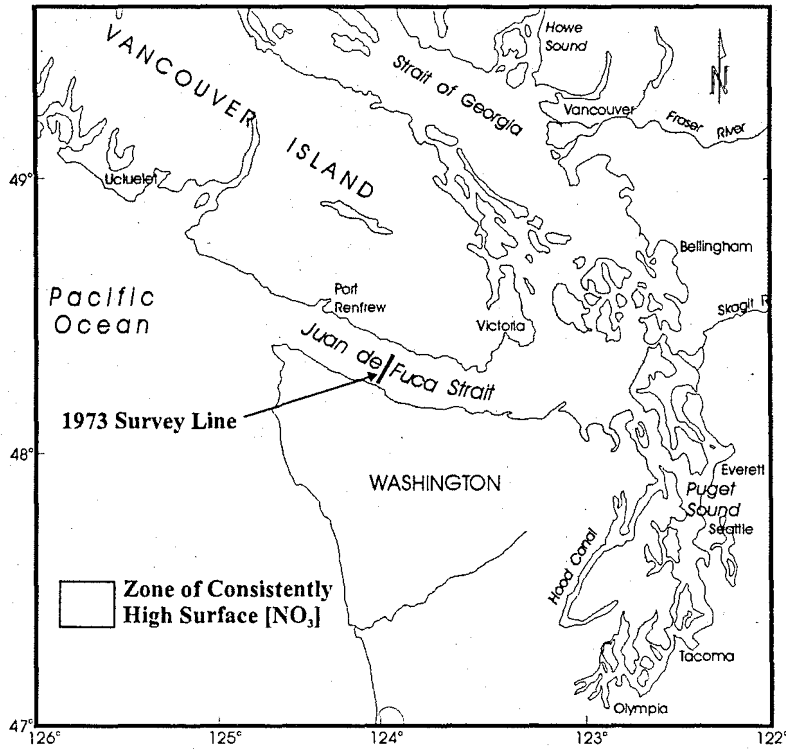

Figure 1. Map of the Juan de Fuca Strait-southern Strait of Georgia-Puget Sound system. Shading indicates zone of consistently high surface nitrate concentration. The major sewage inputs enter via the Fraser River and from marine outfalls off Seattle and Victoria. Line in mid-Juan de Fuca Strait shows the location of extensive 1973 time series measurements made by Lewis (1974, 1978).

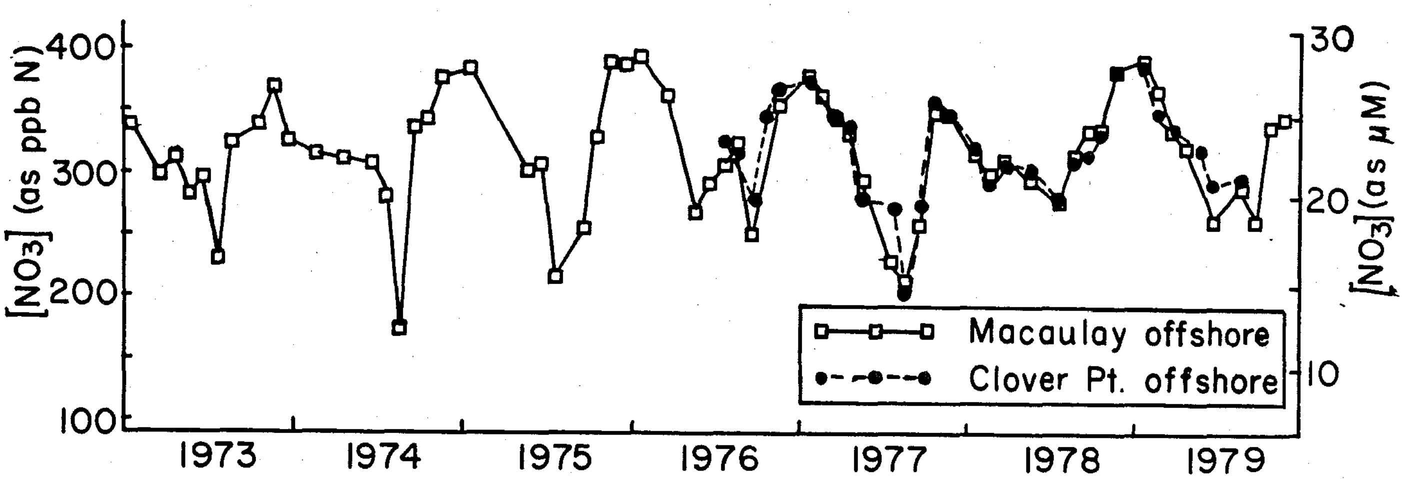

Figure 2. Time series of surface nitrate concentrations near the two major Victoria sewage outfalls at Macauley and Clover Points. Capital Regional District unpublished data from Vassos (1982).

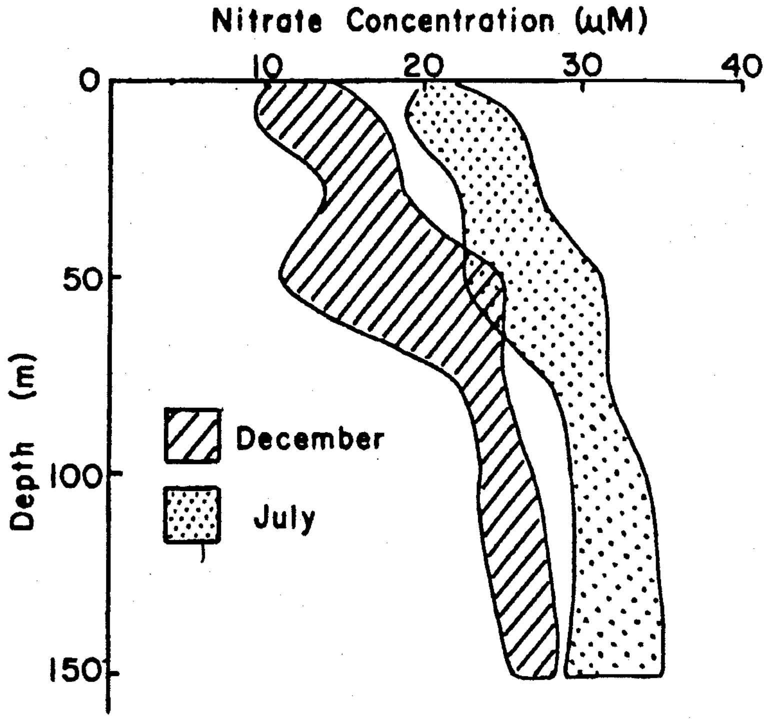

Figure 3. Summary comparison of winter vs. summer nitrate profiles from mid-Juan de Fuca Strait, based on data from Lewis (1974, 1978). Shaded areas are envelopes for >20 individual profiles in each time period. Highest nitrogen concentrations, both shallow and deep, occurred in summer.

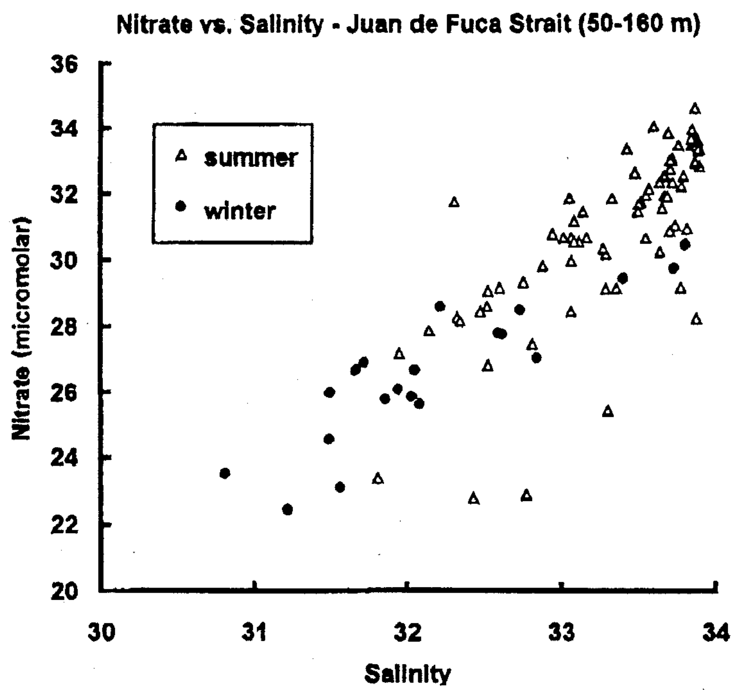

Figure 4. Approximately linear relationship between salinity and nitrate concentrations in the deeper layers (shoreward mean flow) of Juan de Fuca Strait. Seasonal changes in subsurface nutrient concentration result mostly from upward and downward displacement of isopycnals, driven by large scale outer coast upwelling.

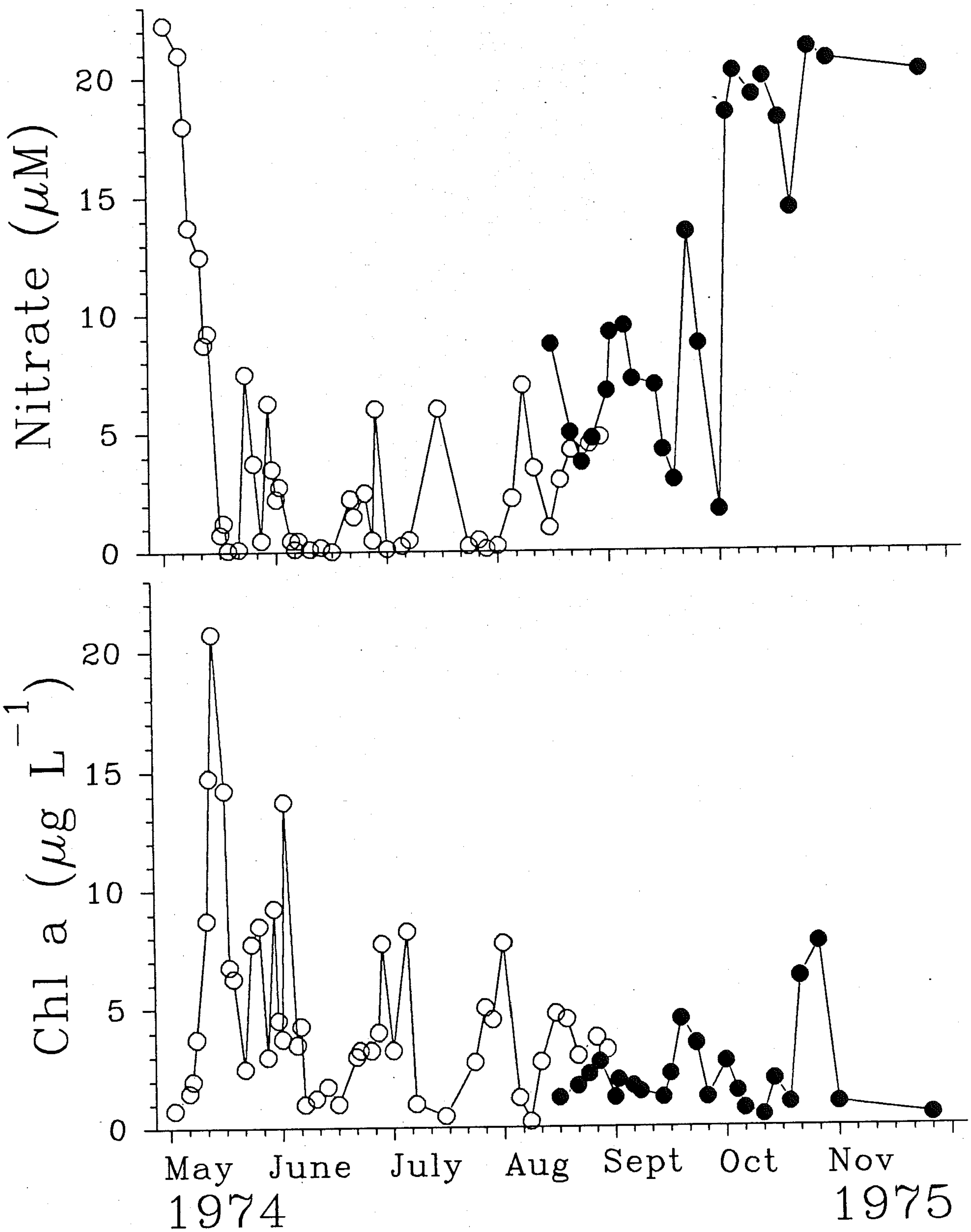

Figure 5. Weekly changes in nitrate and chlorophyll a in the water column (0–10 m) in Saanich Inlet at two closely spaced stations (• and o) during the summer of 1975 (Takahashi et al. 1977).

distribution and water mass source-composition of the Juan de Fuca Strait deep water (Mackas et al. 1987). In summer, it is nearly all California Undercurrent water. This water upwells strongly along the Vancouver Island continental shelf break each year from about April through September (Freeland and Denman 1982) and from there moves shoreward across the outer shelf and into the Juan de Fuca Strait submarine canyon system. Both on the outer continental shelf and in Juan de Fuca Strait, seasonal changes in physical properties of the subsurface water are produced mostly by upward and downward displacement of isopycnals; the T, S, nutrient relationship remains quite linear and stable (Figure 4).

Within the Strait of Georgia, wind mixing during the winter results in surface nitrate concentrations of about 25 μM (Parsons et al. 1980). During the summer, nitrate concentrations oscillate from >1 μM to about 10 μM, due to interacting factors such as tides, winds and zooplankton grazing. The best time series (sampling was biweekly) which shows the details of these oscillations is for Saanich Inlet (Figure 5), (Takahashi et al. 1977). Many parts of the southern strait appear to show a similar pattern in temporal variability in nitrate and chlorophyll concentrations (Clifford et al. 1990). Of course from the point of view of eutrophication it is the number (and duration) of times that nitrate is less than 2 μM that is important. Phosphate concentrations in the summer are generally greater than 0.1 to 0.2 μM (Clifford et al. 1990; Harrison et al. 1991). However, when the samples were filtered and then analyzed, the plume samples frequently showed undetectable PO_4 concentrations (Jones et al. 1991). This observation indicates that a large amount of phosphate is adsorbed to the suspended sediment in the plume. When these samples were reanalyzed without filtering, the PO_4 concentration was increased by an order of magnitude (K. Yin, pers. comm.). Preliminary experiments indicate that the phosphate adsorbed to the sediments slowly becomes available to the phytoplankton for growth (K. Yin, pers. comm.).

Nitrate concentrations in the river change seasonally, with the highest values in February (~15 μM) and the lowest in August or September (~2 μM) (Figure 6;

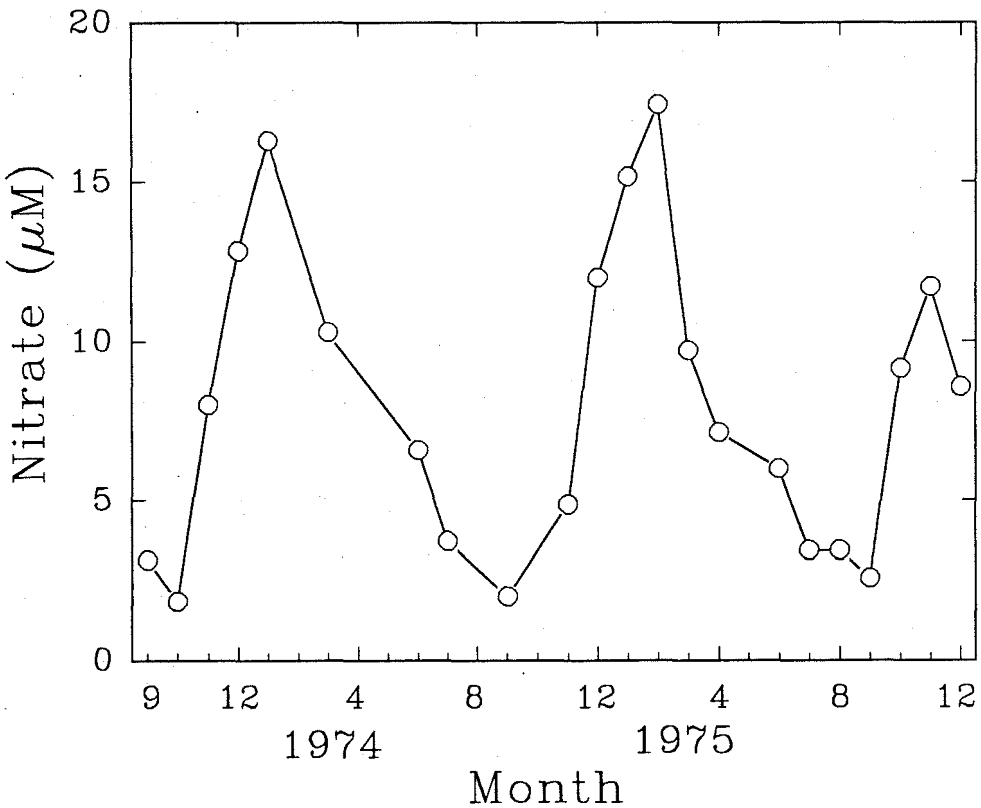

Figure 6. Nitrate in the surface waters of the Fraser River at Hope (from Drinnan and Clark 1980).

Drinnan and Clark 1980). During late July, ambient surface ammonium and urea concentrations 5 km upstream from the mouth of the river (between 100 m to 1 km downstream of Annacis Island sewage treatment plant) was greater than 0.2 and about 0.7 µM respectively (Harrison et al. 1991). Therefore the total inorganic nitrogen concentration ($NO_3+NO_2+NH_4$) and urea for July/August in the river would be about 3 µM. Note that this nitrogen concentration is mainly due to nitrogen inputs from Annacis Island and Lulu Island sewage treatment plants and agricultural runoff; minor nitrogen inputs come from other sewage treatment plants further up the river (Hall et al. 1991; Schreier et al. 1991) and natural inputs from rainfall and snow melt. From Figure 5, it is evident that the surface waters of Saanich Inlet and the Strait of Georgia (Clifford et al. 1990) periodically have NO_3 <2 µM. Therefore the 3 µM nitrogen in the river will have only a minor effect, especially if it is diluted with nitrate-poor (<2 µM) estuarine plume water as the riverine plume moves over it (Figure 7). Assuming a nitrogen to chlorophyll a ratio of about 5:1 (Harris 1986), 3 µM nitrogen would only result in an increase in the chlorophyll a concentration of about 0.6 µg/L. The natural nitrogen inputs via entrainment and salt wedge breakdown are 2 to 12 times more important than anthropogenic nitrogen inputs from the river (Yin et al. in press a,b). In fact, the Fraser River has an order of magnitude less nitrogen than other rivers, such as the Mississippi and Rhine Rivers, which have NO_3 >100 µM (Meybeck 1982).

In Puget Sound, winter nitrate concentrations are about 25–30 µM (Winter et al. 1975; Rensel Assoc. and PIT Environ. Ser. 1991). Rarely and only briefly does nitrate become exchanged in the central basin of the Sound (Collias and Lincoln 1977). Poorly flushed inlets, particularly at the south end of the Sound, can be nitrogen-limited for large parts of the summer (PSWQA 1993). To put the above discussion of nitrate concentrations into perspective, phytoplankton growth rate is only decreased when nitrate concentrations fall below 2 µM. The topic is further discussed below.

Anthropogenic Nitrogen Inputs

Direct anthropogenic nutrient inputs to the Georgia Basin can be estimated from monitoring data collected by the major waste management agencies and from monitoring of concentrations in major rivers. Our estimates of total sewage and river loading from major Georgia Basin population centers are summarized in Table 1. In some cases, we report both 'upper limit' and 'most probable' estimates.

The 1992 nitrogen inputs from Greater Vancouver Regional District (GVRD) treatment plants totaled about 21.5 tonnes/day from a population of 1.6 million. The total nitrogen input from the Seattle sewage is at present 15 to 16 tonnes/day (F.R. Shuman and D. Hildebrand, pers. comm.) from a contributing population of 1.2 million.

Total nitrogen input by the Victoria sewage system has not been routinely monitored, but can be estimated in a variety of ways. Nearly all of the southern Victoria region sewage entering the Juan de Fuca Strait-Georgia Basin system is discharged through long screened outfalls off Macaulay Point (1.8 km offshore) and Clover Point (1.15 km offshore). The tributary population for these two outfalls is approximately 210,000 people. Wastewater discharges from each site are monitored daily for flow by the Capital Regional District (CRD), and monthly for total suspended solids (TSS), biochemical oxygen demand (BOD), ammonia, and fecal coliforms. Receiving waters near the outfalls are, or have been, monitored for fecal coliforms, ammonia, nitrate and nitrite. In 1991 (the most recent available data), the total ammonia loading for the two outfalls was 2.4 tonnes N/day (CRD 1992). For the Seattle sewage system, the ratio of ammonia to total nitrogen loading is about 0.6–0.75 (F.R. Shuman, pers. comm.); for GVRD treatment plant effluent the ratio is about 0.65. Applying this ratio to the Victoria ammonia data gives an estimated total Victoria nitrogen input of 3–4 tonnes/day.

Total nitrogen loading can also be estimated from the Victoria flow, BOD and TSS data using 'typical municipal wastewater' total nitrogen concentrations and mass ratios (Rohlich and Uttormark 1972; Gross 1976). Estimates of nitrogen input from this approach average 3.0 tonnes/day (range 1.7–3.7).

It is also possible to apply per capita nitrogen input rates measured by other metropolitan areas (these will also be used to estimate total sewage loading for the entire Georgia Basin). From the total nitrogen input data presented above, the per capita input rate for

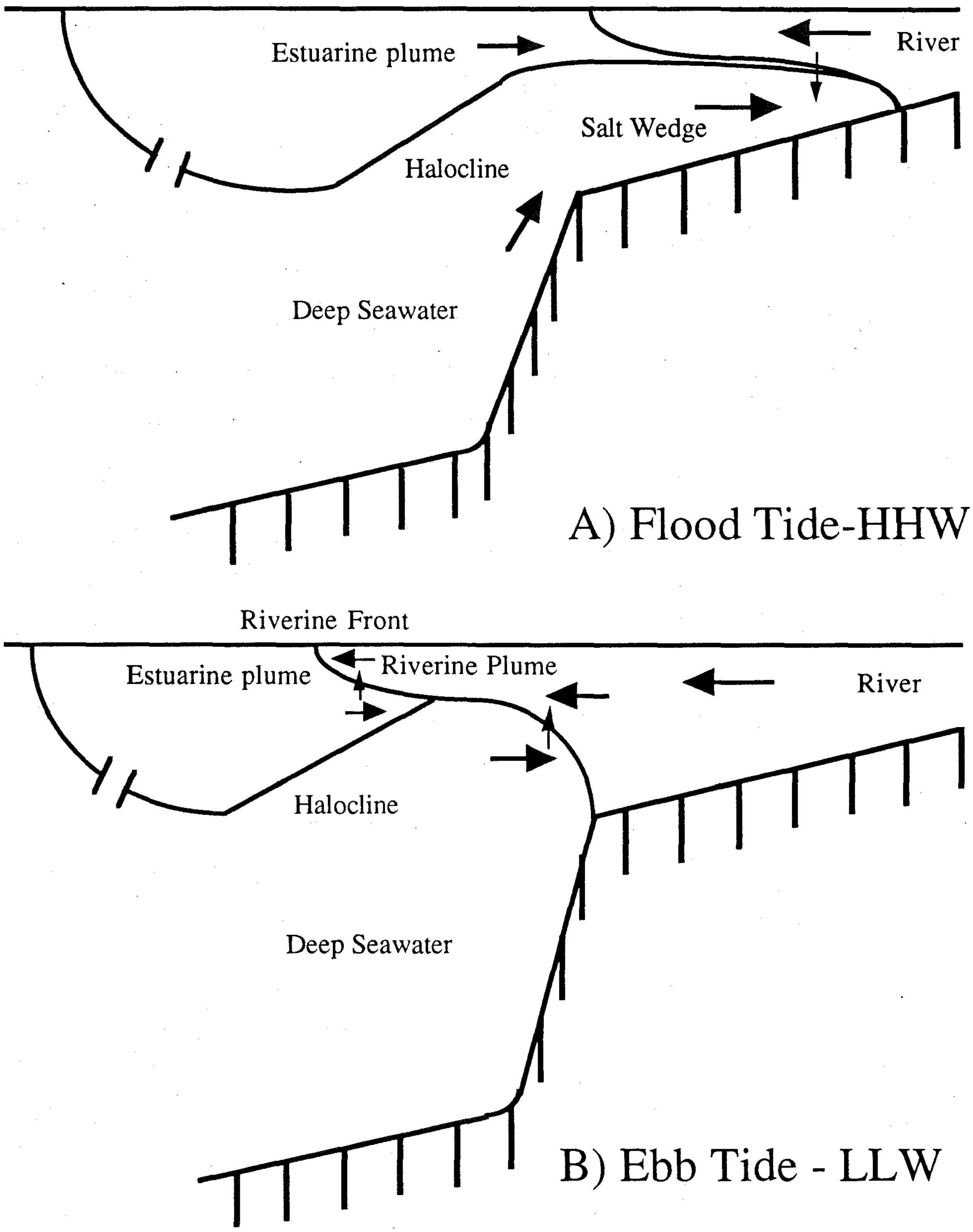

Figure 7. Vertical profile of the mouth of the Fraser River, showing the position of the river, riverine plume, estuarine plume, and salt-wedge during the flood and ebb tides. The main entrainment takes place at the interface between the deep water and the riverine plume during an ebb tide.

TABLE 1

Approximate magnitude of major coastal (sewage and riverine) nitrogen inputs to the Georgia Basin

Source	Estimated total N input (tonnes N day^{-1})	Estimation method
a. Greater Victoria sewage	3-3.5 (most probable) 5-6 (upper limit)	various (see text) 220K population @10 kg yr^{-1} per capita
b. Greater Vancouver sewage	20-22	1992 GVRD estimate [courtesy S. Bertold] (sum over treatment plants of products of average Total Kjeldahl Nitrogen (TKN) concentrations and average plant flows)
c. Seattle sewage	15-16	sampling of 1992-1993 METRO data [courtesy R. Shuman & D. Hildebrand] (ave. effluent TKN) (ave. daily flow) 23 mg N L^{-1}· 700×10^6 L day^{-1}
d. Total Georgia Basin sewage	65-70 (most probable) 100 (upper limit)	5M population @ 5 kg yr^{-1} per capita Vancouver+Seattle (pop. 2.8M) @ 5kg yr^{-1} per capita, remaining 2.2M @ 10 kg yr^{-1} per capita
e. Total Fraser River input =(sewage+agricultural+natural)	50 (upper limit?)	1977 river loads (from Stockner et al. 1979) scaled linearly by Fraser drainage basin population increase 1977-1991
f. Total non-urban riverine inputs	50-60??	(total Fraser input-GVRD sewage) x 1.9 (=ratio of total Georgia Basin FW discharge to Fraser R. flow at Hope, Ebbesmeyer et al. 1989)
g. Total sewage + riverine	115-130 (most probable) 150-160 (upper limit)	(d)+(f)

Seattle sewers is 12–13 g N/day = 4.5–4.9 kg N/year. From GVRD sewers, the rate is 13.3 g N/day = 5 kg N/year. For Victoria, a per capita rate of about 13–14 g N/day again implies a total N input of about 3.1 tonnes/day.

For the entire Fraser River drainage basin, Stockner et al. (1979) used 1977 estimates of river flow and nitrogen concentration to calculate a total freshwater-borne nitrogen input rate to the Strait of Georgia of 42 tonnes per day from a 1977 population of 1.5 million (per capita rate of 27 g N/day = 10 kg N/year). For the Hudson River–New York Bight drainage basin, Mueller et al. (1976) estimated a total nitrogen load of 520 tonnes/day from a population of 17.8 million (per capita rate of 29 g N/day = 11 kg N/year). Both the New York Bight and Fraser River loads include components from agricultural and natural terrestrial runoff. But a per capita rate of 9–10 kg N/year = 5–6 tonnes N/day should be a very conservative upper limit for the Victoria inputs.

Natural Nitrogen Inputs

Juan de Fuca Strait estuarine circulation

How do the nitrogen inputs estimated in Table 1 compare with the magnitude of the natural nutrient input rate? We noted above that the estuarine circulation in Juan de Fuca Strait brings salty, nutrient-rich water shoreward in the deep waters of Juan de Fuca Strait, and that large amounts of this deep water are subsequently mixed and entrained into the surface layer, especially during strong tidal mixing (Figure 8). We believe that this process dominates the total natural rate of nutrient input for all three components of the Georgia Basin (Strait of Georgia and Puget Sound as well as Juan de Fuca Strait).

By approximating the flow in Juan de Fuca Strait as a two-layer estuarine circulation, we can estimate on an annual basis the total transport in the upper and lower layers using conservation equations for salt and total water volume.

$$V_o = V_i + V_{fw} \quad (1)$$

and

$$S_oV_o = S_iV_i + (0.0)V_{fw} \quad (2)$$

where V_o and S_o are the volume flux and salinity of the surface seaward estuarine outflow, V_i and S_i the volume flux and salinity of the deep shoreward estuarine inflow, and V_{fw} the total volume flux of surface and shoreline freshwater inputs.

We will use annual Fraser River discharge $V_{fw} \approx 3.0 \times 10^8$ m³/day as a low-end approximation; the total freshwater discharge is about 4×10^8 m³/day (Ebbesmeyer et al. 1989). $S_o \approx 31$, and $S_i \approx 33$ are additional 'knowns'. By substitution, we can solve for the lower layer transport of incoming oceanic water:

$$V_i = (S_oV_{fw})/(S_i - S_o) = 4.65 \times 10^9 \text{ m}^3/\text{day} \quad (3)$$

Note the very large volume amplification relative to the riverine freshwater flux. From Figure 4, the nitrate content (N) of the $S_i \approx 33$ incoming water is about $[N_i] = 30\ \mu M = 0.42$ g/m³, and the resulting nutrient input rate is given by the product of nitrate content and volume transport:

$$[N_i]V_i \approx 2000 \text{ tonnes N per day} \quad (4)$$

It is clear that, for present average conditions, natural nutrient input rates resulting from Juan de Fuca Strait estuarine response to Fraser River freshwater inputs greatly exceed present sewage inputs from Victoria (by at least 400-fold), Vancouver (about 100-fold), or Metropolitan Seattle (125-fold), and total direct inputs from the Fraser River (by about 40-fold). The very large input rate from the estuarine circulation is in turn controlled by the interaction between offshore upwelling, coastal freshwater discharge, and tidal mixing.

Both volume and nutrient mass fluxes are potentially sensitive to natural or anthropogenic changes affecting this interaction (e.g. effects of changing climate on offshore upwelling, climate and anthropogenic changes in the Fraser River flow). Although we have reasonably good estimates of present annual average values for V_{fw}, S_o, S_i, and $[N_i]$, our knowledge of interactions resulting from their within- and between-year variability is preliminary. But recent work (see e.g. Ebbesmeyer et al. 1989, 1991) suggests important covariance at interdecadal time scales. Resulting variability or trends in the nutrient budget are likely to be much more important than any changes resulting from plausible near-term increases in direct anthropogenic nutrient inputs.

Note that Victoria is located at the south end of Haro Strait where vigorous mixing of nitrate-rich deep water occurs during strong tides (Figure 8). Since the surface

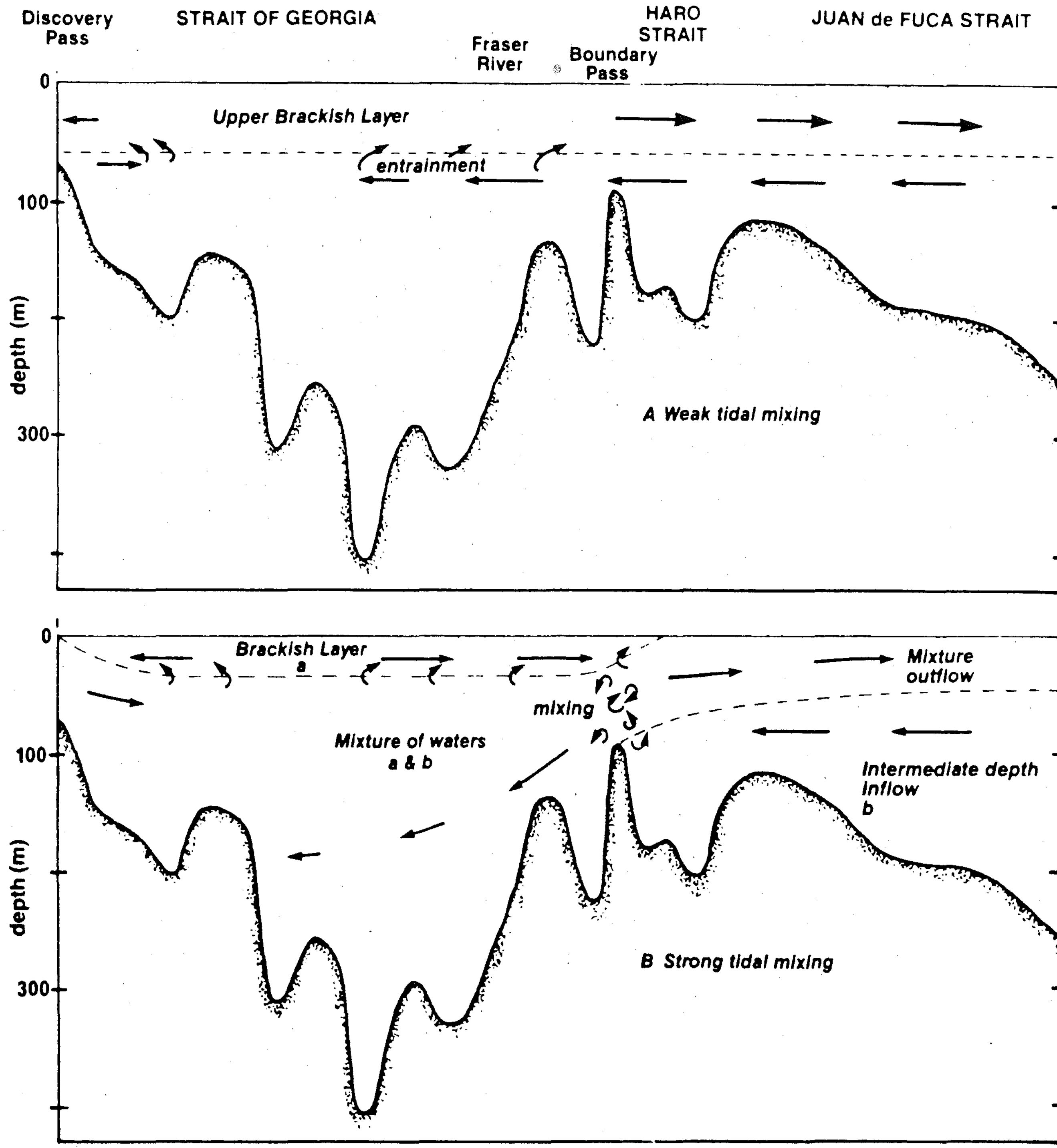

Figure 8. Average circulation in the Strait of Georgia-Juan de Fuca Strait system. (A) Hypothetical circulation that would arise in the absence of strong tidal mixing in the southern and northern approaches to the Strait of Georgia. (B) Actual circulation from vigorous tidal mixing in passes. Brackish Fraser River water (a) mixes with saline oceanic water (b) entering at depth from Juan de Fuca Strait and Discovery Passage. Part of water mixture (a and b) sinks in Strait of Georgia and the rest moves seaward within upper layers of adjoining channels (from Thomson [1981] and modified).

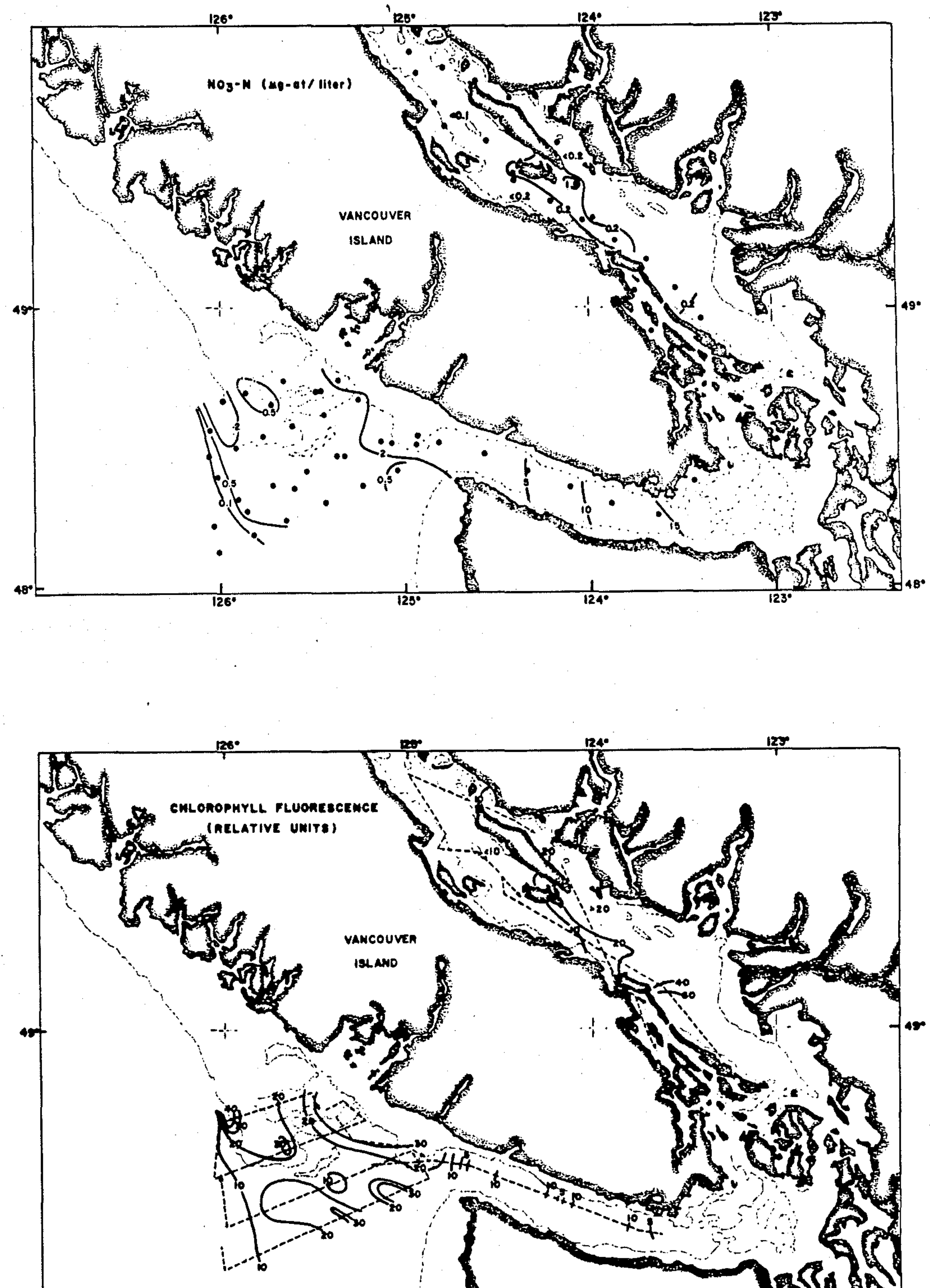

Figure 9. Sea-surface isopleths of: (a) nitrate and (b) chlorophyll (fluorescence). Sampling was continuous along the broken lines for chlorophyll while discrete samples were taken for nitrate (from Mackas et al. 1980).

currents off Victoria mainly carry nutrient seaward, nitrogen inputs in the Victoria area would mainly result in increased chlorophyll concentrations in the coastal waters (Figure 9; Mackas et al. 1980). Since this offshore area is very large, it would probably take several orders of magnitude increase in nitrogen loadings from the Victoria sewage system to produce a significant increase in phytoplankton biomass in the offshore area.

Localized Nitrogen Inputs in the Strait of Georgia

In the main Basin, the total amount of nutrient input to the Georgia Basin is controlled by the large scale estuarine entrainment mechanism. But where, when, and how fast these nutrients reach the surface layer in the Strait of Georgia and Puget Sound are set by more local interactions of wind, tide, and river plume.

Wind mixing is an extremely important factor governing the amount of the natural input of nitrogen into the strait. St. John et al. (1993) have shown in a computer model, that in the summer, winds of about 8 m/s can mix large amounts nitrate (>10 μM) into the surface layer. However, the plume with its much lower salinity (~20) impedes wind mixing and hence nitrate renewal. Therefore, a windy summer (i.e. wind events interspersed with a week of no wind) would be a very productive year.

The second largest (after wind) natural nitrogen input into the strait is entrainment of nitrate-rich salt wedge water directly into the base of the Fraser River outflow. The salt wedge enters the river, with the maximum penetration (about 60 km upriver) coinciding with the minimum river discharge in February–March (Crean

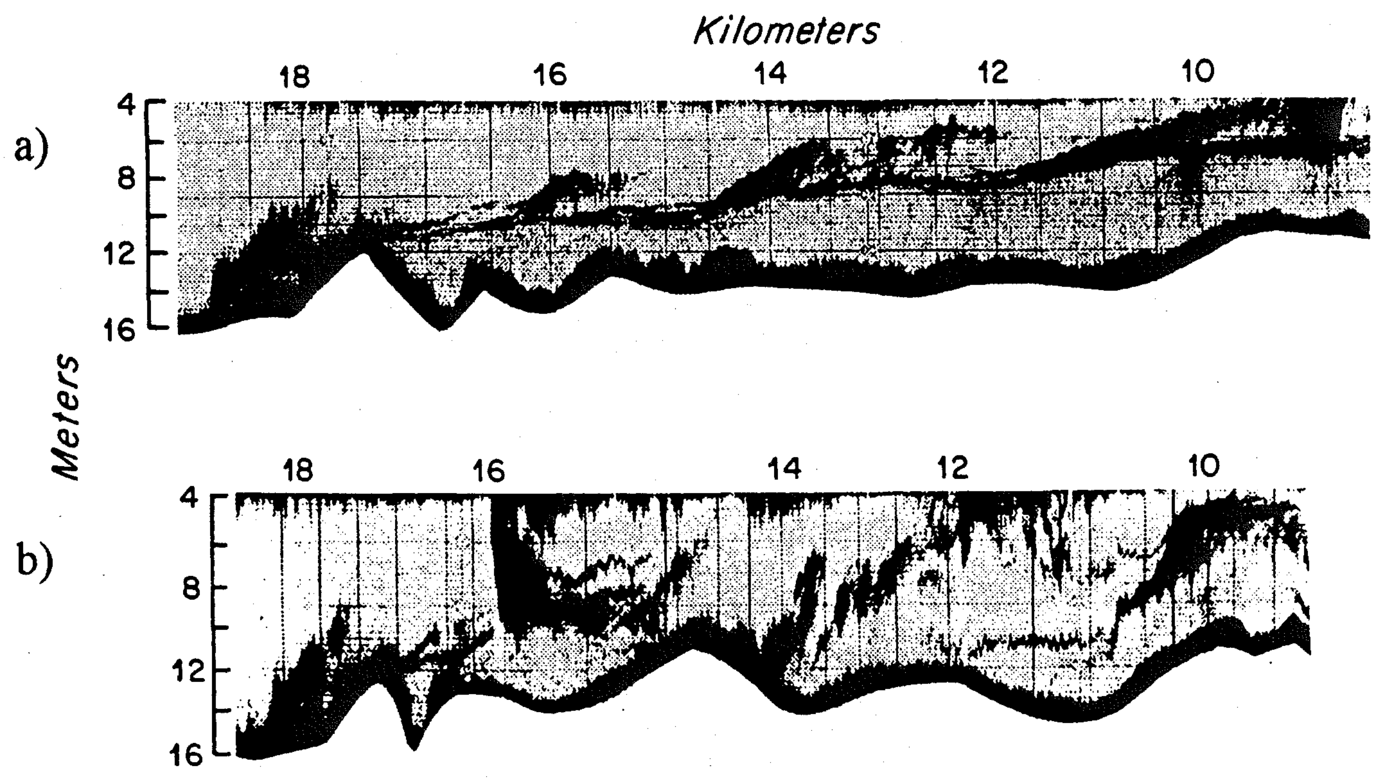

Figure 10. Echo sounding transects during the ebb, when the interfacial structure breaks down. (a) Midway through the ebb, August 1978. Four distinct zones of broadening are evident in the pycnocline, occurring at 18, 16, 14 and 11 km. The positions of these mixing regions correspond to slight lateral constrictions in the estuary. (b) Late in the ebb, August 1978. The same four mixing zones are evident, but amplitude of the mixing plumes is much greater, and the two-layer structure of the estuary has broken down (from Geyer and Farmer 1989).

et al. 1988b; see their Figure 6). The salt wedge pushes further into the river during a flood tide and is pushed back during an ebb tide (Figure 7; Yin 1994). Some entrainment of nitrate-rich deep water may occur during the flood, but entrainment mostly occurs during the ebb tide. Geyer and Farmer (1989) used an echo sounder to observe the breakdown of the salt wedge in August (Figure 10). We have frequently observed a tongue of cold water directly off the mouth of the Fraser River in satellite photographs (St. John et al. in prep.). This tongue is now thought to represent cold (nitrate-rich) water produced by the large-scale erosion of the salt wedge. The amount of entrained nitrate, which is actually contributed by the amount of entrained deep seawater, varies with the tidal range, the river discharge and the magnitude and direction of the winds in late spring and summer (Yin et al. in press a,b,c). Under all the conditions studied, the amount of entrained nitrate was always higher (from 2 to 12 times) than the river-borne nitrate. On the other hand, the nitrate concentration in the river was diluted when it was mixed with the estuarine plume (i.e. with old riverine plumes that were frequently nitrate-poor) (Figure 7).

There are seven well-developed inlets or fjords associated with the Strait of Georgia: Saanich Inlet, Burrard Inlet, Howe Sound, Sechelt Inlet, Jervis Inlet, Desolation Sound, Pendrell Sound and Bute Inlet. Only Burrard Inlet is associated with a large population center. In the 50s and 60s, Burrard Inlet was receiving water for the majority of sewage and storm sewer drainage from the metropolitan area of Vancouver. By 1974, practically all sewers were diverted to the primary sewage treatment plants at Annacis Island and Iona Island which empty into the Fraser River and the Strait of Georgia respectively. Burrard Inlet is relatively well-flushed and tidally mixed, except at the very end in the Port Moody Arm area. Even here, oxygen values in 1975–76 were similar to 1965 values (Waldichuk 1965) and generally >5 mg/L (Stockner and Cliff 1979). Recent monitoring indicates that oxygen values are still similar (B.C. Environment 1993).

To date, there are no large sewage inputs into Saanich Inlet. Hobson measured nutrients, chlorophyll, phytoplankton species composition and primary productivity in the 70s and early 80s. The time series is not long enough to observe a trend in values, but they are similar to values in the Strait of Georgia (L. Hobson pers. comm.). Saanich Inlet is unusual because it is a naturally anoxic fjord which flushes only occasionally (Hobson 1980).

Sechelt Inlet, a fjord off Jervis Inlet has recently been studied because of the number of salmon farms in the area. Haigh et al. (1992) found high chlorophyll concentrations (>30 μg/L) at the south end of the inlet near the town of Sechelt. They were unable to resolve whether this was natural (the shallowness of the area may have led to increased mixing) or a case of mild eutrophication.

Phytoplankton studies in Howe Sound have been associated with pulp mill effluent effects (Stockner et al. 1977). Coloured effluent from two pulp mills and turbid mine tailings had local affects on phytoplankton productivity. There have been reports of sporadic depletion of oxygen in the bottom water of Howe Sound (Levings 1980).

Localized Nitrogen Inputs in Puget Sound

Algal growth in the open waters of the central basin of the Sound is dominated by a number of intense blooms (mainly the same three diatom genera observed in the Strait of Georgia) beginning in late April or May and recurring throughout the summer (Winter et al. 1975; Campbell et al. 1977). Annual primary productivity in the central basin of the Sound is about 465 g C/m^2. This high productivity is due to intensive upward transport of nitrate by the estuarine mechanism and tidal mixing. Chlorophyll concentrations rarely exceed 15 μg/L. Of particular interest is the large (0.5 to 1.5 μg/L) amount of chlorophyll below 50 m. Frequently there is more chlorophyll below the photic zone than within it. Winter et al. (1975) concluded that phytoplankton growth was limited by a combination of factors, including vertical advection and turbulence, light, sinking and occasional rapid horizontal advection of the phytoplankton from the area by sustained winds. Summer winds from the northwest would be expected to transport phytoplankton to the south end of the Sound which could exacerbate the anthropogenic effects that are already evident in some of these inlets and bays. The other role of wind, the vertical mixing of nitrate-rich deep water to the surface, does not appear to have been adequately studied for this area.

The freshwater input into Puget Sound is only about one-third of the freshwater input into the Strait of

Georgia (Ebbesmeyer et al. 1989). The average flow from a number of rivers emptying into the Sound is about 130 m^3/s (Copping and Bryant 1993), with the largest flow coming from the Skagit River near the north end (the Skagit is about 16% of the Fraser River discharge at Hope). An assessment of natural annual nitrogen loadings (~2,000 tonnes/day) and anthropogenic loadings (~15 tonnes/day) indicates that only a few percent of the nitrogen load comes from anthropogenic sources (Figure 11; Rensel Assoc. and PTI Environ. Serv. 1991). While this appears to be a negligible amount, the key issue is, how much is it diluted after leaving the point source and how long does it stay in the immediate area? To answer these questions a detailed knowledge of the physical oceanography of the area is required, especially during the phytoplankton growing season (April to September).

The comprehensive monitoring program of Washington State Department of Ecology (about 60 stations, sampled monthly) has revealed that a number of inlets and bays, mainly in the south end of Puget Sound, have the characteristic early warning signals of eutrophication, namely high chlorophyll, nitrogen depletion (Figure 12) and low oxygen concentrations in the deep water during the summer months. At nearly all of the Hood Canal sites (especially Lynch Cove), oxygen depletion is a chronic problem (Curl and Paulson 1991). In Sinclair Inlet, Liberty Bay, Budd Inlet, Commencement Bay, Dyes Inlet and Oakland Bay, NH_4 >5 µM indicates significant inputs, most likely from sewage or septic tanks. A number of these same stations also exceeded the fecal coliform count standard of 14 bacteria per 100 ml (PSWQA 1993). A list of potentially nutrient-sensitive areas has been compiled (Table 2).

Why does a relatively similar anthropogenic nitrogen load in Puget Sound cause problems in some areas of the Sound but not in the Strait of Georgia or Juan de Fuca Strait? The answer lies in the extreme differences in the physical oceanography of the areas. Some of the inlets and bays (e.g. Budd Inlet and Commencement Bay) at the south end of Puget Sound have both high population centers nearby and relatively weak physical circulation. Hence the nitrogen input is quickly converted into phytoplankton which later decompose and use up oxygen in the deep water. The flushing and dilution off the Fraser River and Victoria is extremely high and therefore the effects of the anthropogenic nitrogen input are negligible at present.

Eventual Fate of Estuarine and Anthropogenic Nitrogen Inputs

Previous sections estimated total 'external' or 'new' nutrient inputs to the Strait of Georgia, Puget Sound and Juan de Fuca Strait system. In this section, we briefly examine the nitrogen budget within the Georgia Basin: where the entering dissolved nutrients go, how rapidly they are used, and their eventual fate. Because we are now looking at small differences between large rates, the uncertainties associated with interpretation of this balance are considerably greater than for the previous comparison of 'natural' and 'sewage' source terms.

We calculated 2000 tonnes N/day as a minimum input rate from the deep (incoming) estuarine circulation, if it

TABLE 2

Potentially nutrient-sensitive areas in Puget Sound where nutrient loadings in these areas are of chief concern (from Rensel Assoc. and PIT Environmental Services 1991)

Budd Inlet	Liberty Bay
Carr Inlet, including Burley Lagoon	Penn Cove and Crescent Harbor
Case Inlet	Port Orchard at Brownsville
Dabob Bay	Port Susan
Dyes Inlet	Quartermaster Harbor (inner portions)
Eld Inlet	Saratoga Passage (particularly the northern end)
Hammersley Inlet near Oakland Bay	Sequim Bay
Henderson Inlet	Sinclair Inlet
Holmes Harbor	Totten Inlet
Hood Canal, central and southern areas including Lynch Cove	

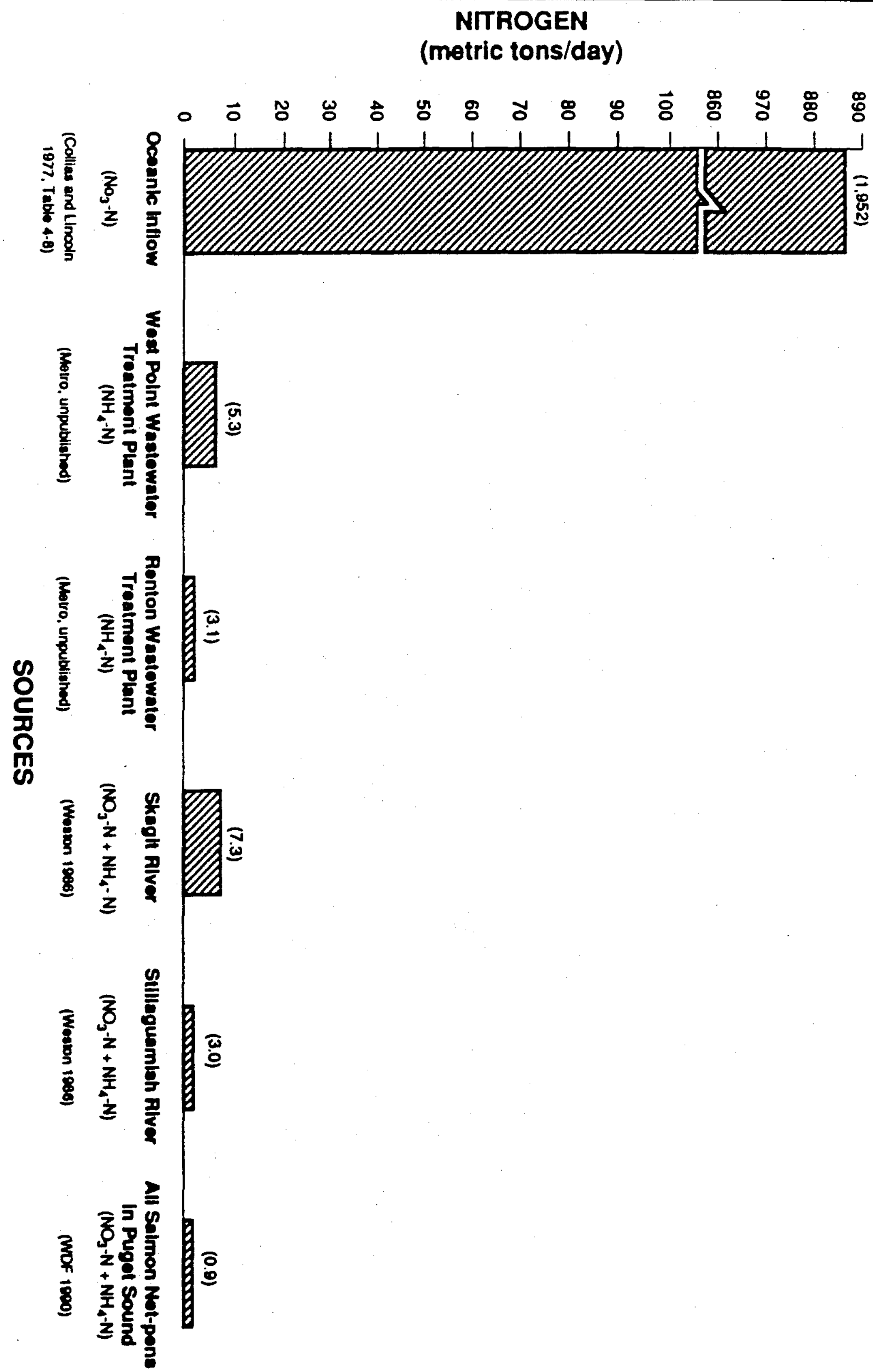

Figure 11. Annual nitrogen loading from oceanic and riverine sources compared with examples of representative anthropogenic nitrogen inputs (from Rensel Assoc. and PTI Environ. Ser. 1991).

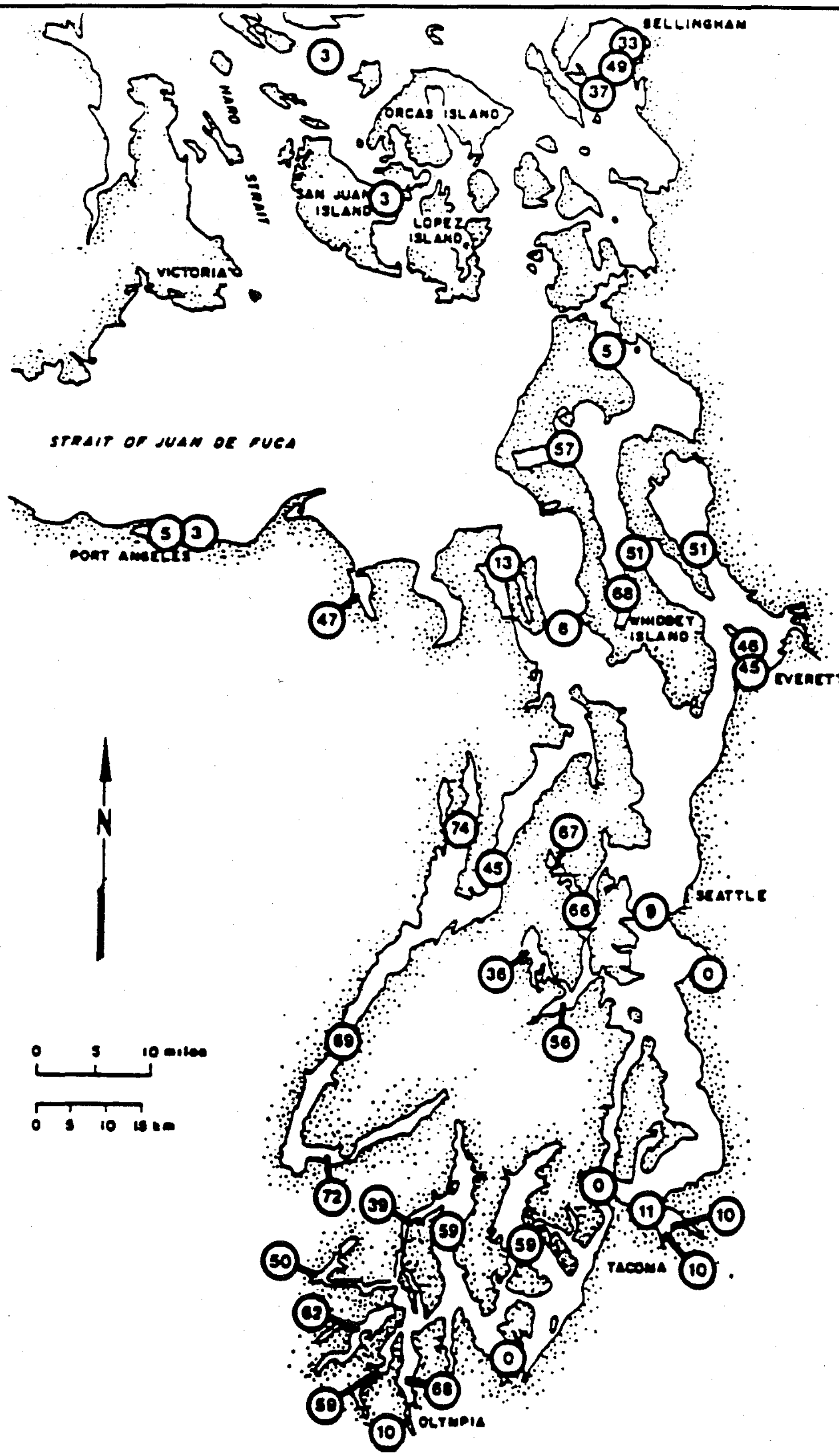

Figure 12. Percent frequency of dissolved inorganic nitrogen depletion <7 μM for surface waters at Washington Dept. Ecology routine monitoring stations in Puget Sound from April to November 1981–85 (from Rensel Assoc. and PTI Environ. Ser. 1991).

were driven solely by Fraser River freshwater input. Because of additional river inputs to the Georgia Basin, the total estuarine input is probably closer to 2500–2800 tonnes N/day.

Some unutilized or remineralized nitrogen is exported directly by the outgoing surface layer. This export consists of (roughly equal) contributions from:

(a) the nutrient content of surface water leaving the Strait of Georgia and Puget Sound, plus

(b) additional nutrients mixed into the upper layer by tidal stirring during transit through Boundary Passage, Haro Strait, Admiralty Inlet, and the inner end of Juan de Fuca Strait.

Assuming a total Georgia Basin freshwater input of 4×10^8 m^3/day, the magnitude of Juan de Fuca Strait surface export is approximately:

$$[N_o]V_o \approx [24\ \mu M = 0.34\ g/m^3]\ (6 \times 10^9\ m^3/day) \approx 2000\text{–}2100\ \text{tonnes N/day} \quad (5)$$

So about 75% of the total nitrogen input is balanced by seaward advection of nitrogenous nutrients. This export supports high rates of downstream biological uptake, mostly over the outer British Columbia and Washington continental shelves (Mackas et al. 1980; Crawford and Dewey 1989).

But our calculations suggest that there is a net nutrient input of about 500–1000 tonnes N/day. What is the fate of this? The immediate sink is biological uptake and formation of organic matter. The carbon to nitrogen ratio (C:N) of plankton is about 106:16 by atoms, or 5.7 by weight. Annual primary production is about 300 $g/m^2C \approx 53\ g/m^2N$ in the Strait of Georgia (Harrison et al. 1983). In Puget Sound, annual production is about 465 $g/m^2C \approx 82\ g/m^2N$ in the main basin, and about 275 $g/m^2C \approx 48\ g/m^2N$ at the southern extremities (Winter et al. 1975). Scaling by surface area gives an estimated average total ('new' plus recycled) nitrogen uptake of about 1500 tonnes/day. These rough calculations also suggest that the average ratio of 'new' to total production in the Georgia Basin is about 50%.

A portion of the 'new' production sediments out of the water column and accumulates on the seabed. Some of this is buried permanently. Macdonald et al. (1991) estimate a net burial rate of 7–8 g N/m^2 per year for sites in the Strait of Georgia that are now depositional (estimated by Lutenhauer et al. (1983) to be about 40% of total area). Areal extrapolation gives a total Georgia Basin burial rate of about 50–100 tonnes N per day. Some additional seabed removal occurs through denitrification in sediments. A plausible denitrification rate of 10–20 μM N/m^2 per hour (A. Devol, pers. comm., Seitzinger 1988) integrates up to about 25–50 tonnes N per day. The remaining Georgia Basin new production (≈65–75%) therefore appears to be exported within the water column, or across the sea surface. We do not have good enough estimates of living and detrital particulate loads in Juan de Fuca Strait estuarine circulation to check for horizontal advective balance. The removal rate attributable to direct human harvest of fish and shellfish is only about 1 tonne N per day.

Detection and Interpretation of Changes in Nutrient Loading

The next question is: What effect would an increase in ambient nutrient nitrogen concentration have on phytoplankton biomass and biological productivity? There is an extensive literature on how the rate of primary productivity covaries with nutrient availability. Results can be quantified in terms of per capita growth rate (Monod equation) or nutrient uptake rate (Michaelis-Menten equation). For either formulation, the nutrient utilization curve is hyperbolic (Figure 13). At very low nutrient concentrations, the slope of growth/uptake vs. nutrient concentration is steeply positive. A small absolute increase in nutrient concentration produces a large percentage increase in productivity. Conversely, at high nutrient concentrations, the response is saturated and the curve plateaus. Further increases in nutrient concentration have little effect on growth/uptake rate because the phytoplankton are limited by their internal physiological capacity (or by other limiting factors such as light intensity). The 'midpoint' between extreme nutrient limitation and nutrient saturation is quantified by the 'half-saturation constant' K_s. For mid-latitude neritic phytoplankton, K_s is usually in the range 0.4–5 μM NO_3; 2 μM is a plausible average. Since ambient nitrate concentrations in Juan de Fuca Strait are usually 5–10 times higher than this value (Figure 3), a moderate increase in nitrate concentration would have a negligible effect on local phytoplankton biomass and productivity in Juan de Fuca Strait.

What research and monitoring efforts do we need to track future changes in the eutrophication status of the

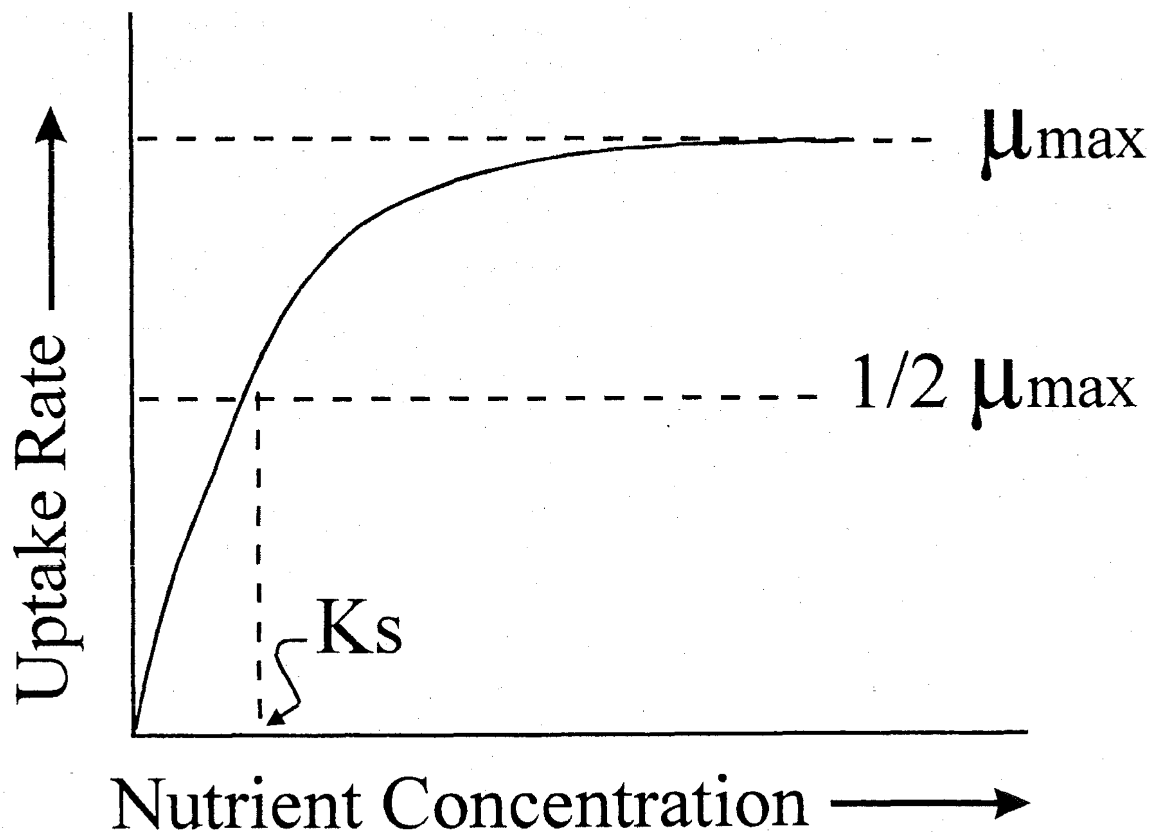

Figure 13. The general relationship between the external nutrient concentration and the rate of uptake of that nutrient by marine phytoplankton.

Georgia Basin? In the preceding sections, we partitioned total nutrient loading into two components: a direct anthropogenic input consisting of sewage, industrial, and agricultural runoff; and a 'natural' input controlled by interaction between freshwater discharge, large-scale upwelling, and local balances between vertical stratification and mixing. Both components can and almost certainly will change over time (Figure 14), and there are good reasons why we should be monitoring both. But motivations and optimal measurement/analysis strategies differ between the two components.

The total input rate is at present very much larger than the direct anthropogenic input for the overall Georgia Basin system, and for many important and ecologically sensitive specific locations within it. Although we have described the input from the Georgia Basin estuarine circulation as 'natural', we stress that there is potential for very significant indirect anthropogenic influence via both regional river management and effects of larger-scale climate modification on precipitation (Redmond 1991) and deep water nutrient concentrations. A substantial decrease in Fraser River discharge would lead to less intense estuarine circulation and less entrainment of nitrate into the surface water. Important consequences of changes in the overall nutrient input include impacts on total ecosystem productivity, carrying capacity for wild harvest fisheries and aquaculture, and uptake and transport pathways for biologically active trace contaminants. The major issues for monitoring of total input are:

- Magnitude, duration and cause of changes in total nutrient flux through Juan de Fuca Strait; and
- Site, rate, and seasonal timing of transfer into the euphotic zone within the main basins of the Strait of Georgia and Puget Sound.

For the direct human inputs, we are mostly concerned with evaluating impacts and control measures in specific locations for which the ratio of direct to natural input is unusually high. Typically, these are enclosed tributary inlets that have low flushing rates and adjoin relatively high concentrations of human population and/or industrial activity. Design of monitoring programs will be driven mostly by local rather than transboundary concerns.

In addition to monitoring nitrogen and deepwater oxygen concentrations, chlorophyll (as an index of phytoplankton biomass) and primary productivity have also been advocated. In the Strait of Georgia, nitrate is rapidly depleted during the spring bloom, giving rise to chlorophyll concentrations of up to 10–20 μg/L, composed of mainly diatoms (*Thalassiosira* spp., *Skeletonema costatum* and *Chaetoceros* spp.) (Harrison et al. 1983). In the vicinity of the plume, primary productivity is temporally and spatially very variable. At one station, primary productivity can fluctuate two- to five-fold within a few days, probably due to horizontal advection. Rates range from 0.5 to 5 g C/m^2 per day (Stockner et al. 1979; Clifford et al. 1990; Harrison et al. 1991).

In the late 60s Parsons et al. (1969, 1970) estimated annual primary productivity to be ~120 g C/m^2. A few years later (1976–77), Stockner et al. (1979) obtained estimates that were three times higher (~345 g C/m^2). It was suggested that this difference was partially due to eutrophication. Reasons for the difference between these estimates of annual primary productivity have been discussed at length (Parsons et al. 1980; Stockner et al. 1980) and summarized by Harrison et al. (1983). There are several key issues:

- The strait is highly spatially variable and therefore station selection is important. The northern portion of the strait may have lower productivity during a non-windy summer, or higher productivity during a windy summer (St. John et al. 1993) than the southern strait. There are frontal areas around the plume with high productivity (Harrison et al. 1991) and at the north and south ends of the strait (Parsons et al. 1981).
- The strait exhibits high temporal variability. Primary productivity can change by 2 to 5 times at one station over a few days, due to horizontal advection (Clifford et al. 1990).

A reasonable estimate of annual primary productivity in the strait is about 300 g C/m^2 (Harrison et al. 1983), but pronounced interannual variability would probably give a range between 250 and 450 g C/m^2. This agrees well with estimates made by independent investigators for adjacent waters. The southern part of Puget Sound has an annual primary productivity of 275 g C/m^2, while the central basin had 465 g C/m^2 (Winter et al. 1975). A reminder of the interannual variability in the estimate of annual primary productivity is given for

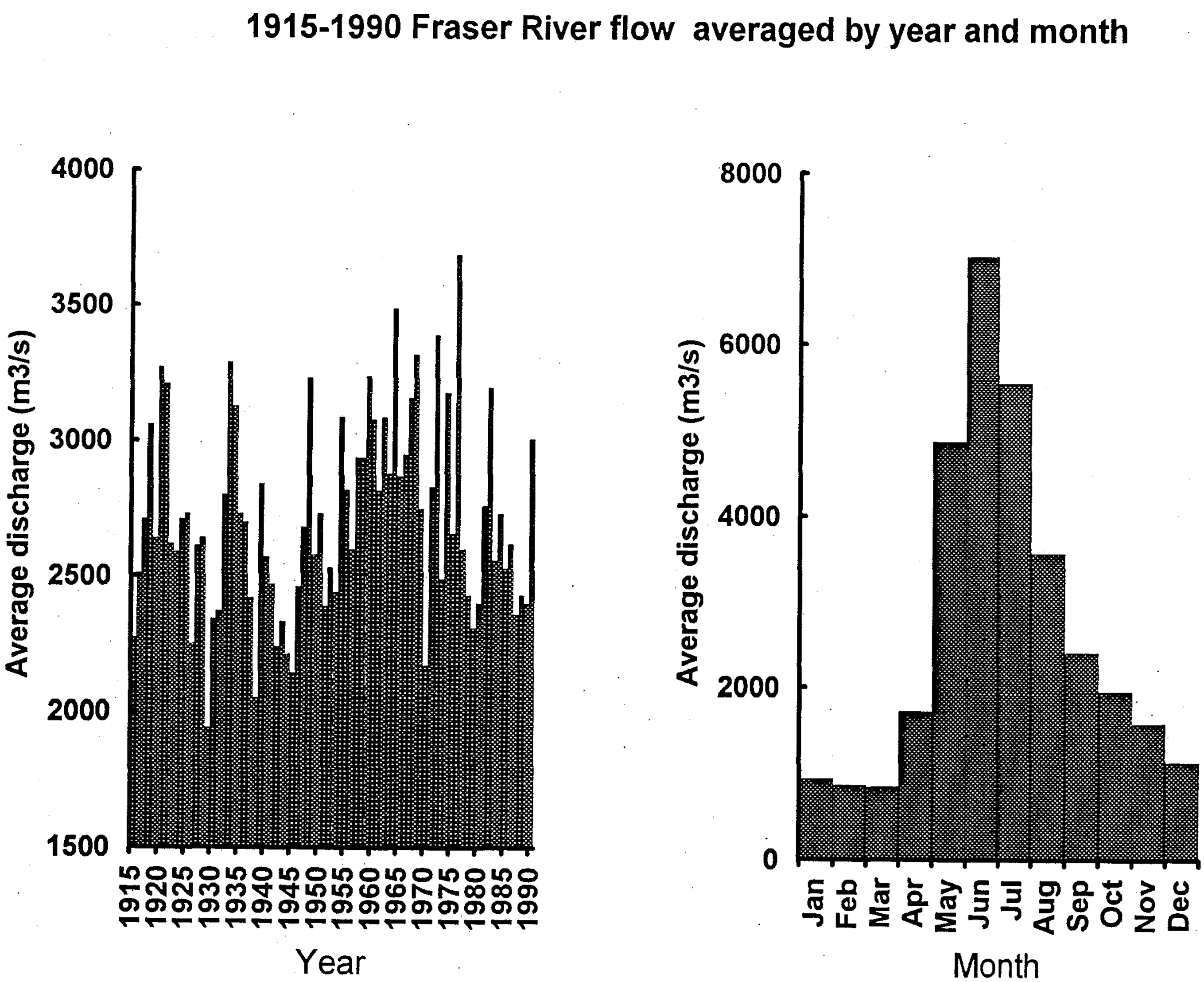

Figure 14. Within- and between-year variability of Fraser River flow. Graphs are based on within-year and within-month averages of time series measurements at Hope, B.C. (Inland Waters Directorate 1991). Downstream sources contribute additionally (33%) to the total Fraser River discharge into the Strait of Georgia.

Saanich Inlet with 250 g C/m^2 in 1975 and 500 g C/m^2 for 1976 (L.A. Hobson pers. comm.).

In summary, annual primary productivity is not a good parameter to use to monitor the onset of eutrophication. An underway sampling system (Jones et al. 1991) to continuously measure surface nitrate (AutoAnalyzer) and chlorophyll (by fluorescence) can easily resolve the spatial variability problem and carefully selected grids can provide a reliable data set for horizontal contouring. Bottom water oxygen concentrations should be measured in high chlorophyll-low nitrate areas.

POLLUTANTS

It should be noted that the importance of the dissolved phase in the transport process for a contaminant depends to a large degree on how readily it becomes attached to particles. Dissolved (i.e. conservative) contaminants move with the water while the particle-active contaminants tend to get scavenged to sediments within the respective basins (Macdonald and Crecelius, this volume). Elements like lead and compounds like PAH and highly chlorinated organics are particle active and therefore we expect that most of these contaminants do not reside long in the dissolved phase. Therefore, they have little opportunity to travel far beyond the basin they enter (Macdonald and Crecelius, this volume). Juan de Fuca Strait, which tends not to accumulate sediments, acts as a short-term buffer between the inner basins (Puget Sound and the Strait of Georgia) and the open shelf.

By virtue of their low concentration in seawater and the high risk of contamination during sampling, data for dissolved phases of most contaminant metals, organochlorines and hydrocarbons must be viewed with a great deal of caution. Earlier data (1960–1980) in particular are prone to orders of magnitude error.

Metals

Data for dissolved concentrations of metals in the Strait of Georgia up to about 1982 have been reviewed by Waldichuk (1983). The major sources of metals include industrial activity and municipal sewage effluent. Here we mention only the few metals of highest concern due to their known toxicity and anthropogenic contamination.

Lead

State of the art isotope dilution techniques were used by Stukas and Wong (1981) to measure concentration and isotopic composition. Dissolved lead (Pb) concentrations were found to be about 100 ng/kg in Vancouver Harbour and 26 ng/kg in Saanich Inlet. These values, which are one to two orders of magnitude higher than open ocean background, cannot be considered abnormal for coastal water and, in view of the elimination of the main source of environmental Pb (leaded gasoline), they have likely decreased since these measurements were made (Hall et al. 1991). Stukas and Wong (1981) note that even though the Pb concentrations in Saanich Inlet are low by coastal standards, virtually all of the Pb is contaminant according to its isotopic signature. It is clear that cross-boundary transport of Pb may take place in Juan de Fuca Strait at the same time that water exchanges; nevertheless, Stukas and Wong (1981) and Macdonald et al. (1991) used isotope distributions to determine that the contaminant Pb in the Strait of Georgia was predominantly from Canadian leaded gasoline. The work of Paulson et al. (1988a,b, 1989, 1991) in Puget Sound also supports the notion that most of the contaminant Pb entering that basin from the atmosphere and municipal discharges tends to be trapped within the Puget Sound basin.

Copper and Zinc

For the Strait of Georgia a major contaminant source of copper (Cu) and secondarily zinc (Zn) came from Britannia Mines, which disposed of its tailings directly into Howe Sound. A further input of Cu continues via acid drainage from the now-abandoned mine site. Elevated dissolved Cu has been measured in the deep water of Howe Sound (Thompson and Paton 1978; Drysdale and Pedersen 1992 and references therein). We would expect this dissolved Cu to exchange with water into the Strait of Georgia proper and thence some of it is captured onto settling particles (e.g. Macdonald et al. 1991). Undoubtedly some dissolved Cu has also escaped into Juan de Fuca Strait where it would be free to exchange across the boundary. It should be noted that Puget Sound is probably also a net exporter of dissolved Cu (Paulson et al. 1988a) so that Juan de Fuca would receive dissolved Cu and Zn from both Canadian and American sources; nevertheless, in view of mixing and exchange with continental shelf waters it is difficult to see how dissolved concentrations for either of these metals could rise to levels of concern within Juan de Fuca Strait.

Cadmium

Due to its longevity in the water, dissolved cadmium (Cd) would tend to move with the water and exchange with continental shelf waters via Juan de Fuca Strait. Sparse measurements made in the Strait of Georgia (W.K. Johnson pers. comm.) do not show abnormal concentrations.

Mercury

The major contaminant input of mercury (Hg) to the Strait of Georgia was from the chlor-alkali plant at the head of Howe Sound. It is estimated that as much as 20 kg/day of inorganic Hg may have entered Howe Sound during the late 60s and early 70s (Thompson et al. 1980). Much of this Hg has not been accounted for and therefore has potentially been transported beyond Howe Sound and perhaps beyond the Strait of Georgia. A similar source was located at Bellingham Bay in Puget Sound (Bothner et al. 1980). Therefore, Juan de Fuca Strait may have received some dissolved Hg from both of these sources. There appears to be no evidence that dissolved Hg increases have occurred in the Strait of Georgia, except by natural processes (Lu et al. 1986), or that it has created a problem except in the vicinity of the sources themselves.

In summing up for metals, Pb, Cu, Zn, Cd and Hg have undoubtedly been input to the marine environment both in Washington and Canada, and transboundary exchanges have possibly occurred in Juan de Fuca Strait. Nevertheless, problems from these metals would tend to arise only in restricted regions near the sources, and the major sources have not been near the border. The concentrations of contaminants in the tissue of mussels has been monitored for the past eight years by the NOAA National Status and Trends Program. Data from mussels sampled at 12 sites in transboundary waters and Puget Sound indicate water in some urban areas is contaminated with Ag, Pb, Cu, Zn, PAHs, PCBs and butyltins. However, mussels from transboundary waters are not contaminated compared to mussels collected from rural oceanic coastal sites. Further, due to various actions (e.g. Pb removed from gasoline, Britannia Mine shutdown, Hg regulations on chlor-alkali plants, secondary treatment at Seattle's METRO) many of the sources have been reduced and the contaminant burdens in recent sediments reflect this (Romberg et al. 1984). Therefore we would expect that dissolved concentrations are probably either decreasing or holding steady for these metals.

Organics

PAH and Hydrocarbons

There appear to be few if any measurements of dissolved hydrocarbons in Canadian waters. Since these compounds tend to be highly particle-active, we would expect transboundary transport in the dissolved phase to be relatively insignificant (Macdonald and Crecelius, this volume). Oil spills which are then chemically dispersed would clearly have the potential to transport dissolved or suspended hydrocarbon across boundaries, particularly if the spill occurred in Juan de Fuca Strait or in the boundary passages. This notion was discussed by Waldichuk (1983) with regard to contamination of deep water in the Strait of Georgia.

Most of the highly chlorinated organochlorines become attached to particles and therefore tend to get removed from the dissolved phase at time scales that are short relative to the water exchanges (e.g., PCBs, dioxins, furans). Probably the chlorophenolics have the greatest potential of transport in the water due to their solubility and the fact that there have been substantial sources for them in the Strait of Georgia, including lumber yards and pulp mills (Krahn et al. 1987; Rogers et al. 1986; Schreier et al. 1991). Some of these compounds (chlorophenols, chloroguaiacols) have been measured in surface water at distance from the sources (Voss and Yunker 1983). It is difficult to estimate how far these compounds can travel as they are subject to loss by photolysis and hydrolysis. Nevertheless, Yunker et al. (1990) show that while pentachlorophenol photodegrades in surface water, it persists once removed from the euphotic zone and may therefore transport further distances in deep water. Pentachlorophenol appears not to bioaccumulate into plankton and is not strongly removed by particles (Yunker et al. 1990). Therefore, problems arising from inputs of this compound would probably only be identifiable near the source. The substitution of other anti-sapstain treatments for pentachlorophenol has reduced this important source in Canadian waters (Rogers et al. 1992). Nevertheless, pulp mills which have recently substituted chlorine dioxide into their bleaching process continue to produce chlorophenolics, usually with a lower percent of chlorine substitution (H. Rogers, pers. comm.).

Other soluble organochlorines, like the HCHs (hexachlorocyclohexanes), occur ubiquitously in surface waters of the world oceans including our inland seas. These compounds are free to move across the border with the water, but they tend to be more of a global problem than a Washington/British Columbia problem. They are probably at about the same concentration throughout the surface waters of Puget Sound, the Strait of Georgia and Juan de Fuca Strait.

Organotins

Tributyltin (TBT) has been used as a marine antifoulant both for boats and fish-farm pens in the Strait of Georgia. Regulations have now come into effect in the US (1988) and Canada (1989) that restrict the use of TBT to boats over 25 m long (low release, 4 $\mu g/cm^2$ per day) and on aluminum structures (C. Stewart pers. comm.). (The US navy is still a big user!) TBT can apparently transport long distances. The leading problem in determining the hazard of TBT is that it has environmental effects at concentrations that presently defy chemical analysts (Bright and Ellis 1990; Saavedra Alvarez and Ellis 1990; Ellis 1991). Despite the controls that have been put on this compound several years ago, significant quantities are still being found in the water. Clearly, this is a compound that requires consideration as an important transboundary pollutant; to remove it from the Strait of Georgia-Juan de Fuca-Puget Sound system would require banning its use on both sides of the border.

TRANSBOUNDARY TRANSPORT

Nutrients and plankton move with the water (except for large zooplankton which can migrate vertically and hence move into a different water mass). For a review of currents and water mass movement see Thomson (this volume).

Nutrients

Most of the anthropogenic nitrogen input comes from sewage treatment plants. The four largest plants in the Greater Vancouver area discharge into the Fraser River or directly into the Strait of Georgia. The fate of these nutrients is either assimilation by phytoplankton (probably in the summer months) or extreme dilution as they move northward with the plume (no wind) or southwest (northwest winds). Most of the latter is thought to exit Juan de Fuca Strait as part of its estuarine surface outflow (Thomson, this volume). Similarly the nitrogen input at Victoria's sewage treatment plants is at about 60–70 m. As this buoyant freshwater plume rises towards the surface, it generally moves seaward along the north side of Juan de Fuca Strait. Since the main entrance of water into Puget Sound occurs via Admiralty Inlet as deep water (the surface water flows out), anthropogenic nitrogen inputs from BC waters which are mainly in surface waters, are unlikely to enter Puget Sound. Conversely, anthropogenic nitrogen inputs from Puget Sound which move out of the Sound via the surface outflow at Admiralty Inlet, could move up into BC waters via Rosario Strait during flood tide (Thomson, this volume).

Phytoplankton

Phytoplankton occur mainly in the photic zone (down to 20 m) and therefore, they would move out of Puget Sound with the surface outflow. During an ebb tide they would mainly exit via Juan de Fuca Strait, but during a flood tide (and especially with southeast winds in addition to the tide) they could move north via Rosario Strait into the southern part of the Strait. Vigorous mixing could take phytoplankton cells to deeper depths (50 m) and these cells could enter Puget Sound with the deep water inflow at Admiralty Inlet.

The species of phytoplankton are relatively similar in the Strait and in the Sound (Winter et al. 1975; Harrison et al. 1983). The main species of concern are the toxic phytoplankton and this issue has been reviewed by Taylor and Horner (this volume).

Zooplankton

The species lists for the zooplankton assemblages in Puget Sound, Juan de Fuca Strait, and the Strait of Georgia are virtually identical (Chester et al. 1980; Harrison et al. 1983; Frost unpublished), but different species may be seasonally dominant in the three major regions. Fox example, the copepod *Neocalanus plumchrus* dominates the zooplankton during winter and spring in the deep (up to 400 m) Strait of Georgia, but it is relatively rare in Juan de Fuca Strait and occurs only sporadically in Puget Sound which is shallower (up to 200 m).

Although no detailed studies have been conducted, substantial transboundary exchange of zooplankton

populations may be expected due to: (a) the general estuarine circulations in the three regions, and (b) more episodic exchanges associated with deep water intrusions. Surface and deep water exchange between Juan de Fuca Strait and Puget Sound occurs over the sill at the southern end of Admiralty Inlet (the entrance to the main basin of Puget Sound) (Brestschneider et al. 1985; Thomson, this volume). While a fraction of the zooplankton in the outflowing surface water is probably tidally mixed into the deeper layer over the double-sill at Admiralty Inlet and refluxed back into Puget Sound in the deep inflow, most (ca. 75%) is probably swept out into Juan de Fuca Strait (Cokelet and Stewart 1985). The deep inflow must bring into Puget Sound components of the deepwater zooplankton residing in Juan de Fuca Strait. Thus, exchanges of zooplankton of the sort observed by Lewis and Thomas (1986) over the sill at the entrance to Indian Arm, British Columbia, are also to be expected in Puget Sound.

Transboundary exchange of water between Juan de Fuca Strait and Puget Sound must also be effected by episodic intrusions of deep water across Admiralty Inlet. Such intrusions can occur in any season, but seem particularly common in late summer and in winter (Lavelle et al. 1991).

Clear biological evidence of transboundary exchanges of zooplankton was obtained in the main basin of Puget Sound during the fall/winter period of 1972–73. During this period at least one intrusion was observed (Cannon and Ebbesmeyer 1978) and the population abundance of the planktonic copepod *Calanus marshallae* increased markedly (Figure 15). The population increase is significant evidence of transboundary exchange because at this time of the year *C. marshallae* is non-reproductive, as evident in Figure 15. In the fall, the population is composed entirely of one developmental stage, copepodid stage V (or CV), a non-feeding, non-growing stage that inhabits deep water (75 m; Osgood and Frost, in press). In mid-winter the CV's become sexually mature adults, but reproduction in the main basin of Puget Sound does not occur until the spring phytoplankton bloom in April (Frost, unpublished), as also observed for the population of *C. marshallae* in the Strait of Georgia (Woodhouse 1971). Thus, the increase in abundance of *C. marshallae* in Puget Sound (Figure 15) must be due to immigration in the deep water inflow, probably due to the combined effects of general estuarine circulation and intrusions. A similar increase in abundance of *C. marshallae* was observed during fall-winter period of 1973–74 (Frost, unpublished) and is likely to be an annual event as are deep water intrusions (Cannon et al. 1990). The source population of *C. marshallae* for Puget Sound is probably Juan de Fuca Strait (Chester et al. 1980). However, sporadic occurrences of the planktonic copepod *Neocalanus cristatus*, an oceanic species (Mackas and Galbraith 1992), in Puget Sound (Frost, unpublished) are evidence of transboundary exchanges involving even more distant source waters.

Transboundary exchanges between Puget Sound and adjacent regions are likely to be highly variable due to effects, for example, of local winds and runoff (Lavelle et al. 1991) and of distant storms, which can alter the density structure of source waters for intrusions (Cannon et al. 1990).

Pollutants

Pollutants in the surface layer would act like nutrients and phytoplankton in their movements (see above). Oil from an oil spill or pollutants concentrated in the surface micro-layer may be a special case since their movement would be more controlled by winds. Prevailing southeast winds in the winter would carry these surface pollutants out of Puget Sound, but northwest winds in the summer could conceivably transport surface pollutants into Puget Sound, if the winds were high enough and for a long enough duration. Oil spills in Juan de Fuca Strait would mainly be swept out to sea, but oil could enter the southern portion of the Strait of Georgia on a strong flood tide and strong southeast winds.

SUMMARY AND CONCLUSIONS

Sewage discharge has only a minor influence on the eutrophication status of Georgia Basin marine waters. We base this conclusion on two main arguments. First, the ambient dissolved inorganic nitrogen concentration in the vicinity of the major sewage inputs is high (>10 μM all year round) relative to expected threshold levels for nitrogen limitation (about 2 μM) of phytoplankton growth. Minor changes in nitrogen concentration should therefore have very minor or negligible effects on realized phytoplankton production. Second, total direct sewer inputs are very small (2–3%)

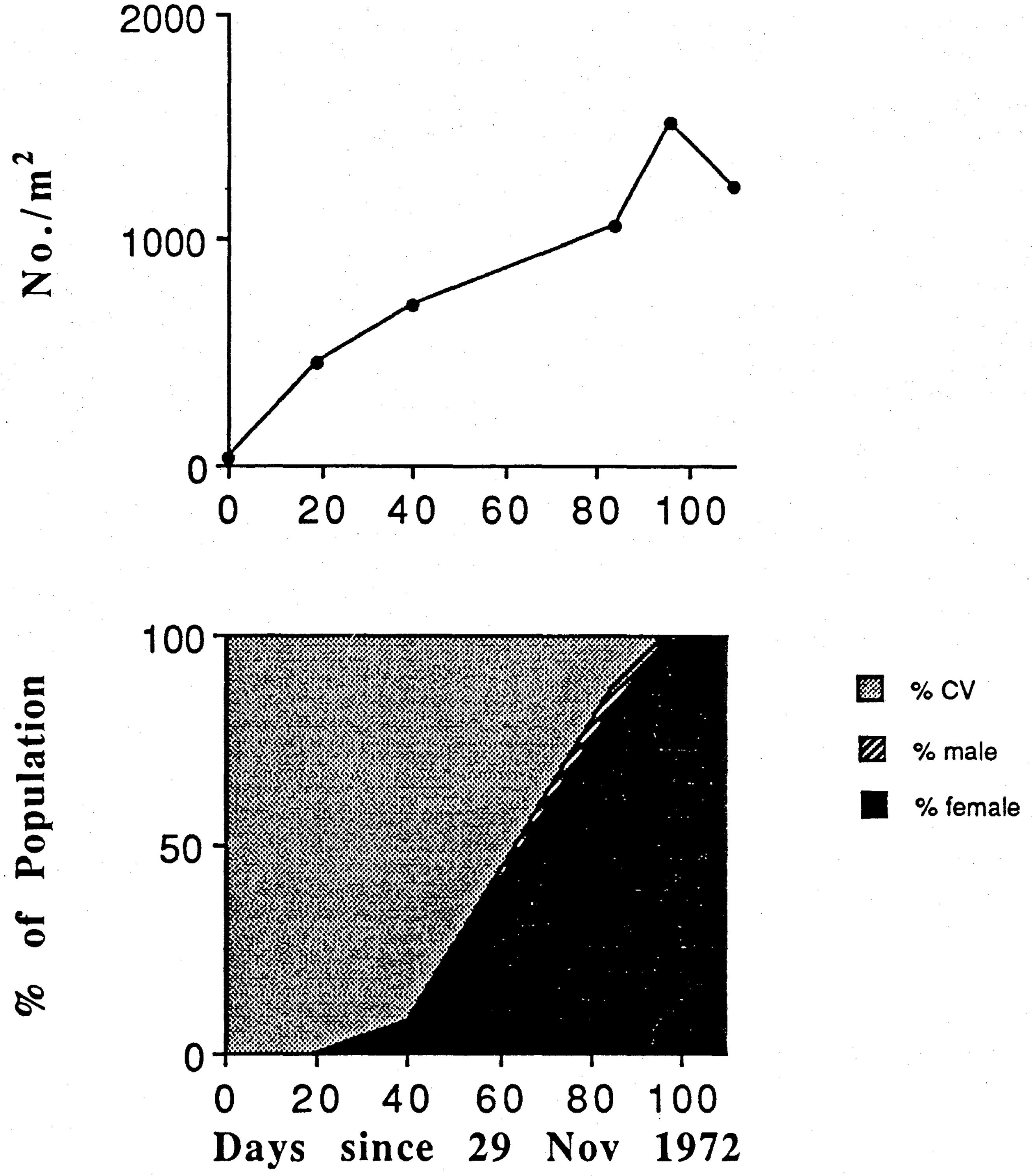

Figure 15. Changes in abundance (upper) and stage composition (lower) of the population of the planktonic copepod *Calanus marshallae* in the main basin of Puget Sound (Frost, unpublished). Data based on zooplankton samples collected in vertical hauls (bottom to surface) at a station off Seattle (west of entrance to Lake Washington ship canal). Only three developmental stages of the copepod (CV=copepod stage V, adult female, adult male) were observed during the sampling period.

compared to 'natural' inputs driven by the Georgia Basin estuarine circulation, and therefore have little influence on the overall nitrogen budget of the system. This is particularly clear for inputs into the mixed waters off Victoria. But because of the large difference in magnitude between natural and anthropogenic nitrogen input rates, it is almost certainly also true for the Strait of Georgia and the main basin of Puget Sound.

Natural nitrogen inputs, which include wind mixing beyond the plume, and entrainment and salt wedge breakdown at the mouth of the river, appear to be several orders of magnitude greater than the anthropogenic nitrogen inputs represented by the river-borne nitrogen concentrations. During July and August, phytoplankton growth may be periodically nitrogen-limited (i.e. surface NO_3 <2 µM). However, during this summer period, river-borne nitrogen (NO_3, NO_2, NH_4 and urea) is only about 3 µM. Consequently this nitrogen input would only produce a minor increase in chlorophyll and more realistically, a negligible increase considering the dilution that occurs by the entrainment of the nitrate-poor estuarine plume.

Nitrate, chlorophyll and primary productivity values for the southern portion of the strait are temporally and spatially very variable. These values are similar to other estuaries and coastal embayments with low anthropogenic nitrogen inputs (Environment Canada 1991, 1993).

In addition to one or two reference stations in the middle of the strait, monitoring sites should focus more on bays and inlets that are close to larger population centers (e.g. Boundary Bay, inner Burrard Inlet, Sechelt Inlet and Saanich Inlet). Depending on their circulation regimes and flushing times, early warning signs of eutrophication would be expected to show up in these inlets/bays first.

The central basin of Puget Sound is highly productive and seldom becomes nitrogen-limited. Nitrate and chlorophyll concentrations are normal and similar to the Strait of Georgia. Some bays and inlets, especially in the south end have low-nitrate, high-chlorophyll, low-oxygen deep water and high fecal coliform counts. Thus, these poorly flushed bays/inlets are showing signs of eutrophication. Even though the annual anthropogenic nitrogen input is only a few percent of the natural input, the effects are showing up in these inlets/bays with poor circulation.

Presently there is not a problem with the concentrations of metals in transboundary waters. This is due to the great dilution that occurs near urban areas or near wastewater outfalls. The areas where water quality problems may exist appear to be limited to urban bays where a variety of sources contribute to contamination of the surface micro-layer and the water column as well as the sediments. The relative importance of different contaminant sources has not been well defined in urban areas, partially due to the uncertainty in estimating discharges from shipyards, stormwater runoff, combined sewage overflows, and atmospheric deposition. Based on historical trends in Puget Sound sediments, it appears that efforts at source control and wastewater treatment are resulting in significant improvement in water quality.

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DISCUSSION

Andrea Copping *(Panel)*: If we go on putting much higher levels of ammonia in these shared waters than we are presently, do you anticipate seeing the kind of species changes and shifts that they have seen in places like Southern California?

Paul Harrison: The ammonia values are relatively low. Coming down the river it's 1 or 2 micromolar, sometimes you see a spike up to 5. Normal values are 1 or 2 in the open ocean, so if it is coming in, it's being used quickly, but we certainly don't see high values. I would be more concerned that urea would change species. Most species use nitrate and ammonium simultaneously, but urea being an organic compound, some species have difficulty growing on that. So large amounts of urea might cause a larger shift in species than ammonium.

Curtis Ebbesmeyer *(Panel)*: I noticed a graph by Andy Backun in Science magazine that showed that winds from the north were getting stronger in the summer. That would lead to more up-welling. Might we get increasing nitrate where we get more nitrate up-welling from the ocean into the whole system? If that is true would those increasing nitrate levels change the biology? I'm worried that the ocean as it changes might change the nitrate levels in the Strait of Georgia.

Dave Mackas: I think the best reference for that is your own paper, Curt, so maybe we should cite that. There is some evidence for long-term fluctuations in the salinity of deep water entering the Georgia Basin system (in your — I think — 1989 paper), and we have good evidence that nitrate content correlates linearly with salinity. So you expect that the same processes that cause within-season and inter-annual/interdecadal fluctuations in the temperature/salinity characteristics of the incoming water to effect the nitrogen content also. But the big question is, how does the interaction between freshwater discharge and oceanography change in phasing within-year and in total amount from year to year.

Curtis Ebbesmeyer *(Panel)*: I haven't had a chance to look at nitrate recently, and with all the concern about urban effects it seems to me that the ocean might swamp those effects. I would like to treat things in a balanced way where we look at the urban effects, and we also look at the ocean effects. The ocean effects seem to be getting lost in the picture.

Rick Thomson *(Institute of Ocean Sciences)*: We've had about a ten year program with the LaPerouse project off the coast. The temperature of the water at depth hasn't changed over the duration of that experiment, which would suggest that the temperature of the deep water is not changing. I am talking about 200 or 300 meters depth. There is a paper coming out by Shea and Boar who have taken the Canadian numerical global circulation model, and they refute the conclusions that Andy Backun came to. They don't in fact find a long-term strengthening of the winds, in their paper they find just the opposite effect.

Bob Wilson *(Institute of Ocean Sciences)*: I'm certainly appreciating the influence of events outside the Georgia Basin on what happens within. Do we understand why the nitrate levels in the deep water that enters the Strait of Juan de Fuca are as high as they are?

Paul Harrison: Most deep water runs 25 to 35 parts per thousand so they are not unusual. The unique difference here is that you have the up-welling bringing up deeper water and so you have a higher nitrate contribution in summer than in winter. This is a unique situation, usually you would expect in the Strait slightly lower nitrate values in the summer than winter. But because of the upwelling you are getting water from deeper being brought up with slightly higher nitrate values, and end up with higher surface values of nitrate in summer than in winter.

John Armstrong *(Environmental Protection Agency)*: A number of years ago we made a decision in the Puget Sound area to stop measuring most contaminants in the water column — most programs don't do that anymore. For our border waters, do you concur with that decision for the present, and if you agree we shouldn't do it now, when would you suggest we start to measure?

Paul Harrison: That's why I added two more co-authors to my paper, Robie Macdonald and Eric Crecelius. I have been corresponding with them, and they tell me not to worry about the water column, because concentrations of some of these toxics are ten times worse in the sediments. But there are probably some local areas near pulp mills that should be looked at, but to focus the attention on the site-specific sources. Many of the pollutants are absorbed to sediments and so you have this concentrating effect.

Tom Pedersen *(Panel)*: What is the proportion of urea today as a part of the nitrogen-nutrient-species budgets and what are the prospects for a relative increase in urea in the future?

Paul Harrison: Typically deep water would have 30 micromolar nitrate, 1 or 2 micromolar ammonium, and 1 or 2 micromolar urea. So, a few percent. In terms of increase in the future from sewage outfalls if they increase their output by an inordinate magnitude, then the urea might go from 1 to 10 for example, so it is still relatively small compared to nitrate, and especially compared to the values of nitrate being added by natural sources. So a natural deep-mixing process, either by wind or tides, is bringing up probably 30 times more nitrate than it is urea.

Ron Thom *(Battelle Marine Sciences Laboratory)*: We've taken samples in very near-shore environments in Puget Sound and found depleted nutrient conditions during the summer for extended periods, and we've also taken samples in streams that come off of urban areas. Small streams contained highly elevated nitrate, for example, 150 micromoles, so in these confined embayments it's a lot different than the open areas.

Paul Harrison: That's a really important take-home message. These small inlets where the mixing is poor, and especially if they have freshwater input from a small contaminated river, then that would be where to focus. The failed septic tanks and agricultural run-off are the hidden things that would make these local effects. We can have one anchor station in the middle of the Strait, and one in the middle of Puget Sound, and then focus attention on these inlets. Puget Sound could narrow down their 61 sampling sites and begin to focus on nutrient-sensitive areas — which they already have done — a great step forward in terms of spending money wisely.

Red Tides and Other Problems With Harmful Algal Blooms in Pacific Northwest Coastal Waters

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ABSTRACT

Harmful algal blooms (HABs) and the biotoxins they produce are a significant and increasing threat to human health and fisheries resources in the Pacific Northwest and globally. The incidence of HABs has increased in frequency, severity and duration in recent years. Moreover, the number and kinds of organisms known to produce toxins are also increasing. Reasons for the spread are not known, but a number of factors may be involved, including increased aquaculture, marketing and awareness. Other anthropogenic influences are being sought, but are not apparent at this time.

In the Pacific Northwest, public health and economic problems are related to paralytic shellfish poisoning (PSP), domoic acid poisoning (DAP), and mortalities of pen-reared salmonids. A potential, and perhaps more serious, problem for the area is diarrheic shellfish poisoning (DSP). The organisms that produce the toxins or cause problems are known and are common, often abundant members of the phytoplankton community in Pacific Northwest waters, yet little currently is known about their distribution, abundance and physiological ecology. Net pen liver disease may also be associated with HABs, but the source organism(s) has not been identified yet. Thus, research into the biology of the causative species, as well as effective management of fisheries and answers to public health and ecosystem questions are urgently needed.

INTRODUCTION

Microscopic algae in the sea are normally thought to be highly beneficial since they make up the phytoplankton upon which most marine food webs are based. However a few species have become well known because of their harmful effects leading to the illness and death of marine life or humans. Cases of harmful algal blooms have increased in frequency, severity, and duration in recent years. This has led to severe economic losses due to loss of product and/or sales. The algae and the toxins they produce pose an increasing threat to human health and fisheries resources in the Pacific Northwest. An obvious concern is whether such an apparent increase, on both local and global scales, has been the result of environmental change due to human activity (e.g. Anderson 1989; Smayda 1990; Hallegraeff 1993). Further, human activity such as discharge of foreign ballast water or shipment of live product may add to the spread of such phenomena (Hallegraeff 1993).

In this paper we review the current state of knowledge regarding HABs in the light of the above concerns, and suggest future research needs.

HISTORY OF HABs IN THE PACIFIC NORTHWEST

SHELLFISH

Paralytic Shellfish Poisoning (PSP)

Although there are some early European cases that may have been PSP, the earliest undoubted incident

recorded is the one death and four illnesses of Captain George Vancouver's crew in 1793. The description he provided in his journal (and republished by Quayle 1969) of the events following a breakfast of mussels in Poison Cove on the coast of central British Columbia, and ending in the burial of John Carter in Carter's Bay, is unquestionably a PSP event. Shortly afterward, in 1799, 100 Aleut Indians working for the Russian fur trader, Alexander Baranoff, died of PSP at Peril Strait close to the Alaskan border with B.C. (Quayle 1969). No further cases were recorded in this region until the 1940s, although Pugsley (1939) reported the presence of toxic shellfish in B.C. in 1939.

In May 1942 a severe outbreak of PSP in the Barkley Sound region of Vancouver Island killed three persons who ate clams and mussels. About the same time, three died in Washington State, presumably a result of the same outbreak (see below). Seabirds were also reported to have died at this time. The next event causing human illness occurred near Comox in the Strait of Georgia in 1957 (61 illnesses, but no fatalities) and implicated oysters for the first time.

A causative organism was not directly linked to an illness or fatality in Northwest waters until 1965 when Prakash and Taylor (1966) observed an abundance of the microscopic dinoflagellate *Alexandrium acatenella* (Whedon and Kofoid) Balech in the water at the time when one death and four illnesses followed the eating of steamed cockles from Theodosia Inlet (northern Strait of Georgia). However, the presence in our waters of several other species of *Alexandrium* (all first attributed to the genera *Gonyaulax* and *Protogonyaulax*), known to be toxic elsewhere, including *A. catenella* (Whedon and Kofoid) Balech (Quayle 1969, and probably Wailes 1939, under the name *Peridinium discoides* Wailes) and *A. tamarense* (Lebour) Balech (Taylor 1975), suggest that previous outbreaks could have been due to these species. Although they appear to be part of the same species complex, they tend to have different distributions, with the *tamarense* morphotype prevailing in more estuarine locations, such as the eastern side of the Strait of Georgia (Taylor 1984). In 1991, a record high level of 32,000 µg of PSP toxin per 100 g of mussel meat was recorded from Sechelt Inlet near the entrance to Salmon Arm (Fisheries and Oceans data cited by Taylor et al. 1994). This was associated with the *catenella* morphotype. The most recent B.C. fatality from PSP occurred in 1980 at Health Harbour on Gilford Island, southern Queen Charlotte Sound. In 1992, two fishermen ate potentially fatal doses of clams in nearby Kingcome Inlet, but were saved by artificial respiration. One individual was totally paralyzed twenty minutes after chewing on (but not swallowing) one clam that had been collected during an unusually low tide. Harvest closures were particularly extensive in southern B.C. in 1993. Two other potentially toxic *Alexandrium* species, *A. ostenfeldii* (Paulsen) Balech and Tangen and *A. hiranoi* Kita and Fukuyo, have recently been identified from B.C. waters, the latter being coincident with early toxicity in Barkley Sound (R. Haigh and F. Taylor, unpubl. obs.).

Although PSP toxicity was long known from the Washington open coast and Juan de Fuca Strait, no illnesses were reported from consuming shellfish harvested in Puget Sound (south of Admiralty Inlet) before 1978, but low levels of PSP toxin (<64 µg/100 g shellfish meat) were detected in some samples. However, in September 1978 widespread toxicity occurred, beginning in Whidbey Basin, where toxin levels in mussels (*Mytilus edulis* Linnaeus) were up to 30,000 µg/100 g of meat, and extending south as far as Des Moines. High toxin levels (>1000 µg) have occurred in Whidbey Basin and central Puget Sound every year since 1978 (Nishitani and Chew 1988). The first closures in southern Puget Sound occurred in Carr Inlet in 1988 when PSP levels in oysters reached 2000 µg. In Hood Canal the only closure due to high levels of PSP toxin occurred at Seabeck in late May/early June 1991. In 1992 the highest PSP levels ever recorded in razor clams, 3480 µg in the viscera and 720 µg in the meat (M. McCallum, pers. comm.), delayed the opening of the fall harvest on the Washington coast.

Domoic Acid Poisoning (DAP)

Domoic acid poisoning, often called amnesic shellfish poisoning (ASP), first occurred on the U.S. West Coast in September 1991 when pelicans (*Pelecanus occidentalis* Linnaeus) and cormorants (*Phalacrocorax penicillatus* Brandt) died in Monterey Bay, California. The cause was traced to domoic acid in their food source, anchovies (*Engraulis mordax* Girard), that were feeding on phytoplankton dominated by the diatom *Pseudonitzschia australis* Frenguelli (Fritz et al. 1992; Work et al. 1993). Domoic acid was next found in razor clams (*Siliqua patula* Dixon) on the Oregon/Wash-

ington coasts in late October 1991, with toxin levels in the edible parts (foot, siphon, and mantle) reaching 160 µg/g shellfish tissue (J. Wekell, pers. comm.) and causing closure of both commercial and recreational harvests for these clams. Toxin levels remained above the Washington Department of Health (WDOH) regulatory closure level of 15 µg/g wet weight until the summer of 1992 (Horner and Postel 1993). (The regulatory closure level in Canada is 20 µg/g wet weight, e.g. Todd 1989). During this event there were no deaths and only seven people sought medical attention (Quick 1992). Domoic acid was not found in oysters and mussels that also were tested, but levels ranging from non-detectable to 38 µg/g were found in the viscera, and 8 µg/g or less in the meat of Dungeness crabs (*Cancer magister* Linnaeus) (Food and Drug Branch, California Department of Health Services, unpubl. data, 1992), and the commercial harvest was temporarily closed in northern California, Oregon, and Washington. No illnesses were reported from eating crabs. In 1993 domoic acid again appeared on the Washington coast with levels rising from non-detectable in September to 8–19 µg/g by mid-November (WDOH, unpubl. data), and the fall razor clam season was closed early. Domoic acid levels remained high in razor clams into spring 1994, with some harvest closures still imposed.

Ceratium fusus/Gymnodinium sanguineum

In southern Puget Sound, the dinoflagellates *Ceratium fusus* (Ehrenberg) Dujardin and *Gymnodium sanguineum* Ehrenberg (= *G. splendens* Lebour) have been associated with mortality of oyster larvae (*Crassostrea gigas* Thunberg) and adults (Cardwell et al. 1977, 1979) and spot prawns (*Pandalus platyceros* Brandt) (Rensel and Prentice 1980). There is no indication that a chemical toxin is produced, although it is suggested that the toxin origin appears to be biological and is coincident with blooms of *C. fusus* and *G. sanguineum* (Cardwell et al. 1979). Moreover, mortality may be due to mechanical means. There was no mortality when oyster larvae were added to water and culture medium from which cells of *G. sanguineum* were removed; however when dinoflagellate cells were added, mortality occurred (Cardwell et al. 1979). Mortality of spot prawns increased during blooms of *Ceratium fusus* and had blackened matter that may have been mucus or decaying dinoflagellates on their gill lamellae (Rensel and Prentice 1980).

Finfish

Chaetoceros convolutus/concavicornis

Members of the diatom genus *Chaetoceros* (*C. convolutus* Castracane, and the very similar species *C. concavicornis* Mangin) have caused deaths of fish reared in net pens at least since 1961 (Bell 1961). These species have small barbs on their setae that all point in the same direction, and early reports (e.g. Bell 1961) suggested that the setae were able to bore into gill tissue causing irritation and excessive mucus production. Recent investigations found no compelling evidence that the diatom setae actually penetrated the gill tissue. Instead, *Chaetoceros concavicornis* cells and chains were found between the secondary lamellae of the gills or in the overlying mucus (Rensel 1992). Fish exposed for more than 12 hours showed massive discharge of gill mucus that obstructed the interlamellar spaces, while 24- to 48-hour exposure caused exhaustion of the supply of both mucus cells and mucus, and caused lamellar degeneration and separation. Further, blood oxygen levels of fish exposed to environmentally common concentrations (generally $<10^5$ cells/L) of *C. concavicornis* were lower, and CO_2 levels higher than control fish not exposed to the diatom.

Heterosigma carterae

Kills of farmed salmon have also been associated with the raphidophyte (chloromonad) flagellate *Heterosigma carterae* (Hulburt) Taylor (previously called *H. akashiwo* (Hada) Hada or, erroneously, *Olisthodiscus luteus* Carter [Taylor 1992]) at least since 1976 (Gaines and Taylor 1986). Indications are that a fish kill near Lummi Island in 1976 and another at Manchester about the same time were caused by *Heterosigma*, but it wasn't until 1986 that a bloom of $>2 \times 10^8$ cells/L in Sechelt Inlet, B.C., caused losses of $2.5 million or about one-third of the production. In 1989 a bloom covering >7000 km² caused farmed salmon losses estimated at $4 million in B.C. (mostly in Agamemnon Channel) (Taylor 1993) and $4 million in Washington (Cypress Island) (Horner et al. 1991). In 1990 a bloom in central Puget Sound killed about 1.3 million fish valued at $4–5 million (Horner et al. 1991). At least 250,000 fish died at sites on the west coast of Vancouver Island in 1992.

In the net pens, *Heterosigma* usually kills larger fish — including breeding stock — before smaller ones, and

some salmonid species are more susceptible than others in net pens. No specific chemical toxin has been identified, although polyunsaturated fatty acids (PUFAs) are thought to be involved, leading to organ damage by superoxide radicals. In fact, experiments over the last three years using Atlantic salmon (*Salmo salar* Linneaus) smolts and *Heterosigma* cultures of cells isolated from the 1990 Puget Sound fish kill and tested under a variety of culture conditions (e.g. high/low cell numbers, different growth stages, nutrient-replete and nutrient-limited, chemically-defined medium) have produced no fish deaths (Rensel, Taub, Matter, Postel, Horner, unpubl. data). However, Yang et al. (1993) were able to kill juvenile sockeye salmon (*Oncorhynchus nerka* Walbaum) with 40 to 120 minutes of exposure to *Heterosigma* cells grown using a semi-defined medium. These authors believe that the toxins are superoxide radicals and hydrogen peroxide formed during late-growth to stationary-growth phase, because the fish can be protected with the addition of superoxide dismutase (also J. McLaughlin, pers. comm.) and catalase.

Gyrodinium galatheanum

A culture of *G. galatheanum* (Braarud) Taylor isolated from near Lummi Island, Washington, in 1992, was toxic to sticklebacks (N. Haigh, pers. comm.). This species has caused fish kills in Norway, but has not been implicated in a kill in our waters yet.

MANAGEMENT

British Columbia

Since the 1942 outbreak, shellfish have been monitored for PSP every year on the British Columbia coast. Unfortunately, as a result of the length and complexity of the coastline (approximately 18,000 km) it is impossible to cover the whole region adequately. Consequently, large areas of the coast are permanently closed to private shellfish collection. Although many locations are sampled from the whole coast (92 sites in 1993, but 17 northern locations are routinely monitored only during the geoduck harvesting period), only the Strait of Georgia, southern Queen Charlotte Sound, Juan de Fuca Strait, and Barkley Sound are monitored regularly, and opened when levels are below 80 µg/100 g meat (the same standard as in Washington State). The AOAC methodology, mouse bioassay following hydrochloric acid extraction, has remained essentially unchanged, although alternative chemical methods are being pursued. In 1992 testing for domoic acid was added, with closures when levels exceed 20 µg/g (= ppm), and a change in extraction solvent (to methanol) was made when it was realised that acid extraction could lead to significant underestimates. In view of the peculiar affinity that razor clams have for domoic acid, they need to be added to the routine monitoring program, but collection of them in British Columbia has proved difficult. Mussels are one of the worst organisms to be used to monitor domoic acid since they rid themselves of domoic acid in a matter of hours to days (e.g. Novaczek et al. 1992; Wohlgeschaffen et al. 1992).

The Fisheries Inspection Branch of the federal Department of Fisheries and Oceans has the responsibility for shellfish monitoring and closures in British Columbia. Chiang (1985) noted that the number of samples analysed doubled for each decade, from an average of 455 per year in the 1960s to 1,694 in the mid 1980s. Currently it is in the order of 4,000/year, approximately 75% involving the routine monitoring of mussels (R. Chiang, pers. comm.). Earlier sampling focused on clams, which retain PSP toxins the longest, perhaps even more than one year (Quayle 1969). Oysters and geoducks (seasonal) are also tested. Warnings are issued via the media and postings at various sites such as marinas, etc. There is no telephone hotline as there is in Washington State. Dungeness crabs have been added to the program as a result of the discovery that they can have both PSP toxins and domoic acid in their guts.

Unlike the east coast of Canada and various other parts of the world (e.g. Japan, the Philippines, Thailand, South Africa, and Australia) there is no routine government phytoplankton monitoring program in British Columbia waters that could provide advance warning of impending toxicity. Shellfish harvesting can simply be postponed until levels are acceptable within the product. The present shellfish monitoring program only records toxicity after the fact. The near fatalities in Kingcome Inlet in 1993 occurred almost coincidentally with the sampling of shellfish by inspectors and could not have been prevented by the usual warning protocol. Fisheries vessels are now requested to collect samples from discoloured water, but this is also after the fact, and blooms are often subsurface, showing no visible signs of their existence. The DFO has provided some support for a university plankton study in Barkley

Sound, but the level of support has been inadequate and such work should be on-going in many areas where aquaculture or other marine resources are important.

The activity with the greatest need for phytoplankton analysis is fish farming, and most operations have learned that daily phytoplankton sampling at farm sites and the vicinity are essential to provide warning of dangerous blooms. This is done by farm employees during the danger period (June to October). The commonest defensive steps are to stop feeding, move the pens, or close them and sink them below 10 m (harmful blooms rarely extend deeper than that except in highly mixed channels).

Washington

In the United States, sampling related to HABs is primarily, or exclusively, a state rather than federal matter. The shellfish monitoring program by the Washington Department of Health and county health departments has greatly reduced PSP risks to human health, with only 5 confirmed illnesses from commercial shellfish operations since monitoring began in 1957. Recreational shellfish harvesting has been severely restricted since the mid 1970s because of more frequent occurrences and higher levels of toxicity. However, the only reported PSP illnesses from sports-harvested shellfish were 10 cases in 1978 in an area previously considered safe, 3 cases from clams in 1979, 3 cases in 1985 from scallops collected in areas where harvesting was closed (Nishitani and Chew 1988), and 2 cases in 1988 from butter clams collected in closed areas of Sequim Bay (M. McCallum, pers. comm.).

Since 1942 the WDOH has imposed an annual closure from 1 April to 31 October for the harvest of all bivalve molluscs for the area from Dungeness Spit on Juan de Fuca Strait to the Columbia River; razor clams were originally exempt from the closure because PSP was found only in the viscera which were removed before eating. Now, however, razor clams are included in the ban. Routine monitoring for commercial shellfish began in some areas in 1957, but rarely for recreationally harvested shellfish until 1971 (Nishitani and Chew 1988).

At present, the WDOH routinely monitors PSP toxin levels in shellfish from commercial and recreational areas throughout the state. Commercial operations, with a 1991 ex-vessel value of $50 million for all shellfish, must submit PSP samples for testing on a regular basis (biweekly during winter and spring, weekly during summer and fall) as part of their certification. Selected recreational areas are sampled biweekly from April through October by state and county health departments, with sampling often done by volunteers, including the Adopt-A-Beach program. Since 1989 WDOH has used caged blue mussels (*Mytilus edulis*) as an early warning system for PSP. Mussel cages are located at 33 sites; some are monitored biweekly throughout the year, others less frequently or only during the summer. Areas are closed for the harvest of all molluscan shellfish when PSP toxins equal or exceed the Food and Drug Administration (FDA) standard of 80 μg toxin/100 g shellfish tissue (WDOH 1990). A toll-free, 24-hour PSP hotline (1-800-562-5632), maintained by the WDOH Office of Shellfish Programs, lists recreational closures.

As in British Columbia, mussels are routinely used by WDOH to test for domoic acid, but clams and oysters from commercial sites are also routinely tested. However, the Washington Department of Fisheries (WDOF) samples razor clams in a number of management areas along the open coast, and these are analyzed by both WDOH and the National Marine Fisheries Service. Retention time and depuration of domoic acid by razor clams are still largely unknown. In 1991/92 razor clams living in their natural environment in high energy beaches on the open coast remained above the Washington State closure level of 15 μg/g of meat for 8–9 months, but gradually lost toxin over that time. Clams collected at approximately four-month intervals between December 1991 and July 1992, and kept in captivity in either open or closed systems for three months, retained their original domoic acid levels (Drum et al. 1993; Horner et al. 1993).

There is also no routine phytoplankton monitoring program in Washington State, although samples are collected at some sites by WDOH and WDOF personnel as part of their shellfish sampling programs, and the Washington Department of Ecology collects phytoplankton samples at a number of locations as part of their Puget Sound Ambient Monitoring Program, and at some additional sites specifically requested by university investigators. These samples are analysed by University of Washington personnel as part of other pro-

jects. Technicians at several local fish farms and a few shellfish growers collect and analyse phytoplankton samples daily during April to October. A phytoplankton hotline (206 685-3756) is maintained on a year-round basis in the School of Oceanography, University of Washington, and is based primarily on information from the aquaculture sites.

DISCUSSION

From the above, it is evident that all the harmful algal blooms mentioned are problems common to British Columbia and Washington. Currents sweep blooms readily throughout Puget Sound, the Strait of Georgia and the open coasts of the Pacific Northwest. None of the bloom episodes can be readily linked to pollution effects. Nevertheless, there has been an apparent increase in the frequency and nature of HABs in these waters. What can we attribute this to?

From the early records (since 1793), high levels in areas of very low habitation, native Indian cultural taboos on shellfish consumption, and adaptive responses to PSP by native marine mammals, birds, and fish (Kvitek 1993), it is evident that PSP is endemic to our coasts, and probably has been for thousands of years. The recent heavy outbreaks, with high localised intensity in 1991 and broad scale closures in 1992, are consistent with the cyclic nature of the phenomenon in the Pacific Northwest (Gaines and Taylor 1985) and elsewhere (MacLean 1989; Hallegraeff 1993). The outbreaks are often correlated with El Niño events (Erickson and Nishitani 1985), but not always. In the austral summers preceding the two most recent local events, outbreaks of PSP and other HABs occurred in Chile (Lembeye 1992) and New Zealand (Chang et al. 1993).

The *Pseudonitzschia* blooms associated with domoic acid occurred off the sparsely populated open coast and apparently were part of very widespread blooms probably extending from northern California (Monterey Bay) to Alaska. These blooms may have been associated with unusually warm weather conditions caused by El Niño. The 1991 incident on the Washington/Oregon coasts occurred after 45 days of warm, dry weather followed by rainfall. Short blooms of *Pseudonitzschia* species were reported throughout Puget Sound during the summer of 1992 (Horner and Postel 1993), all happening after warm periods followed by rain. No *Pseudonitzschia* blooms occurred during the cool, wet summer of 1993, but the fall was warm and dry and domoic acid appeared in razor clams shortly after the fall rains started. Phytoplankton samples collected at Westport in early November contained three species of *Pseudo-nitzschia* (formerly attributed to *Nitzschia*) known to produce domoic acid (R. Horner, unpubl. data). These three species also have been observed as sometimes abundant in areas such as Barkley Sound (Haigh and Taylor, unpubl. data). The B.C. offshore distribution of *P. pungens*, the first species linked to domoic acid poisoning, was most frequent in July or August off southwestern Vancouver Island (Forbes and Denman 1991).

Heterosigma has bloomed in our coastal waters every year since observations began in the 1960s (F.J.R. Taylor, unpubl. data). In the Strait of Georgia it is an almost annual event. In 1989 it filled the entire Strait of Georgia and spread into northern Puget Sound causing losses of approximately $8 million to the finfish aquaculture industry. Due to the influence of the Fraser River on the Strait of Georgia, a possible bloom-enhancing effect by agricultural runoff might be suspected. However, in 1992 no summer blooms occurred in this area, but were present on the outer coast of Vancouver Island. In the Strait of Georgia, *Heterosigma* blooms do not occur before the simultaneous occurrence of a rise in temperature to 15°C and decrease in salinity to 15 psu due to peak runoff of the Fraser River (Taylor and Haigh 1993). The lack of a major bloom in 1993 may be attributed to the latter being anomalous (not as low and peaking earlier).

Dinophysis species and *Chaetoceros concavicornis/convolutus* usually do not form heavy blooms in the area, but are chronic low-level members of the community. Yet *C. concavicornis* bloomed in Dabob Bay, Washington, in October 1991, with cell numbers near 10^5 cells/L (J. Postel, unpubl. data). Little currently is known about the frequency and abundance of *Dinophysis* species other than the maxima are usually subsurface, with *D. acuminata* being the most common potentially toxic species (Taylor and Haigh 1993; unpubl. data from Barkley Sound).

Blooms of usually nonharmful species also may occur in Pacific Northwest waters. The large, predatory dinoflagellate *Noctiluca scintillans* (Macartney) Ehrenberg is present throughout the year and may cause blooms that look like tomato soup. It is generally believed to be

harmless, but may produce large amounts of ammonia that are reported to irritate fish. Another dinoflagellate, *Gonyaulax spinifera* (Claparède et Lachmann) Diesing, formed an extensive bloom in local waters in August-September 1990. It was present at least from Grays Harbor to Barkley Sound on the open coast, covering some 500 km² and extending in a large tongue off Vancouver Island (Gower and Borstad 1991; Heath and Lindsay 1993). It was dense around the southern Gulf Islands (Taylor, unpubl. data) and large patches drifted with the tides and currents throughout the Strait of Georgia, Haro and Rosario straits, and Juan de Fuca Strait. Its presence caused concern among local fish growers, but there were no reports of mortalities among farmed fish. Death of oysters, clams, and mussels in side inlets of Barkley Sound at this time were as high as 60–100% in the worst affected areas, with deaths of crabs, snails, and other invertebrates also reported (Heath and Lindsay 1993). The kills were attributed to oxygen depletion from high BOD as the bloom decomposed. The cost through 1991 and 1992 of this outbreak was put at over $200,000.

Another organism that often blooms in local waters is the ciliated protozoan, *Mesodinium rubrum* Lohmann (Taylor et al. 1971). This small protist contains uniquely integrated, red-pigmented algal symbionts and may turn water red to maroon in color. Oysters growing in areas with *Mesodinium* blooms may become pink from eating the animal, but they are not harmful (Quayle 1969). Central Hood Canal and English Bay, B.C., for example, often have blooms of this organism.

Gymnodinium sanguineum, discussed above as a potentially harmful species, is a common bloom-former in the fall in shallow, enclosed Esquimalt Lagoon where it usually does not cause problems (Watanabe and Robinson 1979). It also blooms regularly in shallow embayments in southern Puget Sound in late summer and fall (Horner, unpubl. data).

Algae that don't usually produce extensive blooms may do so when environmental conditions are suitable. Small, semi-enclosed bays with little water flushing are especially susceptible. For example, the diatom *Rhizosolenia setigera* Brightwell formed a straw-colored mat over a large area of southern Hood Canal in August 1991, the first such phenomenon reported there in 58 years according to one local home owner. This species was also extremely abundant throughout northern and central Puget Sound in the summer of 1993 (Horner unpubl data), but did not form visible mats or cause problems for either finfish or shellfish growers.

FUTURE

In the future, we expect that the discovery of new harmful effects and new harmful species will continue worldwide. In the Pacific Northwest, the presence of at least four species of *Dinophysis* known to produce okadaic acid will most likely lead to the recognition of DSP, particularly if mussel farming increases. Other species, such as *Chrysochromulina polylepis* Manton and Parke, that produce HABs elsewhere, for example in Scandinavia in 1988, are also known from local waters, but have not caused problems here.

Both PSP and DAP will likely continue indefinitely, possibly spreading to new areas and shellfish species, and causing economic losses and health hazards. The growing harvest of non-traditional shellfish, such as moon snails, whelks, barnacles, etc., will increase human health problems and management responsibilities (S. Shumway, pers. comm.; Matter 1993). These non-bivalve molluscs are currently not tested or included in harvest closures due to PSP in Washington. Although *Heterosigma* and other fish-killing blooms are not obviously linked with pollution at present, these phenomena have been linked to changes due to pollution elsewhere (e.g. Seto Inland Sea, e.g. Okaichi 1987), therefore increasing eutrophication could lead to the blooming of other harmful fish-killing species that are presently not a problem. Ironically, the decrease of metal levels such as copper (Paulson et al. 1993) in semi-enclosed bodies of water like Puget Sound could conceivably lead to greater abundances of toxic *Alexandrium* species, because an early study (Anderson and Morel 1978) showed these species to be extremely sensitive to, and inhibited by, copper. Since metal effects are greatly modified by organic matter in the water, this is not a confident prediction, but remains an interesting possibility.

In the U.S. and western Canada, most monitoring and regulatory programs often are not adequate to meet the expanding threat of new HABs. As a result, when new outbreaks occur, the response is often uncoordinated and slow (e.g. the 1991 domoic acid incident). Fortunately, in Washington the programs have been adequate to prevent serious illness and/or death due to

eating shellfish. However, because the program seems to be successful, there is little incentive to provide funding for research on the harmful species. The recent near-deaths in British Columbia were not averted by the shellfish monitoring program; the fisheries inspectors took samples too late to avoid the exposure. Only a properly designed phytoplankton sampling program, in an area historically known be to toxic early in the season, could give such a warning.

As a result of false complacency, one of the most serious problems is the lack of information on the biology of harmful algae. For example, little is known about the abundance, distribution, population dynamics and physiology of most of the harmful species, both in local waters and elsewhere. In our area, long-term, routine phytoplankton and environmental monitoring efforts are essential in order to obtain the data necessary to determine even the most elementary ecology of harmful species (e.g. Taylor et al. 1994). Moreover, because bloom dynamics are complex, the factors that determine bloom dynamics of a species in one geographic area may not affect that species in another area, even though the areas are not widely separated.

Because of the short duration and large spatial scales of blooms, remote sensing has been suggested as a means to identify and track blooms (Yentsch 1989). Satellite imagery, e.g. sea surface temperature (SST), has been used to identify oceanic features and water masses associated with blooms of two harmful species in two different hydrographic regimes (Tester et al. 1991; Keafer and Anderson 1993) and it may be possible to determine physical features of the local coastal ocean, such as fronts or water masses, during blooms and thus be able to follow bloom initiation and decay. However, the resolution or scope of existing systems are not sufficient to recognize bloom patches in the inner waters other than in the Strait of Georgia. Information on the presence or absence of harmful algal species can only be obtained through direct plankton sampling, which must be done at the same time as the satellite imagery, requiring expensive ship time and personnel. Further, because blooms cannot be predicted, there is little information on bloom initiation; investigators usually find out about a bloom when the bloom is already present (or past), or only suspect a bloom occurred because shellfish have become toxic. The necessity for routine phytoplankton monitoring has been stressed repeatedly (e.g. Gaines and Taylor 1986; Heath and Lindsay 1993; Taylor 1993), but has not been effectively implemented, and certainly not in any coordinated cross-boundary way by Government agencies.

Lack of adequate funding and trained personnel are major impediments to the study of HABs, and no single agency has the resources and/or personnel to address all of the problems related to HABs. However, before unexpected outbreaks occur, agencies responsible for managing and providing safe seafood should have in place an action plan that identifies personnel and organizations to call on to respond to the problem.

We recommend a number of goals for the immediate future. Goals should include, but are not be limited to:

- Developing a common, long-term phytoplankton monitoring protocol.
- Compiling available data to determine transboundary trends and data gaps.
- Maintaining a common, toll-free telephone/FAX hotline to advise the appropriate agencies, industries, and other interested persons of developing harmful blooms.
- Implementing joint training programs for agency, industry, and other personnel so they can assist in the visual identification of harmful species.
- Developing educational material (printed, videotaped) for the public and involved persons.
- Strengthening links along the entire west coast of North America, from southern California to Alaska, to understand blooms in the context of the West Coast ecosystem. A West Coast working group including both Americans and Canadians would assist in this process.

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DISCUSSION

Andrea Copping *(Panel)*: Max, can you say a bit about the connection that you and your colleagues see with any anthropogenic inputs, whether it be nutrients or even possibly more esoteric chemicals that we don't tend to associate with these blooms?

Max Taylor: This is really what our paper discusses, whether any of these effects in British Columbia are the result of human activities, and ironically I should point out, that would be good news. If it was human activities, we could do something about it. If it's simply major climatic change and things like that, you can't do anything other than manage it. If you look at the shellfish toxicity data, you see that it's cycling, and the 1992/93 summer increase is exactly what we would have predicted six to eight years ago when we noticed that it's approximately a six- to eight-year cycle — it varies by one or two years either way. So it's a cyclic phenomenon, and does not appear to have anthropogenic effects on it. The *Pseudonitzschia* is something coming from offshore inwards, so again with domoic acid we don't think that is being influenced by humans. *Heterosigma* is something that occurs in areas that could be impacted by humans, and we did a three-year study in Sechelt Inlet, which is one of these enclosed bodies of water that Paul Harrison talked about where you might expect to see this. One of the concerns was that the fish farms themselves might give rise to localized eutrophication and cause blooms. Our study in Sechelt Inlet showed that the blooms were coming from the Strait of Georgia into Sechelt Inlet, and even though there were a lot of farms in there, they had not given rise to these things. So at the moment we don't see signs of *Heterosigma* blooms being influenced by that. The last one, the *Chaetoceros*, doesn't need to make a bloom to be harmful. It's in very low numbers and we know relatively little about its ecology.

Marvin Roseneau *(Ministry of Environment, Lands and Parks)*: You've talked about marine phenomena, does this occur in freshwater at all?

Max Taylor: Others do, so-called blue-green algae can form very noxious blooms in small bodies of water, that have led to the death of domestic animals — cattle and birds have been killed. Particularly in the prairies as a result of blooms similar to the thing that I am describing here, but a different group of organisms. What is so strange about them is they are highly toxic and yet there are no reports of human illness or death as a result of it. But a colleague who has worked in various parts of the world is very worried about places where people drink directly from lakes without treating the water, because in China they've found that these are areas of high liver tumors. So he thinks that, although there have not been human fatalities directly linked to freshwater blue-green algal blooms, there may be tumor-forming effects that have not been appreciated so far.

Fish deaths in freshwater are mostly due to low oxygen rather than to toxins that I am aware of. There are a couple of dinoflagellates that have been known to do it, one in Japan has killed fish in freshwater. I don't know of any in British Columbia. The only case in B.C. that I have looked at where there was a dinoflagellate bloom was near the town of Lund where the drinking water smells bad, and it's because of blooms of a harmless dinoflagellate.

Marine Benthos of British Columbia/Washington State Boundary Waters

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ABSTRACT

The northeast Pacific Ocean is a very high energy system. Exposed coastlines in Washington contrast with sheltered situations in Puget Sound, Strait of Georgia, and the coastal fjords of British Columbia. Fjord ecology varies depending on sill depth. This complexity of habitats combines with the age of the Pacific basin to create a great diversity of benthic community structures. Despite this great diversity, only a few benthic taxa have been studied taxonomically and physiologically. Only a few community studies have been conducted. These are focused on environmental problems involving coastal areas near major population centers (e.g., Commencement Bay, Burrard Inlet, Boundary Bay, Victoria Harbour and foreshore) and attempt to address the impact of industrial and domestic waste effluent. Bioassays employing selected benthic invertebrates have been used to assess sediment toxicity. Sediment bioassays are used as a surrogate means to predict the potential impact of anthropogenically introduced contaminants and nutrients to the resident benthic communities. However, the use of sediment bioassays as an approach to assess contaminant-induced effects on populations and community structures of benthic invertebrates in the Puget Sound and Georgia Basin has yet to be validated. Sediment toxicity bioassays currently are most useful as a comparative screening tool rather than a predictor of complex field conditions. While benthic community structural data provides much information, it remains difficult to link changes and assess risk relative to specific anthropogenic inputs unless simultaneous chemical analysis and toxicological assays are obtained. Benthic monitoring programs can provide important information for assessing risk, but this approach will require strict attention to several fundamental needs. These include clear objectives, standard methods, economy of effort to ensure continued support, and adequate laboratory support for establishing linkages between community structure and function, the causes of observed changes, and risk assessment.

INTRODUCTION

Environmental concerns in aquatic ecosystems are evolving to encompass biological integrity rather than simply water quality. While the determination of the fate and effects of lists of specific contaminants will continue to be a serious issue, it is now being realized that habitat alteration and destruction from a whole variety of causes are degrading living communities. For example, non-point source contaminants are a serious issue, and habitat alteration and destruction, often at sites removed from the area of concern, are known to degrade communities of plants and animals. Legislation designed to preserve rare and endangered species is evidence of an alteration in our conceptual framework,

especially where these actions seem to be in conflict with economic needs. The fact that the legislation is concerned with the protection of the environment in which rare species exist, rather than simply with the species itself, is further evidence of the introduction of ecological concepts into policy making.

There is a need to separate anthropogenic from natural causes of differences in benthic communities observed from site to site. Those natural causes may be as obvious (once described by research) as the relationship between the height of the sill at the mouth of a fjord and the oxygen level of the sea water trapped behind it. Other natural causes of change may be obscure, such as the supposed connections between the impoundments on all of the major river inputs to the St. Lawrence River system and the circulation and benthic ecology of the Gulf of St. Lawrence with its major fisheries. For this reason, the following paper will include some studies and references beyond the immediate concern related to contaminants and spills, and monitoring needs to be extended to include reference sites.

It will rapidly become apparent that there have been a lot of site-specific studies that have provided useful information regarding relatively local concerns, but few long-term integrated efforts that could be used to provide a broader theoretical framework within which to address the questions posed for this symposium. Many of the questions posed for the conference require mathematical models for predictive purposes. Very little existing benthic data is amenable to this kind of treatment. Carefully conceived monitoring programs with a guarantee of continuity will contribute to the ability to interpret local studies as well as providing the necessary information regarding temporal and spatial differences required for modeling.

FACTORS INFLUENCING BENTHIC COMMUNITIES

Natural Factors

Of direct importance to the estimation of the use of the ocean as a disposal site for wastes is the local assimilative capacity of the system. In general, the northeast Pacific Ocean is one of the highest energy oceanographic systems. The very large area of open ocean and the predominant wind direction, the often violent storms that accompany the summer/winter transition, and the physical structure of the land, serve to create very strong currents in many sheltered passages in addition to strong wave action along open shores. Crawford and Thompson (1991), for example, provide an account of the physical oceanography of the British Columbia continental shelf.

During summer, buoyancy flux and topographically controlled eddies influence surface circulation. Such events bring deoxygenated water onto the shelf, and there is some evidence to suggest that these affect benthic communities in a manner resembling the effects of deoxygenation due to organic pollution (Brinkhurst 1991).

Strong southeasterly storm winds in autumn and winter influence circulation within the fjords. Differences in sill height determine how frequently such events are able to circulate the often-stagnant sea water lying in the deepened basins behind the sills. Some fjords (Nitnat Lake) have such high sills that they are permanently anoxic. Others, such as Saanich Inlet, have deep anoxic layers that vary in extent seasonally (Burd and Brinkhurst 1984) and others are only periodically anoxic (Howe Sound — Levings et al. 1983).

There is an obvious relationship between circulation and wave action on the one hand, and the nature of the substrata on the other. Soft substrata exist in depositional areas in sheltered bays and inlets, rocky substrata where currents and wave action are strong or along the steep sides of fjords and other steeply sloping areas. The substrata strongly influence the fauna at this coarse level of discrimination as well as at the level of the separation between silt, sand and clay. Within the silt range, the effect of particle size alone may be more debatable.

Benthic communities in Puget Sound are also influenced by bottom type (sediment grain size), topography (bottom slope and microscale sediment patterns), water depth, and the relative erosional or depositional characteristics of the local environment acting on the local supply of sediment (Lie 1968; Thom et al. 1979; Comiskey et al. 1984; Word et al. 1984; Word 1990). The effects of these factors on benthic communities have been observed in Puget Sound since the work of Wennekins (1959). The communities of benthic organisms respond to these different types of habitats, with the more erosional environments dominated numerically by

relatively more suspension feeders than detrital or deposit feeders, while the more depositional environments end up with more surface detrital and deposit feeders (Word et al. 1984; Word 1990).

Anthropogenic Factors

The effects of chemical contaminants on benthic and epibenthic invertebrates will vary depending on where the contaminants are discharged in relation to circulation and substratum, and on the amounts and toxicity of the contaminants being discharged. In the British Columbia and Washington area, a few major population centers account for the majority of contaminant discharges. The cities, counties, municipalities, and industries located between Olympia and Bellingham discharge approximately 900 million gallons of treated effluent into Puget Sound every day through point-sources, and an average of at least another 10 million gallons of untreated non-point discharge (Puget Sound Water Quality Authority 1989). The contaminants that are released through these discharges include dissolved and particulate-bound nutrients and toxic contaminants. Through interaction with bottom sediment topography and near-bottom current physical characteristics, certain suspended particles will settle to or near the sea floor (Gibbs 1974; Yalin 1977). In fact, sediments are the primary repository of these anthropogenic chemicals (Means et al. 1989; Salomons et al. 1987; Tessier and Campbell 1987). Benthic and demersal marine organisms capture these particles and use them for sustenance or to construct their domiciles (Word 1990). During the capture of the dissolved and particulate materials, the benthic and demersal organisms also come into contact with the toxic contaminants that are associated with the suspended particles.

The innermost regions of Puget Sound, with limited circulation of water and large amounts of industrial discharges and point and non-point releases of municipal wastes have the highest concentrations of sediment-associated contaminants, including polycyclic aromatic hydrocarbons (PAHs), polychlorinated biphenyls (PCBs), and selected toxic metals (e.g. lead and copper) (Striplin et al. 1991; McCain et al. 1988). Levels of PCBs, PAHs and selected metals in sediments have been reported to be significantly correlated with depressed numbers of benthic invertebrate taxa in sediments from these innermost regions (Malins et al. 1982). Elevated levels of these contaminants have also been reported in sediments from sites in Vancouver Harbour (Wells and Rolston 1991). A surprisingly diverse benthic fauna was found over large areas of Vancouver Harbour, but local areas of faunal depletion have been reported (Cross and Brinkhurst 1991).

The location and abundance of suspended and settled particles affect the types of benthic organisms capable of utilizing the available organic matter (Word 1979, 1990). The model of organic enrichment and community-level changes presented by Pearson and Rosenberg (1978) and the relative abundance of communities of organisms observed along organic gradients near southern California sewage discharges (Word et al. 1977; Word 1979, 1980 a,b) provide excellent models for more depositional environments. Depositional environments have bottom sediment topography and benthic currents that act to allow significant quantities of discharged particles to settle near the discharge site.

The greatest accumulation of particles occurs near the point of discharge where the larger, more dense particles settle. This settlement can result in an oversupply of organic materials that produce increased sediment oxygen demand which can result in anaerobic sediments where few or no organisms survive. The organisms that may require the use of symbiotic methanogenic bacteria for sustenance (for example, the clam *Solemya* sp.) can do well in these types of environments (Reid and Bernard 1980). *Capitella capitata* responds to sewage discharge and organic enrichment by greatly increased abundance (Reish 1957; Word 1979). In addition to these responses, there appears to be a gradient of response by other species to organic enrichment of the sediment that has similar attributes throughout the world (Turpaeva 1953; Reish 1970; Anger 1975 a,b; Pearson and Rosenberg 1978; Word et al. 1977; Word 1979; 1980 a,b, 1990; Dauer et al. 1981). At selected shelf environments, the area of effect at given community levels is predictable, given the total quantity of suspended solid material discharged to an environment on an annual basis (Mearns and Word 1982).

The responses of benthic communities to increasing deposits of organic material is well described, certain aspects are predictable, and observations reflect the experience of many community ecologists throughout

the world. The Puget Sound experience is generally not typical and reflects a new paradigm. That paradigm is that more-erosional environments do not readily allow the settlement of discharged particles. The communities of benthic organisms are not exposed to increasing quantities of settled organic material and, as a result, the communities of deposit-feeding invertebrates that have generally been expected around the discharge sites do not occur. The observations in parts of Puget Sound are that the communities of benthic invertebrates responding to discharges of organic materials into highly energetic environments are the suspension-feeding species (Thom et al. 1979; Comiskey et al. 1984; Word et al. 1984; Word 1990). The effects of these factors on those communities dominated by deposit-feeding organisms is not predicted by the Pearson and Rosenberg (1978) and Word (1979, 1980 a,b) models. The additional lack of obligate deposit-feeding species is consistent with the amelioration between deposit- and suspension-feeding communities that has been recognized for years (Rhoads and Young 1970).

In addition, there are also a number of major industrial centers located in small communities that discharge into freshwater close to estuaries, into the estuaries themselves, or directly into the ocean in fjords or the open shoreline. Predominant among these are the pulp and paper mills, and mining and smelting operations.

A growing number of fish farming operations contribute waste food and fish feces to the sea bed, and these have stimulated studies of their effects on the benthos. Balancing the needs of protecting the enclosures and providing adequate circulation beneath them is a significant issue.

BENTHIC COMMUNITY STUDIES

British Columbia

The Continental Shelf

In an account of the benthic ecology of the western Canadian continental shelf, Brinkhurst (1991) indicated that there was only one limited quantitative study of the whole open coast. The results of this study could be interpreted to show an effect on the benthos of local upwelling of oxygen-deficient water, and a difference between communities in sand and in silt.

Strait of Georgia

More work has been done in the enclosed waters than on the shelf. Exactly a decade ago, Levings, Foreman and Tunnicliffe (1983) reviewed the benthic ecology of the Strait of Georgia and contiguous fjords. Much of what follows is abstracted from that source, with references to additional recent work.

Some 88% of the shoreline of the Strait of Georgia is rocky, and studies have related community structure to zonation patterns established world-wide. There have been extensive studies of soft substrata in some of the estuaries, such as those of the Fraser, Nanaimo and Squamish Rivers. In the truly estuarine situations there are few taxa, but there is a rich fauna in the eelgrass beds. Most of the work has been descriptive, with very few adopting a systems approach. The large size of the area in contrast to the small population of marine scientists provides part of the reason. In the Strait of Georgia alone there are calculated to be 1245 km^2 of subtidal area <20 m depth. The taxonomic diversity of the area is illustrated by a study of this zone around Bath Island, where 300 species of algae and 600 species of benthos were found (the benthic data base at the Institute of Ocean Sciences includes more than 750 taxa from a wide variety of benthic habitats). Some early work in Satellite Channel is mentioned.

In the sublittoral (>20 m depth), Levings, Foreman and Tunnicliffe (1983) describe work at a station off Nanaimo, some in Burrard Inlet, and work associated with Ocean Dumping legislation at Point Grey off Vancouver (the primary Ocean Dumping site for that set of communities on the lower mainland of British Columbia). The megafauna found at 300 stations in the Strait of Georgia was mapped. Six communities were distinguished.

The general conclusion from this review of studies to 1983 was that major benthic communities have been established and described, but that there were very few investigations of productivity or benthic-pelagic coupling. There was even very little known correlation between the benthic biology of the area and the physical/chemical regime. Only five species were known to have secondary production data estimated.

In the decade since the review described above, a number of quantitative studies have been completed. Many of those, especially the studies from the Institute of

Ocean Sciences, suffer from the common problem of insufficient resources to permit more than duplication of benthic samples at each site, and no coordination with chemical and physical research programs.

Boundary Bay was surveyed in 1984 (Burd et al. 1987) in connection with a chemical spill in a small tributary of the bay. Two hundred taxa were found at fifteen sites. There was a clear difference between the fauna of the sandy substrata and that of the muddy substrata, but there was no evidence of any effect of the small spill on the fauna of the area. Baldwin and Lovvorn (in Press a,b) studied benthos in the bay in 1990–1992 in relation to bird feeding. In their study, changes in grain size and the low organic content of the sediments did not vary enough to affect the benthos. They described three zones, with the number and biomass of food items for birds being highest in the introduced Japanese eelgrass.

Introduced exotic animals and plants are having a profound impact on the communities of harbors in California and Oregon, and the same is probably true of the area of concern to this report. One such exotic introduction, this time from the Atlantic seaboard of either North America or Europe, is a small marine oligochaete, *Tubificoides benedii* (Tubificidae). The worm was recorded during a survey of Vancouver Harbour and Burrard Inlet in 1987 (Burd and Brinkhurst 1990a).

The survey was repeated in 1989 with concurrent toxicity and chemical analysis of the sediments (Cross and Brinkhurst 1991; Cross et al. unpub.). A gradient of impact in both the chemistry and benthic community structure was observed, but few positive toxicity responses were found. Benthic community structure was primarily controlled by habitat (sediment grain size) and only secondarily by chemical contamination, despite the long history of major industrial use of the harbour. There was a distinct odor to many of the sediment samples, but despite this, 221 taxa were found among the 20 stations investigated in 1989. Only at the innermost sites in Port Moody, where the circulation was minimal, were depauperate sites discovered in 1987. This provides another example of how the massive water circulation of this region leads to high assimilative capacity of the environment.

The statistical evaluation of these data from Vancouver Harbour is of interest. In the first study of 1987 data, cluster analyses with significance testing was used. Statistically significant clusters were found to be geographically coherent. The inner and eastern harbour sites were separated. Some significant linkages between the chemical and benthic community data were obtained, but the weakness of this study is that historical chemical data were used, and values were not available for every element at every station sampled for benthos. Contemporaneous chemical samples were available for the second survey. These were analyzed for 25 inorganic and 5 organic chemicals; eight toxicity tests were used. Principal Components Analysis (PCA) was employed to reduce the multidimensionality of the chemical, toxicological and biological data obtained in 1989, and subsequently to relate the observed spatial response patterns directly to the measured sediment levels for each of the chemical constituents. Significant correlations for cadmium (Cd), copper (Cu), silicon, PCBs, pentachlorophenols, PAHs and sediment volatile residue were documented for spatial changes in benthic community structure. Using linear regression techniques, the predicted benthic community response for levels of sediment Cu / Cd equivalent to those outlined in selected sediment quality criteria were obtained. Predicted spatial impacts (exceeding these criteria) were graphically portrayed on the 2-dimension PCA axes, and transferred directly to a geographic map of the study area. This study demonstrates the ability to relate benthic community studies to probable causes, a possibility that has often been challenged in the past.

Hecate Strait

The benthos of Hecate Strait was studied on three successive cruises between June 1985 and January 1986 (Burd and Brinkhurst 1987). Four different sites were sampled. Each maintained a distinct community, and each community was stable over time in that no statistically significant differences could be detected between data sets for individual sites. Considerable care in sampling and sorting samples provides data that do not reflect the usual criticism of lack of consistency over time. Depth, or some unknown depth-related factor, was most significant in determining community structure, followed by sediment silt content.

Fjords

The soft-substratum fauna of some of the fjords of the British Columbia coastline have been surveyed

qualitatively by taxonomists interested in the distribution of infaunal communities. Extensive quantitative surveys have been documented (Burd and Brinkhurst 1992) but the data have not been analyzed in any way. The surveys were supported by a few oxygen determinations, but no other physical/chemical data. They were designed to test for similarities between the benthic and earlier zooplankton data sets, and the known classification of fjords based on circulation pattern.

There have been a series of studies (1982, 1983, 1986, 1989) of the effects of mine tailings from a molybdenum mine in Alice Arm, near the northern border between Alaska and BC (Brinkhurst et al. 1987; Burd and Brinkhurst 1990b, and in prep.). These studies revealed a quite rapid recovery among the communities of sites closest to the mine. When various 'metrics', such as taxonomic richness and abundance, suggested complete recovery at these stations, multivariate methods were sensitive enough to reveal subtle differences between the colonizing fauna and the baseline community.

The fauna of the rocky substrata of many fjords and the coastal seamounts and hydrothermal vents has been investigated using the PISCES submersible (Levings et al. 1983).

Strait of Juan de Fuca

There has been considerable interest in the effect of the domestic sewage (community waste) effluent from the City of Victoria. The very high mixing rate of water off the Victoria waterfront has made it possible for the city to discharge primary (screened) sewage into the ocean. Historical studies have suggested very little impact of the various discharges, but there has been a history of protest at the exception to the general trend towards at least secondary sewage treatment in Canadian cities. The unusual conjunction of small size of population and very great assimilative capacity has not been seen by some critics as reason for avoiding treatment. Some contamination of beaches was acknowledged, and the outfalls have been largely consolidated at Macaulay Point and Clover Point and extended to 1,800 m and 1,154 m from shore respectively. Ellis et al. (1991) attempted to analyze old benthic data, using the clustering with significance testing described above for the Burrard Inlet study. As with all of these recent benthic studies, only paired samples rather than three to five replicates, were obtained, which limits the power of the analyses. The fauna at Macaulay Point in 1976 was diverse (383 species were found) and abundant, resembling that at the surrounding stations. Earlier surveys had indicated dominance by nematodes and polychaetes typical of sediments with high organic loading. A similar situation was found at the discharge site itself in 1986. It is harder to assess the situation at Clover Point because of the hard substratum there.

The situation was assessed again in 1991 and 1992 (EVS Consultants 1992; Cross 1992). Sediment chemistry, bioaccumulation by bivalves, and community structure were investigated. Few sites were investigated in these studies. None of the chemical analyses from 1991 indicated sediment concentrations at Macaulay Point above criteria set by Washington State and adopted by the Capital Region District of British Columbia. There were *Capitella* within 100 m of the outfall, but very low levels of impact all around the immediate area. No impact on the current-swept community at Clover Point was detected. A few more stations were sampled in 1992 than in 1991, but the area was still quite limited. Some mercury and 1,4 dichlorobenzene was found in the sediments at Macaulay Point, but no other significant levels of contaminants and no toxic effects were found. There was no evidence of uptake of chemicals at Clover Point. While there was a moderate impact within 100 m of the discharge at Macaulay Point, there was no evidence of this at 400 m, the next nearest sites.

Washington State

A comparison between sediment bioassays and macroinvertebrate structure was made for sites in Commencement Bay (Becker et al. 1990). Amphipod, oyster and Microtox assays were run. Both benthic structure and bioassay results were related to the level of contamination observed. All three bioassays performed well in situations where the benthic community was severely altered, but differences were observed in the ability to detect effects at sites with less structural change. Tiered application of both Microtox and oyster larvae improved the accuracy of detection of somewhat altered sites.

Central and southern Puget Sound was studied quarterly in 1979 (Malins et al. 1980). Analytical chemistry, fish and invertebrate pathology, fisheries ecology and benthic structure were determined. The benthic data

were used to calculate an infaunal trophic index (ITI). Organisms were categorized in four groups, with only 6 to 17 taxa per group (in contrast to the large overall numbers of taxa found in many studies described above). Total abundance, diversity, richness and evenness were used in this multimetric approach. Correlation coefficients, coefficients of determination, both simple and multiple, were employed. Multiple regression analysis was performed using backward stepwise selection to remove variables which did not contribute significantly to the regression equation when entered after all other variables. Forward stepwise regression was then run to produce the overall regression equation. The study was somewhat compromised by the discovery of contaminants in the sediments and organisms from the reference sites, but at lower levels than at non-reference sites. Tissue levels of contaminants generally reflected sediment levels from the same area, which is not always the case. Chlorinated hydrocarbon levels in fish and crustaceans were higher than in associated sediments. Species richness values among the benthic metrics used correlated best with sediment contamination levels, but the richness data consists of only those 48 taxa used to determine the ITI, many of which are identified to the family level. Only about 40 organisms were found in each 1,000 m^3. The assumption here, as in many such multimetric methods, is that all species in the higher taxon have equivalent ecological requirements unless exceptions are made (Capitellidae and *Capitella* itself appear in different categories in this study, for example).

Furthermore, wastes discharged to the marine environment provide additional dissolved and particulate-bound organic matter and contaminants. The settling characteristics of these particles, in conjunction with the physical characteristics of bottom topography and near-bottom currents, determine how the materials can come into contact with the indigenous communities of bottom organisms. Under more erosional conditions, the materials are maintained in suspension and captured by suspension-feeding organisms. If the environment is food limited, then the number of benthic suspension-feeding organisms that can be supported at that location will increase. If these organisms are tube dwellers or burrow constructors, then eddy currents may be created around their structures, which can allow additional settling and subsequent capturing of materials. This can also result in the increase of surface detrital feeders. Many of these species are able to switch between suspension and surface detrital feeding. Responses of this type have been observed around the discharge at West Point in Puget Sound (Comiskey et al. 1984; Word 1990).

Under more depositional conditions, particles will settle to the sea floor. The settlement of particles can change sediment characteristics. The change of sediment characteristics will occur if the rate of particle addition is faster than the rate in which particles can be incorporated into the sediment. The sediment then accumulates organic materials, and surface and subsurface deposit-feeding communities are able to occupy that environment and become more abundant while the suspension feeders are eliminated. In Puget Sound, these types of environments and discharge practices have been observed in embayments, such as near the Denny Way CSO in Elliott Bay (Armstrong et al. 1980; Comiskey et al. 1984), in areas surrounding pulp and paper mills in Commencement and Bellingham bays (Becker et al. 1990), deeper water environments of Seahurst Bay (Word et al. 1984), and constructed waterways, as in Commencement Bay (Becker et al. 1990).

TOXICOLOGY

Sediment toxicity bioassays were developed as a means of assessing the effects of sediment-derived contaminants on marine organisms. Bioassay organisms are often used as surrogate species to assess the potential toxicity of contaminants in sediments to benthic organisms in the environment. The presumption is that if the sediments are toxic to a select set of test organisms, then the sediments are considered likely to be toxic to selected species in benthic community. Swartz et al. (1985a), for example, found that there were significant increases in the concentration of most sediment contaminants and significant decreases in the richness and abundance of the benthos at stations where sediment was acutely toxic to amphipods along a pollution gradient from the Los Angeles County Sanitation District's sewer outfalls on the Palos Verdes shelf in California. Although organic enrichment and anaerobic sediment conditions contributed greatly to the observed effects, chemical contaminants were also believed to contribute to the observed effects. Similarly, EVS Consultants (1992) found that at the Macauley Point outfall near Victoria, British Columbia, the benthic community

near the outfall was different than the surrounding community. These changes were consistent with sediment bioassay tests where toxicity was found in sediments that were nearest the outfall. However, the predictive capability of sediment toxicity bioassay to reflect impacts of anthropogenic contaminants to benthic community structure still remains to be validated.

If these relationships can consistently be found, it is possible that, based on sediment toxicity bioassays, threshold levels of toxicity for a variety of anthropogenic contaminants in sediments may predict contaminant impacts on benthic communities. For example, Swartz et al. (1993) found that concentrations of DDT and its related metabolites in field-collected sediments were correlated with increased mortality of the amphipod *(Rhepoxynius abronius)* and with the disappearance of amphipods from the natural benthic communities. Using the same species, Plesha et al. (1988) reported that amphipods exposed to selected PAHs and PCBs, at environmentally relevant sediment concentrations, had significantly higher mortality rates compared to controls.

A variety of biological assays have been used to assess the toxicity of marine sediments in the Puget Sound/Georgia Basin region. For the most part, these studies focused on assessing the quality of sediments near urban centers in the Puget Sound region, such as in Commencement Bay near Tacoma (Williams et al. 1986; Pastorok and Becker 1990; Becker et al. 1990), Elliott Bay near Seattle (Pastorok and Becker 1990; Casillas et al. 1992), Eagle Harbor (Swartz et al. 1989), and Port Gardner near Everett. Similar studies were conducted in British Columbia, including Burrard Inlet near Vancouver (Swain and Nijam 1991) and Victoria Harbour near Victoria (EVS Consultants 1992; Chapman 1988). Bioassays have typically used a small but representative and established set of benthic organisms including various life stages (larval, juveniles, adults) of amphipods, polychaetes, and echinoderms (ASTM 1991; US EPA 1991; Casillas et al. 1992; Plesha et al. in press); and toxicity tests have been conducted on both bulk sediments or sediment elutriates using a variety of toxicity endpoints, including mortality, abnormal development and behavior, and impaired growth and reproduction.

The evidence to date indicates that sediments from urban environments in the Puget Sound/Georgia Basin region are generally toxic to representative infaunal members of the benthic community. If contaminants were being transported from these urban centers to areas outside their immediate influence, we would expect sediment toxicity to extend well beyond the sills of the bays around these coastal urban centers. However, the detection of such toxicity may require the use of more sensitive bioassay systems because the identification and regulation of contaminated sediments have principally relied on acute lethal sediment bioassays. Reliance on mortality as the single measure of toxicity can underestimate deleterious effects of xenobiotics. Therefore, bioassays employing sublethal adverse effects, such as growth inhibition or reproductive impairment, that provide more sensitive measures of the effects of contaminants may be needed to detect subtle increases in sediment toxicity resulting from transboundary transport.

It is difficult to distinguish the effects of toxicants and nutrients from the changes brought about by reduced competition from species lost as a result of toxicants. Toxic contaminants reduce the abundance of sensitive individuals, species, and populations. Toxicity can occur as a result of organisms being exposed to contaminants not only attached to sediment, but also present in interstitial water, attached to suspended or settled food materials, and contained in the water column that may be captured by suspension-feeding or during use of dissolved organic materials.

Benthic communities should retain the same overall community structure in terms of response to suspended or deposited particles, whether contaminants are present in the available food or not. Suspension feeders will not take over a deposit-feeding environment, nor will deposit feeders take over a suspension-feeding environment in the presence or absence of toxic materials. The influence of toxicants will remove the sensitive individuals, species, and populations from each of these generalized types of habitats. Therefore, the loss of individuals, species, and populations from each of these habitat types needs to be compared habitat by habitat, not by diversity, species richness, or overall abundance and biomass. The reduction of species or individuals from habitats as a result of toxic chemicals will need to be evaluated relative to an appropriate control environment. Comparing species richness or diversity within a deposit-feeding community to that within a suspension-feeding community is not appropriate.

What does this mean to benthic community studies at Macauley or Clover Point and throughout Puget Sound? Since the majority of these areas are energetic erosional environments, the typical scenario of the Pearson and Rosenberg organic enrichment model will not hold. Instead, the organic enrichment model of enhanced abundance of suspension-feeding communities is predicted. The influence of toxicants will be on sensitive organisms that will be absent from areas and communities where they are expected to occur. It is also probable that sediment bioassays will not predict the toxicant effects on benthic communities that are dominated by suspension-feeding invertebrates. The Puget Sound Models have the same types of species as found in the Straits of Juan de Fuca and can therefore be used for Canada. The lack of depositional enrichment and the absence of communities from the Pearson and Rosenberg Model does not indicate the lack of effects in the marine environment, nor that the environment rapidly assimilates the discharged materials. It only indicates that we need to look at new paradigms regarding the way benthic invertebrate communities respond to the ocean disposal of particulate matter. We also have to realize that sediment repositories of toxic contaminants are not the only route of exposure for benthic organisms. Suspension-feeding benthic organisms are also exposed to contaminants that remain suspended.

MONITORING NEEDS

In this section, we present some ideas concerning the needs of monitoring, and some of the current context for this. The arguments will not provide a blueprint for future studies, but may identify some factors to be weighed.

In a review of monitoring of Puget Sound, Chapman, Dexter, and Goldstein (1987) raised many important issues. Not all of the authors of this MS necessarily agree with all of the suggestions, but there is much food for thought. One essential suggestion is the need to acquire data that can be used well into the future. The data base will be needed to evaluate changes over time (trends) and to alert managers to developing problems. The authors of the proposal take a very wide view of monitoring. They tabulate eight objectives met by monitoring 29 variables! They include the need to understand the processes that control the area monitored (Puget Sound in their evaluation). This may call for sophisticated research-level studies of a multifactorial nature. While most scientists would enjoy being charged with performing such a study on a long-term basis, it is our experience that such investigations can lose focus on the applied purpose that provided the initial stimulus.

It is important for monitoring of marine systems to include chemistry and biology, and, in the present boundary waters situation, a good deal of physical oceanography to determine circulation patterns and deposition sites for suspended materials that may be transported over long distances. Symmetrical data matrices (measure all variables at all sites) will permit multivariate statistical testing of the data (see the following section).

Another significant issue is the line between scientific information and policy decisions. The former should be obtained without any regard to the political implications. The evaluation of scientific recommendations takes place in a political sphere in which scientific logic is not the only issue, and scientists should recognize that reality, painful though it seems. This point is elaborated in the following section.

Data Reduction and Presentation

There is an ongoing debate among monitoring agencies as to data reduction and the presentation of results to managers. On the one side, the proponents of the so-called multimetric approach believe that purely statistical treatment of data can produce false but statistically significant conclusions, as demonstrated by the use of randomly generated data sets. They also claim that biological information can be used to weight or reduce the data to a series of metric values (taxa abundance, richness, evenness, diversity, proportions of various taxonomic groups). There is an element of assumption in much of this, especially when the taxa are the very diverse but relatively poorly-known invertebrates (in contrast to the fewer and better-known birds and fish, for example). Multimetric values can be scaled to fit a consistent 1–10 rating. There seems to be a tendency in this development to ask the scientists to relieve the manager of his socio-economic and political responsibilities by making them determine the point along the scale used that represents 'acceptable' conditions. The question might well be: Acceptable for what purpose?

A reduction of complex data to a few geometric shapes was proposed by Chapman, Dexter, and Long (1987) in a paper dealing with synoptic measurement of chemistry, toxicity and community structure in San Francisco Bay. The use of such an approach can be generally supported, but the method of converting the data to triangular shapes calls for some interpretation when, in later versions, the areas of the triangles produced are used to classify sites. It might be instructive, for instance, to plot all measured parameters, even if ratio to reference has to be used (assuming good reference sites are available and are identified correctly). The resulting 'starburst' figure might indicate specific variables to test for causality, rather than suggesting that chemical contamination as a whole is high or low in respect to reference concentrations.

The use of the Apparent Effects Threshold (AET) approach for assessing sediment quality was addressed by the Science Advisory Board of the Environmental Protection Agency (EPA 1989). The conclusion was that the approach incorporates the net effect of complex factors such as the interactive effects of chemicals, unmeasured potentially adverse variables, matrix effects and bioavailability. AET cannot distinguish and quantify these, although it can be affected by them, but in the Puget Sound data set the results using this approach were relatively reliable. In the attached letter of submission, the Subcommittee suggested that AET not be used to generate broadly applicable sediment quality criteria, because of its site specific nature, its inability to describe cause and effect relationships, its lack of independent validation, and its inability to describe differences in bioavailability.

The advocates of multivariate methods claim that there is less data reduction and loss involved in looking for pattern in the data and then attempting to explain it. They believe that the many environmental factors and the infinite number of interspecific interactions among the fauna cannot be neatly dealt with by even the longest list of multimetrics. These scientists would agree that multimetrics may be better than reliance on single toxicity values, or simple indicators (certain species, or diversity indices used in isolation), but they mistrust the decisions about tolerance of taxa (often whole genera, families or even higher groups) to stress in general, or even stress reduced to few broad categories, such as organic chemicals, inorganic chemicals etc. The challenge to the multivariate statistical school is to render their data understandable to managers, though in many instances this can be done by representing results as maps of the study site with the significant data projected onto the sites. While there is a voluminous literature on these subjects, a current review in freshwater biology is actually quite relevant to marine biologists in regard to philosophy, statistical methods and other issues (Rosenberg and Resh 1993). No equivalent summary of marine benthic ecology in biomonitoring exists, though the review by Burd et al. (1990) examines data reduction methods for benthic infaunal studies.

ENVIRONMENTAL INITIATIVE QUESTIONS

Six questions were identified in relation to the purposes of the Environmental Cooperation Council. The responses in terms of the benthic community and toxicology are as follows:

1 & 2. Transport Mechanisms and Movement of Biological Resources

Most adult benthic organisms are relatively limited in the degree to which they move from one location to another, with the possible exception of some epibenthic forms and, of course, bottom-feeding fish. Planktonic phases may be distributed across geographic boundaries by oceanographic circulation, but it is unlikely that they would transport sufficient accumulated contaminants to create a significant input to food chains in non-source areas. The redistribution of fish and shellfish as adults or as marketed products should be determined by fishery biologists.

3. Invertebrate Populations

Benthic communities on both sides of the international boundary have been described, and relative abundances of taxa estimated. Differing methods make intercomparisons of data difficult. Some comparison between the benthic fauna of the Canadian continental shelf and that of Washington State and Puget Sound was made by Brinkhurst (1991). Most of the other benthic studies described above are site-specific. There is little reason to believe that there would be any significant differences in community structure in equivalent habitats on either side of the border. No long-term studies are available for the estimation of trends. Few studies have been

extended beyond a single visit. Repeated estimations of the benthos of the same sites were made by Brinkhurst et al. 1987, Burd and Brinkhurst 1987a, and Malins et al. 1980. In some instances, such as Vancouver Harbour, the fauna is surprisingly diverse for such an intensively industrialized area. There are areas in Port Moody that appear to be depauperate, and this is also true of the oldest and most industrialized port areas in Washington, such as Commencement Bay and Elliott Bay. The area around the Capital Regional District outfalls off Victoria are well populated beyond the immediate mixing zone.

4. Transboundary Pollution and Anthropogenic Effects

There is no evidence of transboundary pollution among benthic communities. Evidence for anthropogenic influences can be clearly demonstrated close to point source discharges and heavily industrial waterfronts wherever circulation is limited. Trend analysis is not possible in a quantitative sense. It may be possible to obtain information of an anecdotal nature based on the field experience of regional biologists.

5. Impact of Population Changes

There is a balance between population density and the assimilative capacity of its supporting ecosystems. The transboundary region of the Pacific Northwest is supporting a relatively small population within an area of active circulation in general. The major exception to this can be found in parts of Puget Sound. Continued population increase within the sheltered harbors will have to be linked with a sustainable environment concept if remediation efforts are not going to be overwhelmed. There may be sufficient chemical/physical data to develop mathematical models to examine this issue. Physical circulation models are already in existence.

6. Focus for Monitoring

Benthic long-term monitoring cannot cover the entire area. There will continue to be a need for site-specific studies, but some reference sites need to be monitored to provide bench marks (for ratio to reference calculations for variables, for example) and to monitor non-point source responses to factors such as global warming. Historical data should be examined in order to select stations representative of various levels of disturbance, from reference to grossly disturbed. Long-term monitoring of benthic community structure with adequate replication of samples should be established as part of the mandate of some organization that can guarantee continuity. Sample analysis should be complete enough to enable both multivariate and other data reduction techniques to be applied. The benthic community tends to integrate a great many stress variables. While precise experimental methods, such as toxicity tests, are very useful in monitoring for compliance to permits and for attempting to attribute cause to observed changes in structure, field observation provides direct evidence of the effect of management practices.

Data from an extensive set of benthic community samples across a wide range of reference and disturbed habitats need to be identified or created. These should be used to determine the best 'metrics' or indicators to use in the region, and to evaluate the possible use of multivariate statistical methods. This process has been followed by US EPA in developing indicators in the EMAP — Coastal and Estuarine Program.

In terms of transboundary transport of contaminants, oil spills are the most obvious candidates with historic evidence of the northward track of material from Washington State along the Canadian coastline in winter (Harding and Englar 1989). The reverse flow is established in summer. Littoral benthos is affected by oil spills, and a base line of pre-disturbance community structure should be derived from literature and filed sources and/or created for each habitat type in potentially exposed situations. Monitoring is not required.

Non-point source effects must be monitored from reference sites that are never likely to be exposed to disturbance. Benthic community structure is very useful in this regard because of the lack of mobility of the infauna, the ease of collecting quantitative samples, the extensive existing data bases, the appropriate longevity of many species (much longer than microorganisms and plankton, much shorter than vertebrates), and the richness of the fauna, which improves sensitivity.

Current monitoring practices in freshwater ecosystems include quantitative estimates of various habitat variables in a systematic manner. Such methods could easily be adopted in littoral habitat evaluations, but would be less relevant in open water situations in which oceanographic parameters will be more useful.

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DISCUSSION

Richard Beamish *(Panel)*: Could you elaborate on the basis on which you claimed that dumping at the Point Grey dump site was in fact slightly beneficial.

Ralph Brinkhurst: There were organisms living in solid chunks of masonry that wouldn't have been there, so the diversity of the structure of the environment went up, and therefore the diversity of the fauna. We put three dimensional structure onto that otherwise sandy area and the benthic studies suggested that you couldn't pick up much impact from the dumping. Of course there's all the transportal sediments from the river, but that was the fundamental basis.

Curtis Ebbesmeyer *(Panel)*: Ralph the impression that I have so far about the benthos in the Strait of Georgia is that it seems to be reasonably healthy, do you think that's a correct impression?

Ralph Brinkhurst: I think that our story fits in almost exactly with the sediment story as you would expect it to. The toxicology shows the hot spots, Commencement Bay, Elliott Bay, a little bit less in Vancouver Harbour, a good deal less in Victoria Harbour, and all the way up Portage Inlet. But for the most part, I think we're looking at pretty normal communities. One of the studies in Puget Sound did find there were contaminants mixed in, in what they thought were their reference areas.

Richard Beamish *(Panel)*: What about the Fraser River? I know that this is a little bit out of the marine environment, but still we're talking about a major contributor to the marine environment. What's the benthos like in the Fraser River? Is it more or less healthy too?

Ralph Brinkhurst: The area that Peter Chapman studied in the North Arm of the Fraser showed quite dramatic classical gross organic pollution syndrome. It's not a very huge patch, or it wasn't in those days, 15 or so years ago, but I would assume it's a lot better. That was the only study that I was involved in, and that's where I would expect the most trouble up in that short piece of the North Arm.

Curtis Ebbesmeyer *(Panel)*: I had a question about Fred Nichols data off West Point in Seattle. I had the impression that there was a burst of oceanic organisms that came in, that he monitored for his PhD thesis in the 60s, and then he saw it slowly die out. Has it been established that an oceanic burst of water can come in, put a population down in an area, and then it will slowly decay?

Ralph Brinkhurst: You've got potential for the recruitment because recruitment of plankton will depend on marine circulation. I imagine that you might well get things brought in that then have life cycles which involve them travelling out, or being drawn out and then actually not being brought back.

Peter Striplin *(Striplin Environmental Association, Olympia)*: There did appear to be a pulse of recruitment of one polychaete worm that appeared to settle just north of West Point, and that population slowly disappeared between 1975 and 1982. In 1989, when the Department of Ecology started its ambient monitoring program, that population had picked up again slightly, but not very much. It was pointed out that there has been a slow shift in the dominant mollusc at the deep subtidal stations. Pre-1982 the dominant mollusc north of West Point was *Macoma carlottensis* and then south of West Point it was more of another called *Axinopsida serricata.* Now it appears that *Macoma* is becoming dominant throughout the central basin of the Sound. So it looks like it is beginning to displace the smaller, shorter-lived bivalve in that habitat.

Ralph Brinkhurst *(Panel)*: There is no question of that being an exotic introduction I presume, I'm not familiar with them. That's the other thing that we wanted to mention. I know an example right in Vancouver Harbour where the dominant pollution tubificid of the Atlantic coast of Europe and North America is now in Burrard Inlet, and a few introductions like that could play havoc with the natural fauna and disturb communities all over the place.

Bill Austin *(Khoyatan Marine Lab, Cowichan Bay)*: I'm a little concerned about the sense that the benthos is healthy, because I'm not convinced that we necessarily know enough without those longitudinal studies. Do you have any sense that at least around the edges there's been a lot more work done in Washington, at least in getting an initial baseline of fauna,

than there has up here, and also that the studies that EPA has mandated be done in sufficient detail that we have some confidence in the taxonomy. Do you have any feeling one way or the other on how we're doing that way?

Ralph Brinkhurst *(Panel)*: I wouldn't be an accurate source, I feel the US studies on the east coast are much more extensive than anything I know on the Canadian side. I think there are relatively fewer of us of course involved in benthic studies in Canada, and not a whole lot of work in the West, but when we did the shelf work it was obvious that there was very little comparable either to the north or to the south. So I don't know whether that is true in general. There's probably a higher density of marine benthic biologists on the southern side, which partly accounts for that.

Your comment about changes in the fauna could well be important, but this comes to the big gap between science and policy. Are we going to put up with a 50% change? People have wreaked so much havoc around the world, what are we looking at? There's nothing on land or in freshwater that's natural or not human-affected. If we've got a viable ecology, that's maybe all we can hope for with the population we're trying to sustain on this planet. So what is it we are trying to do? I don't imagine we're going to be able to manage the virginal conditions of the benthos of the West Coast, but I think we are going to have to live with that.

The Present and Future for Molluscan Shellfish Resources in the Strait of Georgia-Puget Sound-Juan de Fuca Strait Areas

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ABSTRACT

Invertebrates, particularly molluscan shellfish, are a valuable and widely utilized resource in the Puget Sound-Juan de Fuca Strait-Strait of Georgia area. In the Puget Sound-Strait of Georgia area they support a valuable multimillion dollar industry that provides employment to several thousand people. In addition they are used extensively in the native food and recreational fisheries. A major advantage of molluscan shellfish, particularly bivalves, compared to many other fishery resources, is that they can be cultured (farmed) thus adding substantially to their economic potential. Culture operations exist and are developing for several species of bivalves, including oysters, clams, mussels and scallops, in the Puget Sound-Strait of Georgia area. We briefly describe fisheries for natural bivalve stocks and the various culture operations, and summarize the effects that natural forces have had on trends in the industry. Bivalve resources and culture operations are currently facing many problems that either curtail existing utilization or prohibit expansion of operations in both Puget Sound and the Strait of Georgia. The major problem in both areas is an expanding human population that brings many associated problems with it, such as pollution and multiple use conflicts. Problems for both areas are similar but those in one area do not appear to affect the other area. The present and potential for the resource and the industry are assessed and solutions to problems are discussed.

INTRODUCTION

Marine invertebrate resources, which include crustaceans, echinoderms and molluscs, have long been important to people on the west coast of North America. A wide range of species have been utilized, however molluscan shellfish have been of major importance (Quayle and Bourne 1972; Ketchen et al. 1983; Schink et al. 1983; Jamieson and Francis 1986; Cheney and Mumford 1986). Molluscan resources not only provided food for native people but they were used as money and jewelry. Molluscs were used extensively by early white settlers, and in the 19th century these resources began to support commercial fisheries which continue today. Landings in these fisheries are small when compared to total west coast fisheries landings but they are important to the economies of many coastal communities. In addition, molluscs are utilized extensively in the native food and recreational fisheries. It is important that our molluscan resources continue to be managed with considerable skill if we are to obtain optimum benefit from them.

In the following the current status of molluscan shellfish resources in the Puget Sound-Juan de Fuca Strait-Strait of Georgia areas is examined briefly, trends in fisheries discussed, current and future problems for the resource described and possible solutions to these problems given. It is hoped that this discussion will assist managers to maintain the resource in a healthy state so that it can be utilized in perpetuity to provide optimum benefit to all people.

DESCRIPTION OF THE AREA

The areas under consideration in this paper will undoubtedly be described more completely and accurately in other papers in this symposium. Here the following descriptions are used.

Puget Sound is that body of water southward from a line drawn between Port Townsend and Bellingham and includes South Sound and Hood Canal. The southern part of the Sound generally has warmer surface water temperatures in summer and lower salinities, 28–29 ppt, compared to those in the northern part where salinities may be as high as 30–31 ppt.

Juan de Fuca Strait is the body of water from the Cape Flattery-Port Renfrew area eastward to the mainland and northward to the international boundary and includes the San Juan Islands. It generally has cooler surface water temperatures and higher salinities than the other two areas.

Strait of Georgia is the body of water between Vancouver Island and the mainland from the international boundary north to the Seymour Narrows-Yuculta Rapids area. Like Puget Sound, it generally has warmer surface water temperatures and lower salinities during summer than the Juan de Fuca Strait area.

There are two bodies of water, Puget Sound and the Strait of Georgia that have similar marine environments separated by Juan de Fuca Strait.

THE RESOURCE

Commercial fisheries for marine invertebrates in this area include those for Echinoderms, Crustaceans and Molluscs (Table 1).

Echinoderm resources support valuable commercial fisheries that have developed in the last twenty years for red sea urchins *(Strongylocentrotus franciscanus)*, green sea urchins *(S. droebachiensis)*, and sea cucumbers *(Parastichopus californicus)* (Table 1).

Crustacean resources support valuable commercial fisheries for one species of crab, Dungeness crab *(Cancer magister)*, and six species of shrimp, sidestripe *(Pandalopsis dispar)*, pink *(Pandalus borealis)*, smooth pink *(P. jordani)*, coonstripe *(P. danae)*, humpback *(P. hypsinotus)*, and prawn *(P. platyceros)* (Table 1).

Commercial fisheries for these species are important in the region, however for brevity only molluscan resources and fisheries in the classes Cephalopoda, Gastropoda and Bivalvia are considered in the following. Emphasis is on bivalves since they support the largest fisheries in the three areas (Table 1). Of the three areas, commercially important molluscan resources occur primarily in Puget Sound and the Strait of Georgia and most of the following discussion is focused on these two areas.

Cephalopods include squid and octopus. Harvest in commercial fisheries in all three areas has been minor (Jamieson and Francis 1986; Cheney and Mumford 1986).

There is no directed commercial fishery for squid in the three areas, landings are mostly from by-catches in other fisheries. Squid are used to some extent in the recreational fishery. Opal squid *(Loligo opalescens)* resources supported an extensive recreational fishery in central Puget Sound in 1993. Total commercial landings for the three areas were under 100 tonnes in 1992.

Only one species of octopus, *Octopus dofleini*, is used commercially and it is generally caught as a by-catch in other fisheries. There was a small trap fishery in the Juan de Fuca Strait area (Cheney and Mumford 1986). Commercial landings in Washington were under 30 tonnes in 1991 and 1992. A small directed dive fishery occurs in the Strait of Georgia but landings have been small, total British Columbia landings were 131 and 102 tonnes in 1991 and 1992 respectively (Table 1).

Although stocks of cephalopods in the region are probably fairly extensive, landings in commercial fisheries are not expected to increase significantly until improved technology for detecting and catching them is developed.

Gastropods comprise the largest number of molluscan species along the coast (Bernard 1967) and include the snails. Several species of snails may be used in the native food and recreational fisheries. The only gastropod harvested commercially was the northern abalone *(Haliotis kamtschatkana)*, but the fishery was small. Minor landings occurred in Juan de Fuca Strait, particularly in the recreational fishery in the San Juan Islands (Cheney and Mumford 1986; Sloan and Breen 1988). Recent studies indicate northern abalone populations are much reduced in the San Juan Islands area and landings are minor. All British Columbia fisheries for abalone were closed 1991 (Table 1).

Bivalves include oysters, clams, mussels and scallops and are the most important molluscan resource in com-

mercial and recreational fisheries in the three areas, providing about 95% of molluscan landings. There are extensive oyster and clam industries in Puget Sound and the Strait of Georgia, and minor fisheries for mussels and scallops. Small landings of bivalves occur in Juan de Fuca Strait.

The oyster industry in Puget Sound and the Strait of Georgia is based almost entirely on culture of one species, the Pacific oyster *(Crassostrea gigas)* although some culture of the native Olympic oyster *(Ostrea conchaphila [lurida])* continues in south Puget Sound (Beattie et al. 1983; Quayle 1988). Oyster landings in both areas have tended to remain steady or increase slightly during the past ten years (Table 1). Current landings are about 30,000 tonnes in Washington, of which almost half are from Puget Sound and 4,000–5,000 tonnes in British Columbia, of which about 80% is from the Strait of Georgia. Increased culture efforts will be required to increase oyster landings in both areas.

The clam industries in both Puget Sound and Strait of Georgia include harvest of intertidal and subtidal resources (Table 1). The most important intertidal species is the manila clam *(Tapes philippinarum)* followed by the littleneck *(Protothaca staminea)*, butter

TABLE 1

Landings of molluscan shellfish in metric tonnes whole weight in commercial fisheries in Washington and British Columbia, 1991 and 1992

	Washington State		*British Columbia*	
Species	*1991*	*1992*	*1991*	*1992*
Echinoderms				
Red sea urchin	2,723	83	6,945	12,018
Green sea urchin	83	120	607	984
Sea cucumber	1,880	1,735	490	455
Crustaceans				
Dungeness crab	2,696	6,986	1,887	3,300
Shrimp	4,664	5,653	3,265	2,250
Prawn	22	19	961	1,042
Molluscs				
Cephalopods				
Octopus	16	28	131	102
Squid	Tr	Tr	116	93
Gastropods				
Abalone	0	0	0	0
Bivalves				
Oysters:				
Pacific	31,600	25,400	4,482	5,000
Olympic	Tr	Tr	0	0
Manila clam	1,962	1,569	1,151	1,139
Littleneck clam	304	257	201	116
Butter clam	Tr	Tr	42	132
Mixed	0	0	137	107
Cockles	0	Tr	0	0
Soft-shell clam	32	34	0	0
Geoduck	1,523	788	3,333	2,864
Horse clam	Tr	2	110	2
Mussel	268	364	0	0
Scallops:				
Scallop sp	0	49	0	0
Pink and spiny	24	12	82	89

(Saxidomus giganteus), with minor landings of cockles *(Clinocardium nuttallii)* and soft-shell clams *(Mya arenaria)*. Landings of manila clams peaked in the mid 1980s and have declined since, partly because accumulated stocks were harvested, but in 1991 and 1992 landings were still over 1,500 tonnes in Washington and over 1,000 tonnes in British Columbia. Most (about 75%) of these landings were from the Puget Sound-Strait of Georgia area. Landings from natural fisheries are probably at their maximum production but they might begin to increase as culture operations for this species become widespread. Landings of littlenecks were approximately 200–300 tonnes in both areas in 1991 and 1992. Landings of butter clams have been generally under 100 tonnes in recent years.

The main subtidal clam species harvested is the geoduck *(Panope abrupta)* with minor landings of two species of horse clams, *Tresus capax* and *T. nuttallii.* Landings of geoducks in both areas have remained steady or declined slightly in the past ten years because of management policies. Landings are expected to remain reasonably steady because of these policies. All Washington landings were from Puget Sound and about 10–15% of British Columbia landings were from the Strait of Georgia.

Some harvest of wild stocks of blue mussels *(Mytilus edulis)* has occurred in all three areas, but recent production has resulted from culture operations, almost entirely in Puget Sound. Annual landings were 230 and 314 tonnes in 1991 and 1992 in Puget Sound. Landings could increase as culture operations for the strain *M. edulis galoprovincialis* become more widespread.

In the past ten years small fisheries for two species of scallops, spiny *(Chlamys hastata)* and pink *(C. rubida)* have developed in all three areas. Total landings have been under 100 tonnes for all three areas (Table 1). Landings could increase as culture operations become established.

A major advantage of many bivalves is that they lend themselves to culture operations. Virtually the entire oyster industry in both areas is a culture operation and culture industries are developing for manila clams, scallops and mussels (Skidmore and Chew 1985; Quayle 1988; Bourne et al. 1989; Toba et al. 1992).

In addition to landings in the commercial fishery there are extensive landings in the recreational fishery. Estimates in Washington show that over 1,000 tonnes of clams were landed annually in the recreational fishery, and in British Columbia it was estimated that over 30,000 people harvest clams annually in a similar fishery (Schink et al. 1983; Bourne et al. 1987). This represents a considerable fishery and it will probably increase as more people with more free time move into the area.

Generally, landings of molluscan shellfish in the Puget Sound-Strait of Georgia area have been high in the past ten years and production could remain stable or increase if sound management policies are followed, and culture operations become more intensive and widespread. However, this is dependent on further closures of harvesting areas because of pollution. There does not appear to be any trend to increased or decreased populations because of changing natural environmental factors such as global warming although there are periodic fluctuations in populations caused by phenomenon such as El Niño. These may periodically produce above-average breedings and hence larger year-classes of some species.

IMPLICATIONS OF MOLLUSCAN BIOLOGY TO TRANSBOUNDARY PROBLEMS

An understanding of some of the basic biology of molluscs is necessary in order to assess implications of anthropogenic and transboundary problems to the resource. The biology of all three groups of molluscs has been well described and only information pertinent to the discussion here is considered (Yonge and Thompson 1976).

Cephalopods have a larval stage that is planktonic (Hartwick 1973; Jamieson and Francis 1986). Adult squid and octopus can swim, particularly squid. Whether there is significant movement of adult squid populations between Puget Sound and the Strait of Georgia is unknown but it is believed that populations in both areas are discrete. There may be movement of populations between Juan de Fuca Strait and Puget Sound, and Juan de Fuca Strait and the Strait of Georgia, but again this is unknown.

Most gastropods have a larval stage that may or may not be planktonic. The northern abalone has a planktonic larval stage that has a duration of about seven days (Sloan and Breen 1988). Whether abalone larvae are

transported long distances is unknown, but recent evidence suggests it may be limited (Prince et al. 1987). There may be limited movement of abalone larvae within the Juan de Fuca Strait area and between there and the northern part of Puget Sound and southern Strait of Georgia, but probably little if any occurs between Puget Sound and the Strait of Georgia. Although adult abalone can move, actual distances covered are limited and there would be no movement of abalone between the three areas after the juvenile stage was attained (Sloan and Breen 1988).

Bivalves have planktonic larval stages that can last for as long as five weeks. During this time larvae can be transported considerable distances, at least 70 km (Quayle and Bourne 1972). It is believed movement of bivalve larvae from Puget Sound to the Strait of Georgia or the reverse is slight, although there could be limited movement between Juan de Fuca Strait and either Puget Sound or the Strait of Georgia. Late juvenile and adult stages of most bivalves are sedentary and there is virtually no natural movement of bivalves after the late juvenile stage. Most bivalves remain in the immediate area where larvae settled and are unable to move to avoid deleterious conditions.

Bivalves are filter-feeders. Water is pumped into the body and sieved through the gills which remove food and pass it forward to the mouth. Bivalves are efficient filter-feeders and can remove toxic phytoplankters, bacteria and viruses from the water. When such conditions occur they become unfit for human consumption.

IMPACT OF MOVEMENT BY NATURAL FORCES

Molluscan species, particularly those of commercial importance, are similar in the Puget Sound and Strait of Georgia areas, populations have developed over past years. However, there are differences in characteristics of some populations in the two areas; e.g. the Olympic oyster *(O. conchaphila)* has never been as abundant in the Strait of Georgia area as in Puget Sound; growth of manila clams is faster in Puget Sound than in the Strait of Georgia; densities of manila clams are higher in Puget Sound than in the strait (Quayle 1988; Quayle and Bourne 1972; Toba et al. 1992).

The general conclusion from molluscan studies in this region is that there are two bodies of water, Puget Sound and the Strait of Georgia, separated by Juan de Fuca Strait. Populations of invertebrates such as sea urchins, sea cucumbers and abalone may form one large stock with local variations in the Juan de Fuca Strait area. However, probably little natural exchange occurs between molluscan populations in Puget Sound and the Strait of Georgia. Exchange between Juan de Fuca Strait and either Puget Sound or the Strait of Georgia is more important than exchange between Puget Sound and the Strait of Georgia. Exchange of water in the northern part of the Strait of Georgia is from the north and hence waters in this area would be little affected by waters in Puget Sound or Juan de Fuca Strait.

Both the Puget Sound and the Strait of Georgia areas have warm surface water temperatures in summer when most breeding occurs and are separated by the colder waters of Juan de Fuca Strait. There may be a slight exchange between areas such as Boundary Bay and either Puget Sound or the Strait of Georgia, but it is believed that Juan de Fuca Strait acts as a barrier to the free natural exchange of molluscan populations in the two areas. There is evidence to support this hypothesis.

The so called 'summer disease' was common in Pacific oysters *(C. gigas)* in Puget Sound from 1960–1980s but unknown in the Strait of Georgia. No pathogen was identified for these mortalities and it may have been related to physiological stress during the reproductive cycle. 'Denman disease' occurs in Pacific oysters in the Strait of Georgia but has not been reported in Puget Sound. The relic population of eastern oysters *(Crassostrea virginica)* found in Boundary Bay has never spread from there into either Puget Sound or the Strait of Georgia in spite of numerous warm summers that would promote general breeding.

Additional evidence for the lack of exchange between molluscan populations in Puget Sound and the Strait of Georgia is seen in the distribution of two exotics that were introduced into both areas from Japan, the Pacific oyster *(C. gigas)* and the manila clam *(T. philippinarum)* (Quayle 1964). Although both species have planktonic larval stages, it is believed that spread of both species in the two areas was from deliberate plantings in each area and not from one area to the other. Even spread of both species along the west coast of Vancouver Island is not believed to have been from either Puget Sound or Strait of Georgia populations via

Juan de Fuca Strait but from intentional plantings in areas such as Barkley Sound (Bourne 1979, 1982).

Paralytic shellfish poisoning (PSP) has not been a major problem in bivalves in the Strait of Georgia but it has become a problem in Puget Sound where it now occurs south of the Tacoma Narrows (Quayle 1972; Nishitani and Chew 1984). The causative organism, *Alexandra (Protogonyaulax) catenella*, probably did not spread from Puget Sound to the Strait of Georgia or the reverse. The principle documented spread, especially into Central Puget Sound, occurred in 1978, and contributes to regular PSP outbreaks now. This was a major phenomenon where optimal climatic conditions and rainfall spawned record mussel toxicity levels in Saratoga Passage, and spread throughout Central Puget Sound and north into Juan de Fuca Strait (Nakatani and Chew 1984).

There are examples of the natural dispersal of some species across this boundary, e.g. soft-shell clam *(Mya arenaria)* which is found in soft substrate high in the intertidal zone in both areas. This species spread northward, probably from the San Francisco area in the late 19th century, through Oregon and Washington, across to British Columbia and up the coast to southern Alaska (Quayle 1964). This points out the fact that any introduction of an exotic must be carefully considered since it could possibly spread along much of the coast and impact other areas.

ANTHROPOGENIC EFFECTS ON MOLLUSCAN RESOURCES

There has always been great transport of bivalves between the Strait of Georgia and Puget Sound since commercial shellfish industries began in Washington and British Columbia. This involved mainly oysters and clams but probably has included abalone, scallops and mussels. Live adults, juveniles (seed) and dead shell, which was used as substrate for setting Pacific oyster larvae (cultch), have been involved in these transfers. Much of this movement has stopped in the past five years because of the introduction of Transplant Regulations on both sides of the border. However, considerable movement of molluscs continues. At present much of the oyster and manila clam seed (juveniles) used in the British Columbia industry, which is centered in the Strait of Georgia, is from hatcheries and nurseries in the U.S., mainly in the State of Washington.

Any damage that human transport caused to molluscan stocks was probably done years ago and the effects have manifested themselves in various populations.

A major impact on molluscan stocks in Puget Sound and the Strait of Georgia occurred when Pacific oysters were introduced to both areas along with the accidental introduction of manila clams. These stocks came from the same area of Japan, Miyagi Prefecture, and spread quickly in both Puget Sound and the Strait of Georgia. Both species appear to have had little deleterious affect on native stocks (Bourne 1979; Chew 1979). Introduction of the Pacific oyster was not responsible for the demise of the Olympic oyster *(O. conchaphila)* but actually revived the oyster industry in both areas. Manila clams have inhabited an ecological niche that was not occupied or dominated prior to the accidental introduction and are now the most valuable intertidal clam species in both areas.

Some pests and diseases were imported to both areas along with oyster seed — e.g. Japanese oyster drill *(C. inornatum)*, nuisance seaweed *(Sargassum muticum)*, predator flatworm *(Pseudostylochus ostreophagus)*, parasitic copepod *(M. orientalis)*, and the wood borer, *Lignorum tripunctata*. However, the presence of these organisms in Puget Sound and the Strait of Georgia is due to direct imports into each area and not from dispersal from one area to another. Transplant regulations, designed to prevent further spread of these pests and diseases are now in place, although much of the damage has been done already.

The intentional introduction of Pacific oysters and accidental introduction of manila clams is now regarded as being beneficial to the industry and the local area. With modern knowledge and technology, such as hatcheries and use of quarantine facilities, it would be possible to carry out these introductions without the negative effects of the introduction and this should be followed in the future.

Other anthropogenic forces have probably caused some effects on bivalve populations in the two areas because of movement between the areas.

- There is considerable commercial shipping (freighters, liners, tug boats, barges) between the two areas. This could lead to transfer of some organisms through attachment on hulls. Recent work has shown that larval and spore stages of several organisms can

be transferred great distances in ballast waters. It could be important in the spread of pests or diseases.

- There is considerable movement of fish boats between the two areas which could lead to direct transfer of organisms between regions.
- There has been considerable movement of logs by logbooms along the coast that may have affected local populations of the wood boring mollusc, *Bankia setacea.*
- Considerable pleasure boat traffic occurs between the two areas and could result in transfer of organisms either through deliberate or inadvertent transfer. It is believed the wood borer, *Toredo navalis,* was introduced into Pendrell Sound in the Strait of Georgia by pleasure boats from the United States (Quayle 1992). Adult wood borers that were present in the hulls of boats spawned while the boats were in Pendrell Sound and a population of *T. navalis* became established there.
- Another anthropogenic factor that might be of local importance is the deliberate or inadvertent transfer of organisms from one area to another by industry, scientists, local residents or tourists.

AQUACULTURE

A great advantage of molluscs, particularly bivalves, when compared to other organisms is that many species can be cultured or farmed. Methods are well-established and indeed much of the world's oyster, clam, mussel and scallop production is from culture operations (Quayle 1988; Manzi and Castagna 1989; Shumway 1991; Lutz 1980).

Bivalve culture is important in Puget Sound and the Strait of Georgia and it is becoming more so in both areas. Culture has many advantages over harvest of wild stocks: an individual owns the area and strives to improve the crop, production per unit area can be greatly increased, mortalities can be controlled, quality and marketing can be improved, and returns to the industry increased.

Both Puget Sound and the Strait of Georgia areas are ideal environments for molluscan culture. These are protected waters that are productive, temperate and relatively clean. Seed (juveniles of certain commercial bivalves) and labour are available and both areas are close to markets.

The oyster industry in both areas is essentially a culture operation. Seed is obtained naturally or from hatcheries, grown to market size by different methods and harvested (Quayle 1988; Cheney and Mumford 1986). Manila clam culture is developing in both areas (Toba et al. 1992). It is estimated that about 25% of manila clam production from both areas is from some type of culture. With the introduction of the blue mussel strain, *M. edulis galoprovincialis,* renewed efforts are being made to culture mussels (Skidmore and Chew 1985). Culture of the introduced Japanese scallop, *Patinopecten yessoensis,* is developing in the Strait of Georgia and interest exists to culture rock scallops, *Crassadoma gigantea,* in the Puget Sound area (Bourne et al. 1989). There are even attempts to culture geoducks and abalone, although more research and development will be required before these operations become commercially successful.

In Puget Sound most oyster and clam culture is undertaken in intertidal areas that are privately owned. Subtidal and floating culture is undertaken in areas that are leased from the State. In British Columbia all intertidal and subtidal areas are owned by the government and both intertidal and floating culture is undertaken in areas that are leased from the Province.

Bivalve hatcheries exist in both areas that are capable of producing seed (Pacific oyster and manila clam and, to a lesser extent, blue mussels) to meet requirements of the present and an expanded molluscan culture industry. To date these hatcheries have not only supplied seed but they have permitted development of new techniques to improve the industry, e.g. triploidy of oysters (Allen et al. 1989). These hatcheries can be used to develop selected broodstock lines that could lead to even greater benefits to the industry.

Molluscan culture industries are important and could be greatly expanded, which would provide revenue to local economies and much-needed employment. In the next decade a major portion of bivalve landings in both areas will probably be from culture operations. It is not unreasonable to predict that production could be increased two- to three-fold in both areas over the next decade if progressive culture methodologies were adopted. Technology is available, areas for culture are

ideal, and markets exist that could be greatly expanded. Every encouragement should be given to ensure that mollusc culture is successful and becomes a major industry in both areas in the future.

PROBLEMS FOR THE MOLLUSCAN INDUSTRY

The molluscan shellfish industry in the Puget Sound and Strait of Georgia areas faces critical problems that affect its current status and future development. If production is to remain at current levels or expand to meet its potential, these problems must be faced and solved.

The intertidal clam fishery, particularly the fishery for steamer clams, has enjoyed a period of high landings because of strong market demand. This has lead to great increases in effort and there is the concern of overharvest in some areas.

The major concern is the increasing human population with associated problems. The general area is becoming known as an ideal place to live and people are moving there to take up residence, seek employment or initiate new industries. Further, the area is widely advertised as an ideal vacation location and this attracts great numbers of people. This influx of people has and will continue to lead to conflicts with molluscan shellfish resources and the industry.

Pollution

Pollution is a major problem and can be industrial, agricultural or domestic. Two things should be kept in mind when considering the effects of pollution on molluscs: 1) bivalves are efficient filter feeders and can filter bacteria and viruses from the water, and 2) after larvae settle, most bivalves are sedentary and cannot move to avoid deleterious situations.

Industrial pollution can be lethal or can cause sublethal effects to bivalves through stress. The pollution may arise from direct discharge at industrial sites or through municipal sewage systems. Molluscs are either killed outright or they become stressed and may die from secondary causes. They also become unfit for human consumption. Pulp mills are one of the major problems and have caused closure of some areas to harvesting. The effects of industrial pollution are local and it is not believed that industrial pollution in Puget Sound causes problems in the Strait of Georgia or the reverse.

Agriculture Pollution results from runoff from upland areas, particularly agricultural land. This runoff carries bacteria and viruses which are accumulated by bivalves, making them unfit for human consumption because of high fecal counts. An example of such pollution is Boundary Bay, which was once a major oyster-producing area and is now closed because of runoff from the upland agricultural area. Again it is believed that effects of agriculture pollution are local and situations in one area do not affect another area.

Domestic Pollution makes bivalves unsuitable for human consumption because of high fecal counts. It can arise from several sources including municipal sewage discharge, faulty septic tanks or discharge from boats. Bivalves filter bacteria and viruses from the polluted water and accumulate them in the gut. In the Strait of Georgia nearly 100 areas are closed to harvest of shellfish because of sewage pollution. In Puget Sound over 30% of shellfish-growing areas have been classified downward to 'conditional' or 'restricted' because of such pollution. Even in areas with strong currents, domestic pollution can cause closures, for example, the Brotchie Ledge-Constance Bank area in Juan de Fuca Strait was closed to scallop fishing because of high fecal contamination. Again, sewage pollution problems are probably local and it is believed there are no transboundary effects to shellfish resources between Puget Sound and the Strait of Georgia.

Although pollution probably does not cause transboundary problems to shellfish resources the effects of industrial, agricultural and domestic pollution are similar in both the Puget Sound and Strait of Georgia areas and cause serious problems to the molluscan shellfish industry. Solutions to the problem will undoubtedly be the same in both areas. Pollution must be controlled and corrected if shellfish industries are to survive and prosper in both areas.

Oil Spills are another form of pollution that can affect bivalves. They appear to be inevitable to some degree since our economy requires oil and oil products, and much of this is transported by tankers and barges. To date minor oil spills in Puget Sound, Juan de Fuca Strait and the Strait of Georgia have caused local damage to shellfish. Spills in Puget Sound have not affected molluscan resources in the Strait of Georgia and vice versa because of the separation of the two bodies of water. Major spills in Juan de Fuca would

probably affect molluscan resources there as well as some bivalve resources in either or both of the Strait of Georgia and Puget Sound.

Multiple Resource Conflicts

Multiple resource conflicts are becoming a major problem for the shellfish industry in both the Puget Sound and Strait of Georgia areas. The influx of people into the Puget Sound-Juan de Fuca Strait-Strait of Georgia area is placing greater stress on molluscan resources. More people have more free time and recreational activities for these people include visiting beaches, collecting oysters and digging clams. The problem is compounded by increasing numbers of tourists. Conflicts between recreational harvesters and the commercial industry, either for wild harvest or aquaculture are increasing. Increased recreational harvest will lead to overharvest of resources in some areas. To alleviate this situation, some areas have been removed from the wild fishery and set aside for the recreational fishery in both Puget Sound and the Strait of Georgia. As human populations increase consideration will probably be given to removing more and more areas from the commercial wild harvest and assigning them to the recreational fishery.

Recreational activities can severely impact bivalve aquaculture operations. People believe they have free access to beaches and they do not like to see a favourite beach removed from their use by aquaculture operations. However, if bivalve aquaculture is to succeed, farmers must have complete control over their beaches and be able to restrict use and even trespass in these areas.

It must be remembered that the amount of intertidal area suitable for bivalves is limited in both Puget Sound and the Strait of Georgia. Quayle (1988) estimated there were only 1,000 hectares of good intertidal area suitable for oyster culture in the southern part of British Columbia. Intertidal areas are in demand from many user-groups and they must be managed with great care if we are to obtain the maximum benefit from them, including culture of bivalves.

Another serious problem for the culture industry is that it is becoming difficult, if not impossible, to obtain new areas, particularly intertidal areas, for bivalve culture operations (Beattie et al. 1983). If the industry is to expand and become a significant factor in the economy, every encouragement must be given to culture operations, and this will include a guarantee of sole right to people in the industry to undertake culture activities in prescribed areas. Conflicts can be alleviated to some extent by using different culture methods, for example, floating culture for oysters, as is used extensively in Japan and Korea (Quayle 1988). However, intertidal areas are still required for some oyster and clam culture operations. Further, obtaining areas for off-bottom culture is becoming difficult because of other user conflicts. People do not wish to have aquaculture facilities in front of their property or such sites interfere with other activities such as recreational boating, fishing, etc.

THE FUTURE

Bivalve resources, fisheries and culture face serious problems in both Puget Sound and the Strait of Georgia. Although problems in one area do not significantly impact the other area, the problems are the same and solutions will be similar. These problems must be dealt with adequately if the shellfish industry is to survive and attain its full potential. As we have seen the fisheries are small when compared to total fishery landings and it is important that authorities not overlook them because of their size nor succumb to pressures from recreational harvesters or upland owners to close areas to the commercial fishery. Solutions will be varied and could include a number of approaches:

1. Continue with the status quo and gradually allow the shellfish industry to decline. This is an unacceptable solution since it is morally incorrect; further shellfish resources are valuable and contribute significantly to local economies. It is imperative to preserve and develop shellfish resources for the benefit of all residents of the area.

2. Encourage removal of some operations, e.g. oyster culture, to less sensitive areas such as the west coast of Vancouver Island. This would reduce user conflicts in some areas, but the solution is largely unacceptable since it ignores the problems in the Puget Sound-Strait of Georgia area where much of the industry is centered.

3. Fishery regulations must be strictly adhered to by the industry in areas where harvest occurs on public grounds in Washington and in all areas in British

Columbia to ensure that overharvest does not occur and that the environment is not damaged by harvesting operations.

4. Every effort must be made to control pollution, particularly industrial and domestic pollution. Progress has been made in this field but greater efforts are required to maintain high quality growing areas if the shellfish industry is to survive and expand. The goal should be to reduce pollution levels so that areas that have been closed can be reopened for harvest and culture of bivalves. Examples exist where this has been achieved, Burley Lagoon in Puget Sound and part of Ladysmith Harbour in the Strait of Georgia. The goal is attainable, but it will require the concerted effort of everyone to achieve it.

   The effects of sewage pollution can be alleviated to some extent by use of depuration facilities to purify contaminated bivalves. However, this is only a partial solution and it ignores the real problem which must be corrected.

5. Creation and possible expansion of recreational reserves will help to reduce conflict between the public and the shellfish industry. Such areas must be sufficient to meet the demands of the public and recreational harvesters, and the existence of the reserves must be well-advertised so that the public is aware of them and can make use of them. Some recreational reserves could be established by improvement of marginal areas as is being attempted in Puget Sound (Toba et al. 1992).

   Authorities must realize that establishment of recreational reserves may necessitate shellfish enhancement programs to ensure stocks are maintained at levels that will satisfy public requirements. This could entail a significant expenditure of funds and personnel.

6. Aquaculture offers the greatest promise for expansion of the shellfish industry and policies should be adopted in both regions that rigorously support shellfish culture. This includes preservation of existing growing areas and adoption of regulations that permit acquisition of new areas for culture. Further, every effort must be made to reduce bureaucratic regulations that discourage people entering the shellfish aquaculture business.

7. The example of agriculture should be considered and 'green belts' established around sections of shorelines. No building, industrial or domestic, would be permitted within 0.5 km of the shoreline in these areas. This would help to preserve intertidal areas and also reduce effects of pollution.

8. Consideration might be given to allowing management of shellfish resources to reside with local residents (Pearse 1982). These people would not only manage the shellfish industry, including recreational fisheries, in their immediate locality, but could also undertake enhancement operations when required.

9. In considering the future of the shellfish industry it must be remembered that negotiations are underway in both Washington and British Columbia to allow management of natural resources in some areas by native people. This will probably lead to some restructuring of the shellfish industry, but with sound management practices production should not be affected.

10. An essential element in the solution to problems of the molluscan shellfish industry in the Puget Sound-Juan de Fuca Strait-Strait of Georgia areas must be a vigorous educational program to inform the public of the issues, so that they can be a part of the solution to these problems. A well-informed public is the best method to ensure that a healthy shellfish resource and vigorous industry are maintained in perpetuity.

Shellfish resources and the industry are important to the economies of communities in the Puget Sound-Juan de Fuca-Strait of Georgia areas. Through continued good management they should continue to serve the people in this region in the future.

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DISCUSSION

Chris Garrett *(Panel)*: Could you tell us how sensitive some of these invertebrates are to long-term — or even seasonal — changes in temperature and salinity?

Neil Bourne: It depends on the species, but most of the species that occur in the Strait of Georgia have pretty wide tolerances of salinity, from 20 ppt to 30 or 32 ppt. Temperature is critical because if you don't get to a certain temperature, you don't have spawning — 14 or 15° for the Manila clams, 20° for Pacific oyster, and so forth.

John Armstrong *(Environmental Protection Agency)*: In Puget Sound we've noticed in the last few years a dramatic increase in marine invertebrates that are not regulated: moon snails, other smaller predatory snails, small shore crabs, etc. I wondered if you have those same expanding harvests of non-regulated species in British Columbia and if you do, do you think there is an ecological concern there?

Neil Bourne: If you do wish to collect anything, you are supposed to get a permit. What we end up doing in a lot of cases, if we feel that there is uncontrolled harvest of something like shore crabs, is to put a bag limit into the sport fishing regulations. It's a stopgap measure, but then we see if this is a continuing trend or if it's just momentary. We haven't been bothered terribly with it, no.

Laurie MacBride *(Save Georgia Strait Alliance)*: Mine's not exactly a question, it's more of a concern. I guess it concerns me when I hear things presented only from the resource point of view and only from the point of view of what is commercially valuable to us as human beings, rather than what is important to the ecosystem. That's the concern that I want to express. I didn't hear that in your remarks.

Neil Bourne: I think that's a very valid comment. Ken and I wrote this almost as a position paper from a resource point of view. That was our understanding of what we were to present. I take it that there will be other presentations that will address your concern about the environment, which is also a concern of ours.

Anthropogenic Influences on Fish Populations of the Georgia Basin

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ABSTRACT

British Columbia and Washington share waters that are home to over 200 species of fishes. For most, very little is known about population condition, transboundary movements, or the consequences of human activities. From our review of the available information for 12 key species, we speculate on the sensitivity of fish populations to human activities and recommend actions to monitor and manage these effects.

Because of their importance to recreational and commercial fisheries, salmon species are the most well studied. Although the status of some populations is not known and others appear healthy, some populations are at very low levels. Habitat degradation and fishery management decisions contributed substantially to these declines.

Populations of lingcod and rockfishes have seriously declined since the mid-1980s in the inside waters of British Columbia and Washington. Others, such as herring, Pacific hake, walleye pollock, and Pacific cod, are at very low levels in Puget Sound, but appear to be relatively to very healthy in British Columbia. We believe that fishery harvests, environmental conditions, increased marine mammal predation, and habitat degradation all likely contribute to the declines, but we do not have adequate information to evaluate the importance of each factor. We are just beginning to assess the consequences of human population growth and to develop the necessary remedies to safeguard our fish resources during the future. We propose a coordinated and prioritized effort to focus on monitoring, research, and management of our fish resources over the next decade.

INTRODUCTION

This report is divided into two parts, salmonids and marine fishes, because of differences in their life histories and potential types of anthropogenic influences. Anadromous salmonids spawn in fresh water and their populations are significantly affected by anthropogenic activities in rivers, streams, and uplands. Most salmonids also migrate to the open ocean and spend a relatively brief period in the marine waters of the Georgia Basin. In contrast, marine fishes live entirely in salt water and are generally less affected by anthropogenic activities in the watersheds. Also, all marine fishes in the Georgia Basin, with the exception of some herring stocks remain in the basin throughout their lifetime.

PART I: SALMONIDS

Thomas P. Quinn

INTRODUCTION

Anadromous salmonids dominate commercial and recreational fisheries in the Puget Sound-Strait of Georgia region and also have received a great deal of public and scientific scrutiny. Their life cycles vary among and within species, but all involve spawning and incubation of embryos in fresh water (usually streams), emigration from fresh water as early as immediately after emergence (pink salmon, *Oncorhynchus gorbuscha)* or after as much as two years in fresh water (steelhead trout, *O. mykiss*, and cutthroat trout, *O. clarki).* Their period of marine residence ranges from a few months in cutthroat trout and Dolly Varden *(Salvelinus malma)* to four or more years for chinook salmon *(O. tshawytscha).* See Groot and Margolis (1991), and Meehan and Bjornn (1991) for reviews of the life histories of the major species. After marine residence, the great majority of salmonids that survive return and spawn in their natal or 'home' stream, resulting in populations that are spatially (and often temporally) separate, genetically distinct, and differing in production characteristics. These populations must be managed as separate units or they can be permanently destroyed (McDonald 1981; Wright 1981; Riddell 1993).

While one is tempted to draw quick conclusions on the status of salmonids as a group, the picture is complicated by several factors. Salmon can be difficult to count accurately for various reasons (Bisson et al. 1992). Even if accurately counted, their populations are inherently variable, owing to fresh water and marine factors. Long time-series are required to detect even rather large changes in abundance statistically (Lichatowich and Cramer 1979). In addition to this inherent variability, abundance changes may be non-linear, hence not be revealed by simple regression (Bledsoe et al. 1989).

Population status may also be difficult to determine if catch statistics are relied upon, as these can be very misleading. One example is the often-displayed graph (e.g. Kaczynski and Palmisano 1993, p. 150) of salmonid landings in the lower Columbia River. The graph ranges from a high of nearly 50 million pounds prior to 1920 to less than 5 million in 1990. The authors noted that in-river fisheries were supplemented by offshore trolling in the mid-late part of the century but casual readers may assume that the depiction represents the total decline. Also, catch statistics tend to be biased towards very abundant populations, either because fisheries focus on them and ignore small populations with unusual timing or because catches of the large population mask patterns of smaller ones. An example of this is the time series of Puget Sound sockeye catches (Bledsoe et al. 1989, p. 59). A dramatic decline in catches is apparent after 1913 but this is entirely explainable by the rockslides on the Fraser River. Puget Sound fishermen were catching primarily Canadian sockeye whose abundance would mask any trends of Puget Sound populations unless more refined data were examined.

Despite these and other difficulties in determining the status of salmon populations (Bisson et al. 1992), it is the consensus of scientists that many populations in Washington, Oregon, Idaho and California are in jeopardy or have become extinct (e.g. Chapman 1986; Bledsoe et al. 1989; Lichatowich 1989; Nehlsen et al. 1991; Nickelson et al. 1992; Alkire 1993; Washington Department of Fisheries (WDF) et al. 1993; Kaczynski and Palmisano 1993; Palmisano et al. 1993). It is not my purpose to review these reports in detail but I will provide summaries from them. I will also discuss three kinds of problems with this sort of report by comparing the findings of WDF et al. (1993) with those of Nehlsen et al. (1991) and Alkire (1993). There has not been a comprehensive review of the status of British Columbia populations but most of the points made with regard to Puget Sound salmonids pertain to those in the Strait of Georgia as well. I then discuss the factors that have been responsible for the declines of salmon populations and that may interfere with restoration efforts in the future. Finally, I suggest areas where more information is needed and where institutional cooperation can facilitate salmonid management.

STATUS OF PUGET SOUND POPULATIONS

For the purposes of this report, I consider Puget Sound to include Hood Canal and Juan de Fuca Strait in accordance with WDF et al. (1993). WDF et al. (1993) classified populations as healthy ("experiencing production levels consistent with its available habitat and

within the natural variations in survival for the stock"), depressed ("production is below expected levels based on available habitat and natural variations in survival levels, but above the level where permanent damage to the stock is likely"), critical ("experiencing production levels that are so low that permanent damage to the stock is likely or has already occurred"), extinct ("no longer present in its original range, or as a distinct stock elsewhere") and unknown ("insufficient information to identify . . . stock status with confidence"). Overall, 93 of 209 stocks (44.5%) were classified as healthy, 21.1% were depressed, 5.3% were in critical condition, and the status of 28.7% was unknown (Table 1). Only one stock, early chum salmon *(Oncorhynchus keta)* in Chambers Creek, was considered to be extinct.

In general, chum salmon populations were most often classified as healthy, followed by pink salmon. However, for the other species, nearly half or more of the stocks were classified as depressed or critical (Table 1). Compared with other regions of Washington, Puget Sound was considered to have fewer depressed stocks than the Columbia River but more than the coastal region (Table 2). However, almost all of the state's 'critical' stocks are in Puget Sound. Puget Sound was also intermediate between the other two regions in the proportion of stocks whose status was unknown.

This compilation and those like it must be read carefully for several reasons. Compilations differ in subtle but important aspects of their definitions (for example, Nehlsen et al. 1991 used special concern, moderate risk of extinction and high risk of extinction; Nickelson et al. 1992 used special concern and depressed). Moreover, the conclusions of the compilations can be distinctly different in some areas. In the extreme case, stock extinctions, WDF et al. (1993) listed only one stock as extinct in the state whereas Nehlsen et al. (1991) listed 42 stocks entirely or partially in Washington as extinct. Interestingly, the early chum run to Chambers Creek classified as extinct in WDF et al. (1993) was said to be "at low levels . . . but appears to be rebuilding" (Nehlsen et al. 1991). There are also major differences in the ways in which regional groups of stocks are judged. For example, WDF et al. (1993) listed 17 stocks of chum salmon in south Puget Sound and classified 15 as healthy, one as extinct and one as unknown. In contrast, Alkire (1993) stated that "Chum salmon are depleted or extinct in the rivers of southern Puget Sound . . ." Differences in judgment about the status of stocks are sometimes confounded by disagreement regarding the definition of stocks or the number of stocks under consideration. For example, Nehlsen et al. (1991) concluded that the 'Lake Washington' sockeye did not meet the criteria for special concern or risk of extinction but WDF et al. (1993) recognized three stocks in the watershed (Cedar River, Lake Washington and Lake Samammish tributaries, and Lake Washington beach spawners) and classified all of them as depressed. In a more dramatic example of the lack of good stock definition, two 'stocks' of sea-run cutthroat encompassed all of Washington outside the Columbia River (Nehlsen et al. 1991). One consisted of Hood Canal and Grays Harbor and the other was everything else!

Putting aside the differences and discrepancies among the reports, it is clear that a substantial number of wild salmon populations are in some jeopardy and the status of many others is poorly known. We must first address the question: Should the loss of populations concern us? In addition to the legal requirement that populations be protected under the U.S. Endangered Species Act, Alkire (1993) reviewed the substantial economic value of salmonids, as targets of both commercial (native and non-native) and recreational fishermen.

TABLE 1

Status of Puget Sound salmonid stocks as summarized by WDF et al. (1993)[a]

Status	*Chinook*	*Chum*	*Coho*	*Pink*	*Sockeye*	*Steelhead*	*Total*
Healthy	10	38	20	9	0	16	93
Depressed	8	1	16	2	3	14	44
Critical	4	2	1	2	1	1	11
Unknown	7	13	9	2	0	29	60

[a] One stock of chum salmon classified as extinct, and six stocks of chinook in disputed status were not included.

They are integral components of the complex ecosystems in which they live. Salmon are also of great symbolic importance to native people and more recent settlers as well, representing clean water, forests, and the wonders of animal migration. In addition, small populations may contain valuable genetic traits which could not be recreated if the populations were lost and which may have great value to the aquaculture industry (Scudder 1989; Riddell 1993).

CAUSES OF DECLINE

If we accept that many populations are in danger or are too poorly known for us to evaluate their status, and that these populations are valuable, we must consider why they are in decline and why we have insufficient information about them. Many factors have affected salmon populations over their range. In some cases they operated in isolation but often their effects have been 'cumulative'. In the Puget Sound region, these factors include dams that block ascent of rivers, habitat degradation from forestry, urbanization and other landuse practices, overfishing, and interactions between wild and hatchery-produced salmon (Nehlsen et al. 1991; Table 3). Habitat loss or degradation was listed as a contributory factor for 30 of the 35 stocks in Puget Sound classified as in some jeopardy. Dams have blocked or hindered passage in some rivers (e.g. Skokomish, Elwha, Skagit). Palmisano et al. (1993) reported that 5138 miles of stream are accessible to anadromous fishes and 252.5 miles of potentially accessible streams have been permanently blocked by hydroelectric, multipurpose or drinking-water dams in the Puget Sound region. These have caused acute local effects but probably the most widespread problems have been caused by altered riparian and estuarine environments.

There have been many reviews of the effects of forest practices on salmonids and their habitats (Salo and Cundy 1987; Meehan 1991; Bisson et al. 1992). In general, the effects tend to be thermal, sedimentary, hydrologic and structural. Removal of riparian canopy tends to elevate summer temperatures, exaggerate diel

TABLE 2

Status of Washington salmonid stocks as summarized by WDF et al. (1993)[a]

Status	*Puget Sound*	%	*Washington Coast*	%	*Columbia River*	%	*All Washington*	%
Healthy	93	44.5	65	56.5	29	26.1	187	43.1
Depressed	44	21.1	8	7.0	70	63.1	122	28.1
Critical	11	5.3	0	0	1	0.9	12	2.8
Unknown	60	28.7	42	36.5	11	9.9	113	26.0
Total	208		115		111		434	

[a] One stock of chum salmon classified as extinct, and six stocks of chinook in disputed status were not included.

TABLE 3

Factors contributing to the scarcity or decline of anadromous salmonid populations in Puget Sound, including Hood Canal and Juan de Fuca Strait[a]

	Factors contributing to the scarcity or decline			
Status	*Habitat loss*	*Overfishing*	*Biotic interactions*	*Total*
High risk	19	11	5	22
Moderate risk	5	3	3	7
Special concern	6	4	3	6
Total	30	18	11	35

[a] From Nehlsen et al. (1991)

NOTE: More than one factor may contribute to the status of a stock.

fluctuations, and reduce winter temperatures. Depending on the species or life history stage involved, these changes may be deleterious to salmon. Fine sediments enter streams from forest roads and, to a lesser extent, clearcuts. High levels of fine particles can restrict the flow of water bathing the incubating embryos and can prevent emergence from the gravel at the free-swimming stage. Removal of hillside vegetation results in more rapid delivery of precipitation to the stream and also permits greater buildup of snow than would occur on a forested slope. Melting of snow ('rain on snow events') can release particularly large floods that can scour the gravel and dislodge or kill embryos. Past practices have reduced the amount of large woody material in Puget Sound and Strait of Georgia streams and this reduction has tended to simplify the structure of streams, eliminating or shrinking pools that are needed by some salmonid life history stages.

There is ample evidence that estuaries are used by salmonids, to varying extents depending on species and race (Healey 1982; Simenstad et al. 1982). Studies have been conducted describing patterns of fish use in such estuaries as the Nanaimo (Healey 1980), Fraser (Levy and Northcote 1982), Campbell (Macdonald et al. 1987) and Skagit (Congleton et al. 1982). In general, juvenile chum salmon and fall chinook (ocean-type) make most extensive use of estuaries, followed by pink and coho *(O. kisutch)*. Spring chinook (stream-type), sockeye salmon *(O. nerka)* and steelhead trout seem to rely least on estuaries, perhaps because they tend to be relatively large when leaving fresh water. Reviews of major estuaries in the region by Bortelson et al. (1980) and Hutchinson (1988) revealed extensive areal losses in many cases (Table 4), and overall losses of 18% around the Strait of Georgia and 58% around Puget Sound (Hutchinson 1988). While there have been some attempts to recreate or restore wetlands or mitigate their losses (e.g. Campbell River: Levings and Macdonald 1991; Puyallup River: Schreffler et al. 1990; reviewed by Cooper 1987; Rylko and Storm 1991), the overall picture is one of tremendous loss and very slight recovery.

After habitat loss, overfishing was the most common factor contributing to the jeopardy of Puget Sound salmonid populations (18 of 35 listings in Nehlsen et al. 1991; Table 3). There are many reasons why overfishing occurs but the most important are general mixed-stock fisheries, overfishing wild populations to fully exploit hatchery populations, and interception fisheries. Unlike habitat problems, which result from actions or neglect in the freshwater environment and are local in origin and effect, mixed-stock fishery problems result from the mixture of salmon in their feeding areas at sea and on their migratory routes back to fresh water. In general, the farther from the river mouth and the longer the time interval between the fishery and the date of spawning, the greater the tendency to catch mixtures of species and populations. Such mixed fisheries would not be a problem, except that the sustainable levels of fishing vary among species and populations. For example, some populations may be able to sustain fishing pressure of 50%. That is, half the fish that survive to maturity can be caught without reducing the size of the next generation; density-dependent processes in fresh water would otherwise cull the population to the same level, if all fish were allowed to return and spawn. If such a population were distributed with another population that could sustain fishing pressure of 75%, then fisheries that were managed to catch the more productive population would overfish the less productive one.

Compounding the general problems of managing mixed-stock fisheries within governmental jurisdictions, the migrations of Puget Sound and Strait of Georgia salmonids cross state and national boundaries. Pink, sockeye, chum and steelhead all leave the inland waters to rear in the open North Pacific Ocean. These species are fished as returning, maturing adults. Coho and chinook tend to be more coastal in their distributions and are caught during much of their lives at sea. The majority of Fraser River pink and sockeye salmon pass through U.S. waters on their homeward journey and form a substantial component of Puget Sound fisheries. Almost all the 1 to 3 million sockeye caught by U.S. fishermen in Puget Sound originate in the Fraser River and roughly 50–75% of the approximately 2 million pink salmon taken (odd years only, i.e. 91, 93, 95) are also from the Fraser River (Palmisano et al. 1993). This boon to U.S. fishermen does not come without a cost, however. Palmisano et al. (1993) summarized data indicating that 44% of the Puget Sound chinook salmon were intercepted by Canadian fisheries between 1987 and 1990 (compared with 21% of the Washington coastal stocks and 33% of the Columbia River chinook). Coho salmon are inter-

cepted as well (62 and 42% from the north and south regions of Puget Sound, respectively, compared with 48% for the Washington coast and 6% for the Columbia River between 1988 and 1990). This amounts to almost 1.4 million coho salmon and over 0.74 million chinook annually (Palmisano et al. 1993). The catch of these species and populations are regulated by international treaty between the U.S. and Canada. However, negotiations are hampered by conflicts among user groups within the nations and among jurisdictions within the U.S.

Mixed-stock fisheries can sometimes be addressed by shifting the fishery closer to the river's mouth or adjusting the timing of the fishery to protect a weak population. A particularly common and difficult type of mixed-stock fishery occurs when wild and hatchery-produced salmon from the same river or terminal area are exploited together. If the hatchery is functioning properly, its population should be able to sustain higher levels of fishing than wild populations. Almost inevitably, the fisheries must overexploit the wild populations to take advantage of the surplus hatchery fish. Such overfishing can thwart efforts to rebuild wild populations by habitat restoration (Wright 1993). Certain zones of Puget Sound are managed for the exploitation of hatchery populations. Wright (1993) decried this policy and argued that they amount to a planned extinction of wild populations. "The extinction plans are, unfortunately, working, and result in under-use by

TABLE 4

Estimated area of intertidal marshes around the Strait of Georgia and Puget Sound at the time of European settlement and at the present[a]

Marshes	*Presettlement*[b] *(ha)*	*Present (ha)*	*Change (%)*
Strait of Georgia			
Baynes Sound	120	117	−2
Burrard Inlet	150	9	−94
Chemainus	160	121	−24
Courtenay	87	74	−18
Cowichan	191	101	−47
Englishman	54	47	−13
Fraser	3186	2810	−12
Nanaimo	275	130	−53
Squamish	120	117	−2
Other areas	110 ?	110	?
Total	4453	3636	−18
Puget Sound			
Duwamish	260	3	−99
Lummi	580	30	−92
Puyallup	1000	0	−100
Nisqually	570	410	−28
Nooksack	450	490	+9
Samish	190	4	−98
Skagit	1600	1200	−25
Skokomish	210	140	−33
Snohomish	3900	1000	−74
Stillaguamish	300	360	+20
Other areas	300 ?	250	?
Total	9360	3887	−58
Grand total	13790	7523	−45

[a] Compiled by Hutchinson 1988 from various primary sources
[b] All marshes estimated to have been at least 50 hectares are included
? indicates uncertain estimates

coho *(O. kisutch)* of more than 5600 kilometres of usable stream habitat in Washington and along the Oregon side of the Lower Columbia River." He succinctly concluded that "Salmon managers need to abandon the use of hatchery fish management zones."

The third factor that Nehlsen et al. (1991) indicated was contributing to the decline of 11 of the 35 listed Puget Sound stocks was a catch-all category of biotic factors including hybridization, competition or predation by exotic or translocated species, and poor ocean survival. A key component of this is interactions between hatchery and wild stocks, as distinct from overfishing as described above. Hatchery-produced fish may stray and mate with wild fish, reducing local adaptations. If the hatchery produces an introduced stock or if inadvertent selection in the hatchery has changed the genetic makeup of those fish, then matings with stray hatchery-produced fish may reduce the fitness of wild fish (reviewed by Hindar et al. 1991; Waples 1991). Hatchery fish of one species may also hybridize with members of another species and this seems particularly common between planted rainbow or steelhead trout and cutthroat trout.

There may be a variety of ecological interactions between wild and hatchery-produced salmonids, notably predation (e.g. coho smolts eating young-of-the-year pink or chum salmon) and competition for food and space (see Steward and Bjornn 1990 for an extensive review of the literature on supplementation). The magnitude of possible hatchery-wild interactions may be gauged by the numbers of hatchery-produced salmonids released. Palmisano et al. (1993) reported that recent annual releases into Puget Sound and Juan de Fuca Strait numbered roughly 60–70 million fall chinook, 60–80 million chum salmon and 40 million coho salmon. Steelhead releases are much lower, about 6 million in the whole state. In Puget Sound, almost all the pink and sockeye salmon and cutthroat trout are wild, but hatchery production comprises roughly 40% of the chum, 55% of the chinook, 60% of the coho and 70% of the steelhead (Palmisano et al. 1993).

Over long periods of time, salmon populations have adapted to cycles in their physical and biological environment. This paper will not attempt to review all sources of natural mortality, but two components deserve special mention owing to their visibility and the apparent changes in their impact on salmon: marine mammals and oceanographic conditions. Two pinniped species, harbor seals and California sea lions, have increased tremendously in abundance in the Strait of Georgia and Puget Sound in the last 20 years (summary based on data reviewed by Palmisano et al. 1993). California sea lions are a migratory, not resident, population that is most abundant in late winter and early spring. Their population increased ten-fold in British Columbia from 1972–1984 and stabilized at about 2500 animals. The population of the United States has increased at about 6% per year since the late 1970s. Harbor seals are permanent residents in the area, and the Washington population has been increasing at 6–10% per year and was estimated at over 30,000 in 1991 (NMFS 1992). The population in the Strait of Georgia has been increasing at about 12.5% per year (Olesiuk 1993). Salmonids do not dominate the diets of either species (ca. 10% for sea lions and 3–4% for harbor seals). Consumption estimates based on abundance, size and metabolic requirements, were 842,000 salmon lost to harbor seals and 69,200 annually to sea lions in Washington. These numbers are relatively small (9 and 1%, respectively, of the commercial catch). Sea lions were also estimated to take about 1% of the commercial harvest in British Columbia. However, the pinnipeds can exert strong local effects. For example, steelhead runs into Lake Washington have declined sharply and sea lion predation seems to have played a major role. Harbor seals seem to prey heavily on early-returning chinook to the Puntledge River (Graeme Ellis and Andrew Trites, pers. comm). However, it is unwise to reduce ecological interactions to the consumption of one species by another. For example, the most important dietary items for the pinnipeds seem to be Pacific hake and Pacific herring, which can be predators and competitors of salmon, respectively. Overall, these pinnipeds are increasing in abundance but will presumably reach their carrying capacity and level off. Given the data in hand and the legal and public support for marine mammal protection, it seems neither ecologically justified nor politically expedient to hold the sea lions and seals responsible for the declines of any but selected populations.

The unusually warm water off the coast of the Pacific Northwest in 1983 stimulated interest in the responses of salmon populations to changing oceanographic conditions. It is now clear that the century has seen multi-

decadal climatic and oceanographic periods and that fluctuations in salmon abundance have mirrored these physical changes. The period since the late 1970s has been characterized by relatively warm ocean temperatures and high abundance of zooplankton (Brodeur and Ware 1992) and salmon (Beamish and Bouillon 1993). However, the picture of overall abundance of North American salmon is driven primarily by Alaskan catches (about 90% of U.S. catches in most years) and certain highly abundant Canadian populations (e.g. Fraser River sockeye). This abundance masks the fact that conditions have been generally unfavorable for U.S. coastal populations (Pearcy 1992). Cooper and Johnson (1992) concluded that, while many steelhead populations have been impacted by site-specific factors such as land use, the best explanation for the generally low abundance in the early 1990s is unfavorable oceanographic conditions.

The relevance of recent oceanic trends for Puget Sound and Strait of Georgia populations is unclear. The 1983 El Niño-Southern Oscillation event had a deleterious effect on chinook and coho salmon from coastal Oregon streams and those Columbia River populations with localized marine distributions, but northward migrating populations were apparently unaffected (Johnson 1988). The likely effects of oceanographic conditions on salmonids thus depends on their migratory patterns and the precise nature of the oceanographic changes. The temperatures are certainly not 'too warm' for salmon in any physiological sense but rather the temperatures presumably co-vary with other factors exerting a direct or indirect effect on the salmon (Pearcy 1992).

In addition to influencing the abundance trends and inter-annual variation in survival of salmon, the oceanic conditions can also affect migratory routes and timing. The best studied case is the variation in route taken by Fraser River sockeye (between Vancouver Island and the B.C. mainland or around the outside of Vancouver Island and through Juan de Fuca Strait). Sockeye generally take the southern route (entering U.S. waters and encountering U.S. fisheries) but the tendency is reduced markedly when the ocean is warm (Groot and Quinn 1987) and the fish tend to be later than usual in such years (Blackbourn 1987). There is little to do about adverse climatic conditions except be patient and program them (and the uncertainty about them) into forecasts. The public should not be misled into thinking that the ocean functions like a factory, producing salmon to meet our demands and expectations.

SUMMARY

Many but by no means all salmonid populations in the Georgia Basin are in some degree of jeopardy. The problems are not unique to either country but they do vary among rivers to some extent. Land use practices have damaged and continue to damage stream incubation and rearing environments and the estuaries used to varying extents by all species. The links between human activities and salmonid mortalities are relatively well-known for stream habitats. The precise functional significance of estuaries is less well understood and they are less amenable to controlled experiments. We thus assume that estuarine functional loss is more or less proportional to areal loss (though this is likely not true). Given the increasing human populations throughout the region, only strong measures will prevent continued degradation of salmonid habitats. Although there have been many studies of the effects of toxic substances on fishes, they appear to be a relatively minor problem for salmon. Except in such industrialized estuaries as the Duwamish and Puyallup, salmonids generally inhabit relatively clean water, either in streams, lakes, or the surface water of inland marine or oceanic environments. If pollution was a major mortality agent, we would expect lower smolt-to-adult survivals from Puget Sound populations than coastal populations, but the reverse is true. This is not to minimize the potential impact of toxic substances on salmon (e.g. Varanasi et al. 1993) but to put them in the perspective of other sources of mortality.

Excessive fishing pressure, documented for many populations, arises from inherent difficulties in managing salmon and from political compromises (e.g. Strait of Georgia chinook salmon: Walters and Riddell 1986). The management difficulties are not insurmountable, given sufficient political fortitude. This political courage will have to manifest itself at state, national and international levels. The same might be said of interactions between hatchery-produced and wild populations. Hatcheries have a role in salmon management but they have been and continue to be used carelessly. Many hatcheries have directly or indirectly contributed to declines of wild populations and have also failed to

fully replace populations lost to dams or other overt environmental injuries.

RECOMMENDATIONS

Given the amount of attention and money devoted to salmonids, there were a surprising number of populations whose status was listed as 'unknown' (nearly 30% in WDF 1993). There were also many populations that are so poorly known that major surveys (e.g. Nehlsen et al. 1991; WDF 1993) could not agree on their status. Sea-run cutthroat were clearly the least studied of the species surveyed in Nehlsen et al. (1991) and they were omitted from WDF (1993). We are even less informed regarding anadromous Dolly Varden char; none of the surveys mentioned this species.

- Thus the first recommendation is that management agencies maintain existing long-term data sets (e.g. index streams, permanent weirs, etc.), expand their coverage, and integrate multiple species when possible. The merger of the Washington departments of Fisheries and Wildlife may help this process but only if budget cuts do not reduce field operations.

The loss of salmon populations to habitat degradation has not resulted from lack of dedication on the part of agency biologists. They may be required to process so many permit applications that they cannot possibly study them all carefully. However, these individuals often care deeply about the health of the environment and the fish populations.

- Accordingly, the second recommendation is that habitat protection and restoration be high priorities within management agencies and that inter-agency collaboration (e.g. between the Canadian departments of Fisheries & Oceans and the Environment, and between the Washington departments of Natural Resources, Ecology, Fisheries and Wildlife) be encouraged.

Hatcheries have played a complex role in the history of salmon management (Lichatowich and McIntyre 1987). They have probably saved some populations and contributed to the decline of others.

- Hatcheries should be made responsible for the health of wild salmon populations within their region. 'Production' and 'harvest management' must be integrated and proceed towards the goal of healthy, self-sustaining wild populations and fisheries based on them.

- In addition to these recommendations, fundamental changes in attitudes towards salmon are required. Salmon managers sometimes act as though the fish belong to the fishermen and the only real decisions are how many salmon to produce and who gets to catch them. Salmon must be valued not only (or even not primarily) as a commodity to be 'harvested' like a crop, but rather as the epitome of wildlife in the region. Salmon must never be viewed as range-fed beef with fins. Moreover, the attitudes of more than the managers and fishermen are to blame for the reduced abundance and diversity of salmon. We have all contributed to the demands for water, energy, land, wood and other resources that have made the region less suitable for salmon.

- Finally, we scientists must examine our motives and ponder the extent to which our research contributes to solving important problems. As Scarnecchia (1988) pointed out, many of the mistakes have been made knowingly, and research has sometimes been an excuse for business as usual. The Strait of Georgia and Puget Sound salmon populations are not lost, but their continued health will demand a broad societal commitment.

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PART 2: MARINE FISHES

Cyreis Schmitt and Jacob Schweigert

OVERVIEW OF RESOURCES

Well over 200 species of fish inhabit the Georgia Basin, however, we present information only on the following: herring *(Clupea pallasi)*, Pacific hake *(Merluccius productus)*, Pacific cod *(Gadus macrocephalus)*, walleye pollock *(Theragra chalcogramma)*, spiny dogfish *(Squalus acanthias)*, lingcod *(Ophiodon elongatus)*, rockfish (*Sebastes* spp.), and English sole *(Parophrys vetulus)*. These species have been the primary targets for recreational and commercial fisheries, which are the main data sources for population assessment. For the remaining species, very little information is available to assess the status of populations or evaluate the influences of anthropogenic activities.

We describe resources and present statistics for International North Pacific Fisheries Commission (INPFC) Areas 4A and 4B (Figure 1) because these boundaries delineate the portion of the Georgia Basin within British Columbia (Area 4B) and the portion within Washington (Area 4A).

To provide an overall perspective, we have listed the status of marine fish populations in each area in Table 5. The descriptions in Table 5 reflect our best professional judgment rather than precise quantitative criteria. Most fish populations in British Columbia waters (Area 4B) are considered to be in average condition, except for lingcod and rockfish which are below average. In contrast, most populations in Washington waters (Area 4A) are below average, except for spiny dogfish, which are average to high. The status of each species is fully described in following sections.

Fisheries and Economic Importance

In the following sections, historical catch patterns for herring and groundfish are presented to provide a perspective on marine fish resource utilization. Our knowledge of historical trends in abundance is often limited and historical catch patterns provide an indication of stock condition when abundance data are lacking. Herring catch statistics were provided by J. Schweigert, and M. O'Toole (Washington Department of Fisheries

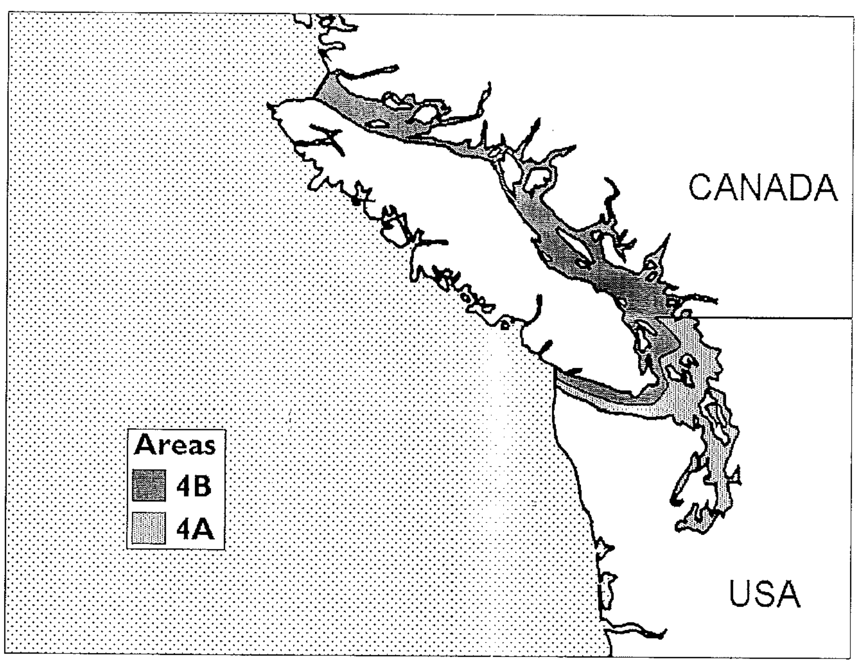

Figure 1. Map showing International North Pacific Fisheries Commission (INPFC) Area 4B (British Columbia) and Area 4A (Washington).

(WDF), pers. comm.). For British Columbia waters (Area 4B), historical catches of groundfish species are taken from Leaman and Stocker (1993), and statistics for English sole were provided by J. Fargo (Department of Fisheries and Oceans (DFO), pers. comm.). Historical catch statistics for groundfish species in Washington waters include recreational and commercial catches in all inside waters east of the Sekiu River. Catches in the small area between the Sekiu River and Neah Bay are omitted from the data for Area 4A because resources in this area are considered part of those off the outer coast and are managed as offshore resources. Commercial catch statistics for 1970–1988 are taken from Schmitt, et al. (1991) and updated through 1991 from upublished WDF data. Recreational catch statistics for 1970–1985 are modified from Palsson (1988) to reflect catches in weight rather than numbers of fish and updated through 1991 from WDF unpublished data. Recreational catches by divers and shore-based anglers in Area 4A are not available annually and are not included in the data presented.

Descriptions of fisheries operating in Washington waters (Area 4A) are summarized and updated from Schmitt (1990). For most of the major groundfish species in Area 4A, the 1970s was a decade of rapidly increasing catches and effort. This was true for both recreational and commercial fisheries. The recreational catch by boat-based anglers increased tenfold and the commercial trawl catch more than doubled. This period of rapid fishery expansion in the 1970s was followed by an equally rapid decline during the 1980s to the very low levels of the 1990s.

Commercial groundfish catches in Area 4A fluctuated between 8 and 16 million pounds (3629 and 7258 tonnes) annually until 1976, when they began to

TABLE 5

Current status of marine fish populations in British Columbia waters (Area 4B) and in Washington waters (Area 4A)

Species	*Area 4B*	*Area 4A*
Herring	high	low
Hake	average to high	very low
Pacific Cod	average	very low
Pollock	low to average	low
Dogfish	average to high	average to high
Lingcod	very low	very low
Rockfish	low	low
English Sole	average	low to average

TABLE 6

The 1992 ex-vessel value of marine fish landings in British Columbia waters (Area 4B) and in Washington waters (Area 4A)

Species	*Area 4B (US$ 000s)*	*Area 4A (US$ 000s)*
Herring	13,594	1,130
Hake	958	2
Pacific Cod	167	243
Pollock	367	0
Dogfish	24	251
Lingcod	1	8
Rockfish	10	71
English Sole	46	212

increase sharply. Commercial catch peaked at 26.5 million pounds (12,020 tonnes) in 1979; hake and dogfish accounted for most of this increase. In 1983, the commercial catch began to drop sharply, so that by 1993 it was only 3.6 million pounds (1647 tonnes), the lowest level in over 55 years. Similarly, the annual recreational catch increased from about 100,000 fish in the early 1970s to a peak of slightly more than 900,000 fish in 1980 and 1981. Catches declined thereafter to a low of 218,000 fish in 1990, but rebounded somewhat to 325,000 fish in 1991, the most recent year for which data are available.

In the Canadian Strait of Georgia (Area 4B), Ketchen, et al. (1983) described historical trends in fisheries and populations of marine fishes through 1980 and we have updated their information. The herring fishery is the largest fishery for marine fish in the Strait of Georgia, both in terms of catch and ex-vessel value. A large fishery for hake developed during the 1980s and has dominated groundfish landings since then. Catches of cod, pollock, and dogfish have been variable over the past 20 years, whereas lingcod catches have continuously declined because of low abundances. Rockfishes became more popular during the 1980s and catches increased until recently, when more restrictive regulations were imposed.

Fishery economics are very complex and the economic value of recreational and commercial fisheries for marine fish has not been analyzed. In addition to their monetary value, marine fish resources have aesthetic and social values, and these are very difficult to measure. The only information available on the economic value of marine fish resources in the Georgia Basin is ex-vessel value, the amount paid by processors to commercial fishers.

The 1992 ex-vessel value of commercial landings of marine fishes is presented for Areas 4B and 4A in Table 6. In general, the ex-vessel values are much lower for landings from Washington (Area 4A) than from British Columbia waters (Area 4B). In Washington, the lower values are a function of reduced fish abundances, more restrictive fishing regulations, and a greater emphasis on recreational fisheries for some species.

Herring provides the most valuable commercial fisheries in both areas. The herring roe fishery is the second most valuable fishery to the British Columbia economy after sockeye salmon. The 1992 landed value was estimated at Cdn$55.3 million, based on total coastwide landings of 35,000 tonnes, representing about 11.0% of the total value of the Province's seafood production. Due to the current strength of the Strait of Georgia herring stocks, they constitute almost a third of the entire British Columbia herring catch. In Washington, herring are also the most valuable commercial species but it is harvested primarily for bait for recreational salmon fisheries and as spawn-on-kelp, a delicacy in Asian markets.

Discontinued Fisheries

Another measure of the overall condition of marine fish resources is the loss of fisheries. Ketchen, et al. (1983) described the long-term absence of a small, local fishery for Pacific halibut *(Hippoglossus stenolepis)* in the southern Strait of Georgia as a 'defunct fishery'. They concluded that this fishery harvested halibut around the turn of the century when halibut was still in a primeval state of abundance and that halibut were strays to the area.

Since the mid-1980s, several fisheries in Washington waters (Area 4A) have ended, at least temporarily, as a result of low abundances of the targeted species. They have either been closed by regulation or have effectively ceased through lack of targeted effort on a particular species. We have chosen to refer to these as 'discontinued fisheries' rather than 'defunct fisheries' because these fisheries reflect relatively recent losses and may be re-established as marine fish populations rebuild. As populations recover, it is likely that these fisheries may be managed and operated differently so as not to repeat the recent declines. To date, none of these discontinued fisheries have shown signs of recovery.

Because of low abundance of Pacific cod in Area 4A, two fisheries for cod have been closed by regulation: the commercial set net fishery in 1987 and the very popular recreational fishery in Agate Passage near Bainbridge Island in 1991. Also in 1991, the daily bag limit for Pacific cod was reduced from 15 to 2 fish in central and southern Puget Sound, and the bottom trawl fishery was prohibited from the Protection Island and Port Townsend areas during the winter when cod are spawning. Recreational fishing for pollock was a popular activity especially for charterboat anglers dur-

ing the mid-1980s in southern Puget Sound. However, pollock abundance in this area declined to an extremely low level and few anglers have fished there for pollock in recent years. Recreational bag limits were reduced from 15 to 5 fish daily in 1990.

The largest fishery in Area 4A, in terms of volume of fish harvested, was the midwater trawl fishery for hake in Port Susan. In 1983, over 6800 tonnes were harvested. This fishery has been essentially closed by regulation since 1987 because of low abundance.

A commercial fishery harvested herring for sac roe in northern Puget Sound near Cherry Point during the early 1970s. It was closed in 1982 because of low abundance of herring.

A bottom trawl fishery has harvested flatfish in Discovery Bay for decades. The primary species was English sole until abundance declined and starry flounder became the target species. English sole catches and catch rates remained low, despite past fishery restrictions, and a closure of the trawl fishery in Discovery Bay is proposed in 1994.

Commercial handline jig and bottomfish troll fisheries were closed throughout Area 4A in 1992, primarily as a result of decreased abundance of lingcod. Other commercial and recreational fisheries were severely restricted to promote rebuilding of the lingcod resource.

Another fishery that has been discontinued for lack of fishing effort is the commercial drag seine fishery for surfperch in Hood Canal. During the 1970s, Hood Canal accounted for the majority of the commercial surfperch catch in Puget Sound, but declines in abundance apparently caused fishers to operate in other areas of central and southern Puget Sound. Recreational and commercial fisheries for surfperch were restricted throughout Puget Sound during the late 1980s in response to the apparent declines in abundance. Although relatively little harvest has occurred in Hood Canal since the mid-1980s, fishers have not returned to this area.

Ecological Importance

The Pacific herring is probably the most important forage species in the marine ecosystem of the Georgia Basin. Herring form an important component of the diet of many marine species in this area particularly during the very productive first year of life when they are ubiquitous in all inshore areas. Adult herring are heavily predated by marine mammals and birds during their annual spawning migrations into the Georgia Basin (Hourston and Haegele 1980). The spawned eggs provide forage for a wide variety of birds and intertidal invertebrates (Haegele 1993a,b). Abundance of many migratory bird species peaks locally coincident with herring spawning to take advantage of this energetic food source. Herring larvae are eaten by a variety of jellyfish, salps, other invertebrates, and juvenile fishes of many species. Schools of immature juvenile herring are easy prey for coho and chinook salmon as well as dogfish, hake and pollock. Once the juveniles migrate out of the Strait of Georgia to join the adult schools off northern Washington and southwestern Vancouver Island they become prey to almost all marine species capable of capturing and consuming them (Brodeur et al. 1987, Prakash 1962, Outram and Haegele 1972).

The trophodynamics of most of the groundfish species within the Georgia Basin are not well understood. The Pacific hake is the most abundant resident fish and has important ecological impacts on the ecosystem both as predators and prey. The hake stocks in the Strait of Georgia prey extensively on euphausiids, amphipods, glass shrimp, and squid as well as small pelagic fishes such as Pacific herring, eulachon, myctophids, and juvenile hake (McFarlane and Beamish 1985). Pacific hake are preyed on by dogfish, walleye pollock, and Pacific cod as adults while eggs and juveniles are predated by lingcod, rockfish, and pollock. Hake juveniles and adults also form the major component of the diets of seals and sea lions both in the Strait of Georgia and Puget Sound where both groups have increased in abundance significantly during the past three decades (Olesiuk et al. 1990, Schmitt, unpub. data). Similar trophic interactions occur among many of the other groundfish species particularly during the juvenile stages when many of them co-occur in inshore waters.

RESOURCE BIOLOGY AND CONDITION

Herring

Life History

The Pacific herring, *Clupea pallasi*, is unique among north temperate fishes in that reproduction takes place

in inshore waters with egg deposition occurring in the intertidal and upper subtidal areas on all available algal substrata (Haegele and Schweigert 1985). About 80% of the eggs are deposited at depths shallower than −1.5 m datum (Hourston and Haegele 1980). The eggs are fertilized almost immediately by males that produce vast quantities of milt that discolours the adjacent water to a milky white. The 1.5 mm diameter eggs remain attached to the algae throughout the course of the 10 to 21 day incubation period that is related to water temperature. Many of the eggs are lost to predators, primarily avian and invertebrate (Haegele 1993a,b), as well as to the effects of storms.

The herring larvae hatch at about 9 mm total length and subsist on the yolk-sac for about six days. Over the next five weeks they develop and grow to a length of about 25 mm at which time they metamorphose (Hourston and Haegele 1980). Initially, herring larvae are at the mercy of the prevailing water currents and disperse passively from the spawning grounds. At this time they are particularly susceptible to predation by jellyfish, arrow worms, and a variety of small fishes. Once they metamorphose, active schooling occurs and a general shoreward movement begins. Metamorphosis is complete at about 35 mm (June-July) and the juveniles grow rapidly, reaching 100 mm by fall with little growth occurring over the winter. Some of the young herring migrate out of the Strait of Georgia during their first winter, while many remain until June or early July of their second year when they join schools of adult and sub-adult herring off the southern west coast of Vancouver Island on La Perouse Bank or in Queen Charlotte Sound.

The immature herring will spend another summer offshore, and in their third fall will become sexually mature and join the schools of adult fish which migrate inshore through Juan de Fuca Strait or Johnstone Strait. The adult schools appear to congregate in a few discrete locations, presumably to minimize predation, and spend the winter and early spring converting the accumulated fat from summer feeding into reproductive products. In mid-February the large aggregations of herring break into smaller schools that disperse to the various spawning grounds throughout the Strait of Georgia. The majority of spawning occurs in early March to early April and the adult schools subsequently migrate relatively quickly back to the outer coast to feed and recover lost body weight in preparation for spawning the following year. Most herring spawn for the first time at age three, and can live up to age 15, although generally they do not exceed age 7 or 8 in the Strait of Georgia. As adults herring are predated by salmon, hake, dogfish, and any other fishes large enough to consume them. During the spawning migration seals and sea lions as well as cormorants and gulls actively feed on the herring schools. It is estimated that on average about 30–40% of all herring die of natural causes every year.

The life history of herring in Puget Sound follows a similar pattern with some significant differences. Spawning occurs over a much longer time period than in the Strait of Georgia beginning in late December (Wollochet Bay) and continuing through early June (Birch Bay) although the egg deposition itself occurs over a period of less than a week and at about the same time each year (Chapman et al. 1941, Trumble 1983). The herring in Puget Sound tend to mature earlier, generally at age two and apparently do not live as long as those in the Strait of Georgia. Growth rates of herring from southern Puget Sound are also somewhat less than for Birch Bay and presumably Strait of Georgia stocks (Chapman et al. 1941).

Distribution and Migration

The results of many years of tagging indicates that Pacific herring are capable of 'homing' to the same general spawning locations each year (Stevenson 1954, Hourston 1982, Schweigert and Schwarz 1993). The major spawning grounds or egg beds in the Georgia Basin are located in the Hornby-Denman Islands-Qualicum Bay area, Ladysmith Harbour-Dodds Narrows, and the Point Roberts-Cherry Point-Hale Passage areas (Hay et al. 1989, Trumble 1983). Smaller spawning grounds occur near Powell River, throughout southern Johnstone Strait, near Jervis Inlet-Pender Harbour, Northwest Bay to Departure Bay, throughout the Canadian Gulf Islands, the San Juan Islands, Samish Bay-Fidalgo Bay, Port Gamble, Port Orchard, Quartermaster Harbour, Hood Canal, Port Susan, and Squaxin Passage. Within both jurisdictions there are many additional small herring spawning beds which may or may not represent separate stocks.

Tagging studies indicate that the majority of adult herring which spawn in the British Columbia waters of

the Georgia Basin migrate out to coastal waters each spring after reproducing. The migrations occur through the Gulf Islands and Juan de Fuca Strait in the south and through Johnstone Strait in the north. These taggings demonstrate that a relatively small proportion of the fish entering the Strait from Juan de Fuca end up spawning in northern Strait of Georgia (Stevenson 1954). Similarly, there is no evidence from the taggings inside Puget Sound that these fish intermix with the herring spawning in the Gulf Islands. There is also evidence that not all adult fish migrate out of the Strait of Georgia each year, as there were summer fisheries for several years in the 1950s in the southern Strait capturing adult fish thought to belong to the Active Pass, Porlier Pass, Point Grey stocks (Taylor 1964). Adult fish also occur in a number of other areas throughout the Strait of Georgia all year and are assumed to be representatives of non-migratory populations. There is no comparable tag return information for the stocks of Puget Sound but it is conjectured that most of the juvenile herring migrate out of the Sound during March-June of their second year to the feeding grounds off the coast of Washington (Trumble 1983). It is probable that they intermingle with herring from the Strait of Georgia on these feeding grounds. It is also thought that as with the resident herring stocks of the Strait of Georgia stocks the southern Puget Sound stocks are resident and migrate no farther than the mouth of Puget Sound (O'Toole, WDF, pers. comm.).

Population Status

Pacific herring are relatively short-lived so that the adult spawning population generally contains at most five to six age-classes. Consequently, significant interannual fluctuations occur depending on the abundance of recruits or first-time spawners. Recruitment to the Strait of Georgia herring stocks is less variable than in other British Columbia herring stocks, due to buffering from the predation and environmental variation of the open ocean (Schweigert 1994). The herring stocks in the Canadian portion of the Georgia Basin are currently at historically high levels having experienced above average recruitments by the 1985, 1987, 1989, and 1991 year-classes.

British Columbia herring spawning abundance has been monitored consistently since about 1950. All herring stocks in British Columbia were at historically low levels in the late 1960s when the intensive reduction fishery combined with several years of poor recruitment resulting from adverse climatic conditions. Stocks rebuilt during the 1970s as the roe fishery began and except for a slight decline in the early 1980s have steadily increased in abundance to the present. The estimate of total spawning biomass for the British Columbia portion of the Georgia Basin in 1993 was over 90,000 tonnes (Schweigert and Fort 1993). Of this total the majority (80%) spawned in the northern Strait of Georgia.

Virtually all of the herring catch in British Columbia goes towards roe production and currently about one-third is taken in the Strait of Georgia (Table 6). There are also very small food and bait fisheries in the Strait of Georgia but there are no spawn-on-kelp operations. By contrast, the major fishery for herring in Washington (Figure 2) is now as bait to supply the various salmon sport fisheries throughout Puget Sound. A small fishery for herring spawn-on-kelp also operates in northern Puget Sound. In the early 1980s there was a small roe herring fishery of about 2500 to 5000 tonnes valued at US$2 to $4 million on the Pacific herring stock spawning at Cherry Point. The fishery was closed in 1982 due to low herring abundance but the stock has not recovered.

The assessment of spawn deposition in Washington State for estimating stock abundance first began in 1972 (Trumble 1983). The largest herring stock occurs in the Cherry Point-Birch Bay area. This stock declined from a peak in 1975 until 1984 (Figure 2) and has not recovered since, despite closure of the fishery in 1982. The numerous small herring stocks which spawn within Puget Sound proper have shown significant fluctuations over the past 20 years with some declines and some increases but overall stock abundance appears to have maintained itself at about 7500 tonnes.

Pacific Hake

Life History

The Pacific hake, *Merluccius productus,* is also known as the Pacific whiting. Four major spawning stocks have been identified of which the coastal stock off California, Oregon, Washington, and British Columbia is the most abundant and widely distributed (Stauffer 1985).

The other stocks occur in central Puget Sound, the Strait of Georgia, and off the west coast of southern Baja California. Within the Georgia Basin, there may be discrete stocks in both Puget Sound and the Strait of Georgia. Spawning occurs from March to May in the deeper waters of south-central Strait of Georgia at depths of 150–350 m. The fish appear to form two distinct mid-water layers, a shallower scattered layer at 50–120 m over a continuous aggregation at 120–350 m. Most of the actively spawning females occur in the deeper layer. After spawning, the adults aggregate in a shallow layer (50–80 m) along the Vancouver Island shoreline in association with a dense plankton layer (McFarlane and Beamish 1985). It is possible that they are actively feeding to replace the 10–15% of the body weight lost during reproduction. The eggs are 1.5 mm and generally occur at 170–220 m in early April while larvae occurred at similar depths and somewhat shallower as they developed. Hatching occurs in about five days and larvae are found throughout the mid-water during April and May. By June, larval hake disappear from the mid-water possibly moving inshore as they metamorphose and begin active schooling. Immature and juvenile hake are found throughout the Strait of Georgia but there is some indication that they aggregate in inshore waters such as the Gulf Islands and some of the mainland inlets away from the concentrations of adults (McFarlane and Beamish 1985). Growth occurs primarily during the summer months and tends to be slower than for the offshore stocks. Fish mature and spawn for the first time at age four and may reach 20 years of age, although the majority of the commercial catches range from 4 to 11 years old. Males tend to grow slower than females and adults range in size from 40–50 cm.

Distribution and Migration

All stocks of hake within the Georgia Basin are resident and genetically distinct from the coastal population based on parasite and electrophoretic studies of stock separation (Pedersen 1985, McFarlane and Beamish 1985). However, there are no tagging data available regarding the intermixing of Puget Sound and Strait of Georgia stocks. Other biological data indicate that size at age is different between these two stocks so that there is likely little or no mixing occurring between them.

Aggregations of Pacific hake occur in Puget Sound in the Saratoga Passage area from September through December. Subsequently these fish appear to move into Port Susan as they mature and form spawning aggregations in this area from January through March. Throughout the rest of the year the fish appear to be scattered throughout Puget Sound in smaller schools (Pedersen 1985).

Within the Strait of Georgia, hake aggregate in spawning schools in the southern Strait just south of Halibut Bank. Subsequently, distribution tends to move westward towards Vancouver Island and then northward towards Texada Island by September and southern Johnstone Strait by December. This is followed by a southerly movement to the pre-spawning areas in the southern Strait by February (McFarlane and Beamish 1985).

Population Status

The Pacific hake fishery in the Strait of Georgia began in 1979 and catches have increased slowly but steadily to the 1993 catch of 10,686 tonnes (Figure 3). The hake stocks in this area are not subject to the infestations of the parasite *Kudoa paniformis*, which results in the rapid degradation of the flesh of the offshore whiting, and so is more desirable for fillets. The hake fishery in the Strait of Georgia is currently the most valuable groundfish fishery approaching US$1 million in landed value. The hake stocks in Puget Sound appear to be considerably smaller than those in the Strait of Georgia and have been harvested since 1965 by a midwater trawl fishery. Hake were harvested primarily for industrial use as meal until the mid-1970s when markets shifted to a headed and gutted product for human consumption. The fishery peaked at 6569 tonnes in 1982/83 and has been essentially closed since 1987–88 (Figure 3) due to low stock levels.

The hake resource in Puget Sound is of considerable importance and so there have been concerted efforts in both monitoring of the fisheries catch and assessment of stock abundance (Pedersen 1985). Annual hydroacoustic assessments of stock biomass have been conducted since the late 1960s. Total stock biomass seems to have peaked in 1983 and has been declining since then from about 15,000 tonnes to about 4000 tonnes in 1992. Total adult abundance remains below the threshold level of 12 million pounds (5443 tonnes) that is required before any fishery is allowed. There have been recent estimates that sea lions and harbor

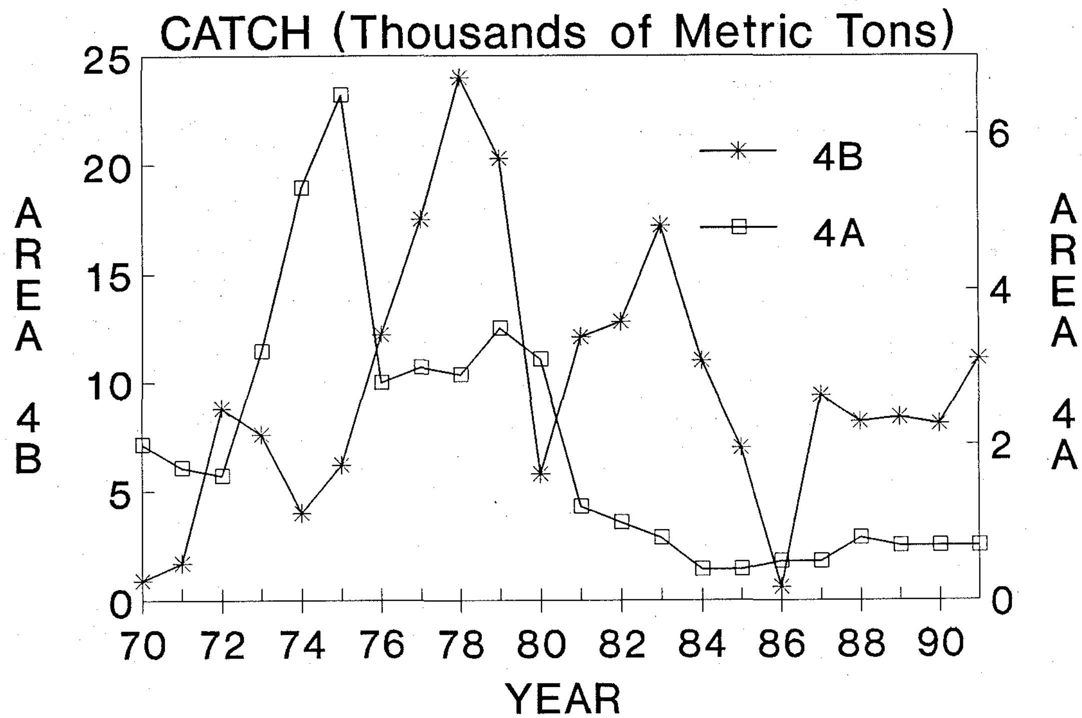

Figure 2. Herring catches in Area 4B (British Columbia) and Area 4A (Washington), 1970–1991.

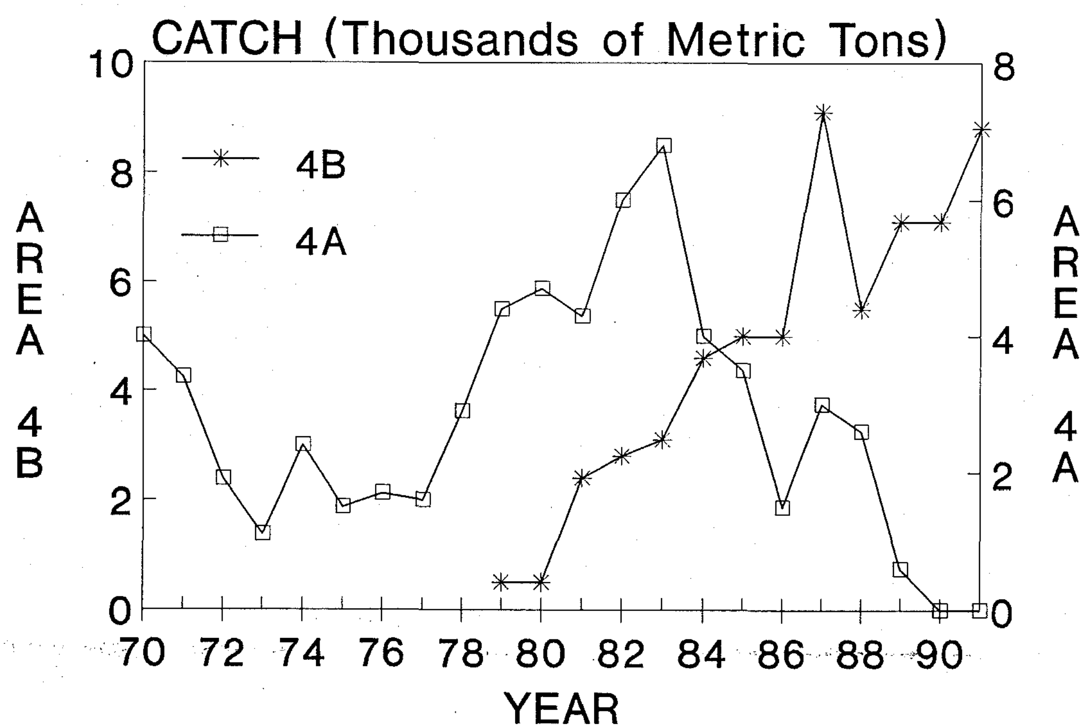

Figure 3. Hake catches in Area 4B (British Columbia) and Area 4A (Washington), 1970–1991.

seals annually consume roughly 1500–2000 tonnes (Schmitt, WDF, unpubl. data). Estimates of annual hake production range from 3500–4500 tonnes when the population was relatively large, so the large biomass being consumed by marine mammals may be restricting the ability of the stock to rebuild to fishable levels.

The hake stocks in the Strait of Georgia have supported a modest fishery averaging 4840 tonnes over the period 1979 to 1992 with a steadily increasing catch that is still below the total allowable catch of 11,000 tonnes estimated for this stock (Figure 3). Hydroacoustic assessments of the Strait of Georgia were conducted in 1981, 1988, and 1993 together with swept volume surveys in the two earlier years. The three surveys in 1981 ranged between 98,000 and 150,000 tonnes while the 1988 surveys estimated about 128,000 tonnes of both juvenile and adult hake. The preliminary estimate for the 1993 survey is for about 245,000 tonnes but there is concern that this estimate could be inflated due to difficulties in assessing the abundance of juvenile hake in the survey area. Nevertheless, based on the relatively limited biological information for this stock and the currently low exploitation levels, these stocks appear to be quite healthy.

Pacific Cod

Information on the life history, distribution, and migration of Pacific cod, *Gadus macrocephalus*, is summarized from reviews by Matthews (1987) and Palsson (1990).

Life History

Pacific cod grow rapidly and females may reach 100 cm in length. The typical size range in the catch is from 40 to 70 cm and 1 to 4.5 kg in weight. Cod mature at two to three years of age. They form large spawning aggregations during the late winter and broadcast eggs and sperm into the water. Fertilized eggs are adherent and sink to the bottom. Although few specific spawning locations are known, cod eggs with attached sand grains were found on coarse sand and gravel habitats in Baynes Sound in the Strait of Georgia. Cod are also believed to spawn near Port Townsend Bay and Agate Passage in Puget Sound. Fecundity of a 40 cm female is about 228,000 eggs whereas an 88 cm female produces about 3.2 million eggs. Fertilized eggs develop into larvae in approximately 8 to 21 days, dependent on temperature. Studies in Canadian waters indicate that the optimum temperature for viable hatches was 2°C. Hatching occurs at the bottom over fine sediment. Juvenile cod are commonly associated with sand-eelgrass habitats.

Pacific cod have a high natural mortality rate and seldom live beyond age six. Small cod feed directly on the bottom and larger cod feed in the water column. Young cod prey upon benthic crab, shrimp and fishes, such as flatfishes, zoarcids, stichaeids, cottids and walleye pollock. Adult cod feed primarily upon pelagic and benthic fishes as well as shrimp. Off Vancouver Island, the main prey items of adult cod are sandlance, herring, and euphausiids, and cod have been implicated as possibly causing strong fluctuations in herring populations in British Columbia.

Distribution

Pacific cod occur throughout the north Pacific from southern California to the Bering Sea, although they are at their southern limit of commercial abundance in Washington waters. Cod associate with a variety of habitats and generally occur in waters 50–200 m deep. Cod distribution is related to water temperature, and adults prefer waters between 0–9°C. Prey abundance may also affect distribution; at times, cod apparently are attracted to a large concentration of herring at the southern tip of Vancouver Island (Westrheim and Pedersen 1986).

Cod are found throughout Puget Sound, although abundance declines from north to south. Spawning cod concentrate in shallow embayments such as Port Townsend Bay and Agate Passage during the winter but disperse to deeper waters during the remainder of the year. Other important spawning, feeding, or nursery areas in Puget Sound include East Sound on Orcas Island, Kilisut Harbor, Port Gamble, Dyes Inlet, and Quartermaster Harbor. In the Strait of Georgia, Nanoose Bay, Hornby Island-Cape Lazo area, and Swanson Channel are important spawning areas (Ketchen et al. 1983).

Migration

During the year, adult cod migrate between winter spawning areas and areas in which they feed during the remainder of the year. Some cod migrate within boundary areas between southern Canadian and adjacent US waters, and there is limited interchange with coastal cod stocks.

In Canadian waters, the presence of more than one spawning population suggests that there are several intermingling units (Ketchen et al. 1983). Migration patterns of cod in the Strait of Georgia indicate that four cod stocks exist. These stocks include a resident stock in the central, western Strait of Georgia, a resident stock in the Gulf Island, a resident stock in Juan de Fuca Strait, and a highly migratory stock that spawns in Nanoose Bay during the winter.

Tagging data for Puget Sound indicate that three stocks exist (Palsson 1990). One stock resides in the Gulf of Georgia, one occurs in Juan de Fuca Strait and Port Townsend Bay, and the third occurs south of Admiralty Inlet.

Population Status

In Area 4B, fluctuations in abundance of Pacific cod are mainly of natural origin (Ketchen et al. 1983). Landings in the Strait of Georgia were 397 tonnes in 1992, substantially above the all-time low of 68 tonnes taken in 1991 (Figure 4). The fishery around Victoria is likely exploiting a temporary concentration of cod and accounts for 96% of the Pacific cod landings in the Strait of Georgia. Potential catches in the remainder of the Strait of Georgia are often not large enough to sustain profitable fisheries, and therefore fishing effort is low. Given the low level of effort, regulation is not considered necessary for this stock. Relatively weak recruitment observed in coastal areas is presumed to prevail in the Strait of Georgia.

In Puget Sound, a severe decline in abundance during the 1980s coincided with a period of warm water temperatures, intense fishing effort, and increased marine mammal abundance. All of these factors likely contributed to the decline in cod populations and cod catches (Figure 4). As mentioned earlier, a very popular recreational fishery in Agate Passage and a commercial set net fishery in Port Townsend Bay have been closed for several years as a result of extremely low cod abundance. Both fisheries targeted spawning concentrations.

Walleye Pollock

Life History

Life history information for walleye pollock, *Theragra chalcogramma*, is summarized from Matthews (1987) and Shaw and McFarlane (1986). Pollock inhabit mid-water or near-bottom environments, and they form spawning aggregations from February to April in localized areas in deep water. Known spawning locations include Halibut Bank, Active Pass-Point Roberts, and Port Townsend Bay. Pollock reach maturity between ages two and four, and as with most marine fishes, fecundity increases with size. A 40 cm female may produce 200,000 eggs whereas a 75 cm female may produce 1.4 million eggs. Females spawn pelagic eggs, which have been found at depths of 100–300 m in the Strait of Georgia. Juvenile pollock settle near the bottom and become semi-demersal. Juveniles have been found in eelgrass, and over gravel and cobble substrates.

Juvenile pollock feed primarily on small crustaceans and then progress to small fishes, including pollock, as they grow to maturity. Cannibalism may be a major determinant of juvenile mortality, based on studies of pollock in the Bering Sea. Most pollock in fishery catches are between two and nine years of age and 28 to 65 cm in length. Pollock have been thought to live to age 17, although recent information suggests they may live much longer (Saunders 1994).

Distribution and Migration

Pollock are abundant in the north Pacific Ocean but are on the southern limit of their exploitable range in Washington waters.

At least four subpopulations are evident in coastal and fjord waters of British Columbia, based on the separation of spawning aggregations, different growth patterns, and different age distributions among stocks (Saunders et al. 1989). Pollock within the Strait of Georgia, including northern Washington waters, are considered to comprise one of these subpopulations (Saunders et al. 1989, Shaw et al. 1989).

Puget Sound fishers harvest at least two stocks of pollock, based on differences in spawning aggregations, growth rates, and limited tagging data (W.A. Palsson, WDF, unpub. data). One stock is part of the Strait of Georgia population, which has been intermittently exploited at its southern limit in Washington waters. The other stock occurs in southern Puget Sound and in the past, supported an important recreational fishery.

Population Status

In the Strait of Georgia, pollock abundance is considered to be at low to average levels (Saunders 1993). Biomass

in 1988 was estimated to be 15,800–29,400 tonnes (Shaw et al. 1989). A hydroacoustic survey of pollock biomass was conducted in 1993, and estimates of abundance should be available soon (Saunders 1994).

Competition between and/or predation on pollock by hake may significantly affect pollock abundance in the Strait of Georgia (Saunders et al. 1989). The commercial trawl fishery has remained small in the past as a result of weak markets and variation in availability. The demand for pollock as foodfish appears to be inversely related to the availability of more desirable species like Pacific cod and lingcod (Saunders 1994). As shown in Figure 5, catches in Area 4B have reflected this variability.

In Puget Sound, the abundance of the southern stock is considered to be very low, based on declining fishery catches and effort. Estimates of abundance are not available. Natural and fishing mortality likely contributed to the severe decline in abundance since the 1980s. The stock apparently declined, in part because of progressively lower recruitment from year classes born during 1975 to 1984. High fishing mortality may have hastened the population decline and suppressed recovery (Palsson, WDF, unpub. data). Declining catches (Figure 5) since 1982 primarily reflect decreasing recreational catches of pollock in southern Puget Sound. At one time, pollock was the most numerous marine fish in the recreational fishery in Area 4A, but currently, it is one of the least common species. The peak catches between 1978 and 1982 resulted from comparatively large commercial catches of the Canadian Strait of Georgia stock which moved south into northern Washington waters during those years.

Dogfish

Life History

Spiny dogfish *(Squalus acanthias)* is a very slow-growing and long-lived species of shark that is abundant throughout the Georgia Basin. Most fish in the commercial catch are females because only a small percentage of males grow to marketable sizes (over 70 cm). On average, males mature at age 18 and older, and may live beyond age 60. The average age of maturity for females is 35 years, and some may live more than 80 years (McFarlane and Beamish 1987; Saunders and McFarlane 1993). After a gestation period of 22 to 24 months, each female may produce 2 to 20 young, but usually 6 or 7. Breeding is thought to occur during December through January and young are usually born during October-November, two years later.

Dogfish feed on a wide variety of fish and shellfish and may form feeding schools where food is abundant. In early life, food consists mostly of invertebrates but as age advances, the diet changes to mainly fish and large invertebrates. Herring, hake, sandlance, and smelt comprise the majority of their diet.

Distribution and Migration

Based on tagging data, dogfish within the Georgia Basin are considered one stock (Saunders 1985), with limited interchange with coastal stocks. Within the Georgia Basin, dogfish make considerable movements and often school for feeding and perhaps spawning. For example, females apparently congregate in East Sound, near Orcas Island, during the summer prior to spawning.

Population Status

The dogfish population in the Georgia Basin is at average to high levels. The estimated biomass was 60,000 tonnes in 1988 for Areas 4A and 4B combined. Because current harvests (Figure 6) are low (about 2000 tonnes), the population is expected to continue increasing over the next decade (Thomson 1994).

Catches of dogfish have varied greatly over the years, primarily as a result of changes in market demand and restrictions on fisheries for other species. Currently, dogfish account for about half the total catch of groundfish in Area 4A. They are harvested commercially in the trawl, longline and set net fisheries.

Lingcod

Information on lingcod *(Ophiodon elongatus)* life history, distribution and migration is primarily summarized from Cass et al. (1990).

Life History

Adult lingcod prefer rocky bottom habitats with high current velocities. They are voracious feeders, preying upon other fish and some molluscs. Males may reach 9 kg and are generally found at depths under 37 m. Females may exceed 23 kg and, except when spawning,

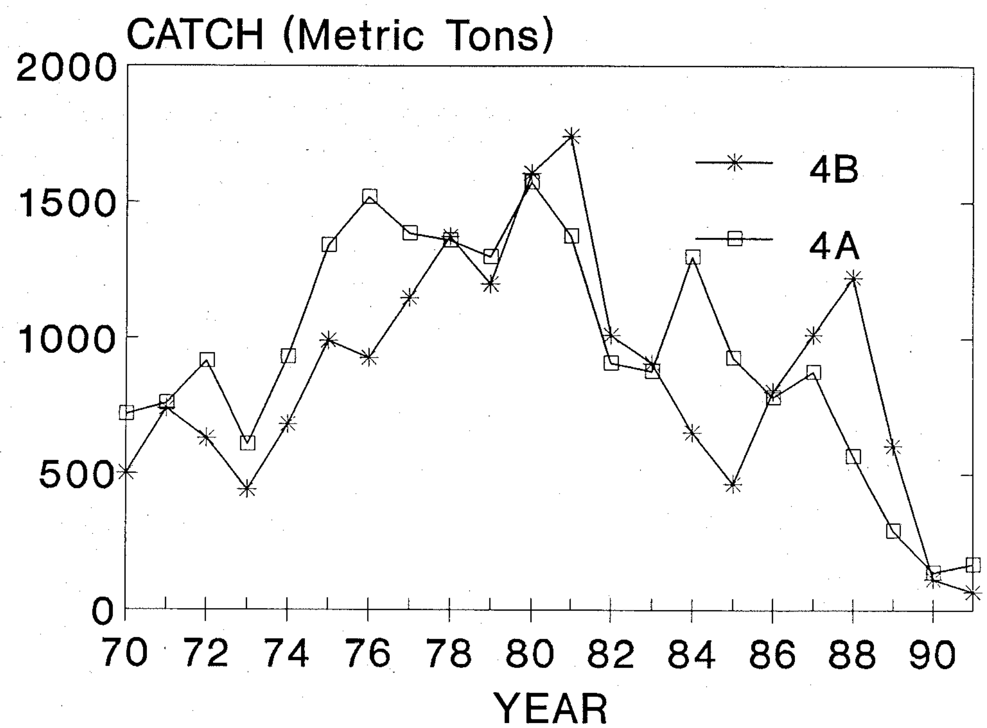

Figure 4. Pacific cod catches in Area 4B (British Columbia) and Area 4A (Washington), 1970–1991.

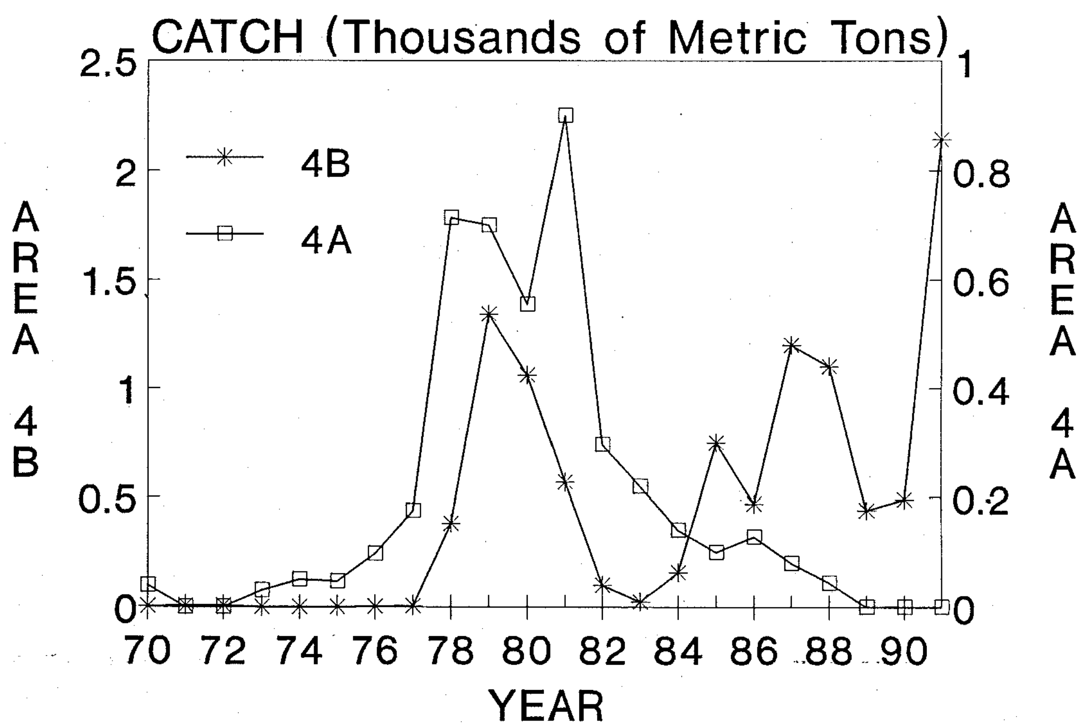

Figure 5. Pollock catches in Area 4B (British Columbia) and Area 4A (Washington), 1970–1991.

are found at greater depths (55 to 90 m). Most females are mature by age five and most males mature at age two. Prior to spawning, males establish territories in shallow, rocky habitats by December. During the winter mature females lay adhesive egg masses in crevices. Males guard the eggs until hatching, about seven weeks, and are extremely vulnerable during this time to capture by hook and line and spear gears and to predation by marine mammals. Hatching is nearly complete by April. After a two- to three-month pelagic stage, larval lingcod inhabit sandy, estuarine areas for about six months before moving to the adult habitat.

Distribution and Migration

Lingcod are found only off the west coast of North America and are considered non-migratory. Tagging studies show that most adults (>95%) move less than 35 km from their release site after years at liberty (Smith et al. 1990). Because lingcod are so sedentary, those within the Strait of Georgia are considered a single stock (Smith et al. 1990). Tagging data for Puget Sound also indicate that most lingcod move very little and make only short transboundary movements between British Columbia and Washington waters (Davis 1986).

Population Status

Lingcod abundance is at an extremely low level throughout the Georgia Basin and severe fishery restrictions have been implemented in Areas 4B and 4A. Catches (Figure 7) and catch rates have severely decreased over the past decade (Murie et al. 1993). Catches in both areas showed a small peak during the early 1980s, when a few strong year-classes apparently supported the fishery (Bargmann 1986). However, catches declined continuously since 1982 and total less than 50 tonnes in each area.

In Area 4B, the commercial lingcod fishery is primarily a handline/troll fishery, although longline and trawl fisheries have minor catches. In Area 4A, the trawl fishery is the main commercial fishery, although the longline fishery catches small amounts. Lingcod is also a very popular sportfish for anglers and spearfishers throughout the Georgia Basin.

In Area 4B, the sport fishery is likely the main human cause of a continuing decline in lingcod landings (Murie et al. 1993). In addition, natural mortality in recent years, particularly for males and small females, has included increased predation by marine mammals (Smith et al. 1990). In Area 4A, both commercial and recreational fisheries likely contributed to the decline. Over the past several years, both fisheries have harvested approximately equal amounts with commercial fisheries primarily harvesting females and sport fisheries primarily harvesting males. As in Area 4B, increased marine mammal predation may also have contributed to the abundance decline in Area 4A.

Rockfish

Life History

A variety of rockfish *(Sebastes)* species inhabit the Georgia Basin, but eight species comprise most of the harvest. These eight species include black, bocaccio, brown, canary, copper, quillback, yelloweye and yellowtail rockfish.

Rockfish show a diversity of life history patterns. Although the particular diet of each species differs, rockfish feed on a variety of small crustaceans, molluscs, and fish. Quillback, brown, and copper rockfish are slow-growing species. In sport catches, they average 33 cm in length and about 1 kg in weight, although they may weigh up to 3.6 kg. Canary and yelloweye rockfish are also slow-growing, but those in the catch are larger, on average. These species may average 1.4 to 1.8 kg, although yelloweye may weigh up to 11 kg. Black and bocaccio grow faster than the other species and are commonly 1 to 3.6 kg and 30 to 50 cm in length. Few mature yellowtail rockfish occur in Puget Sound and most average 30 to 40 cm in length.

The age and size at maturity, as well as the spawning season, varies among species. Most female quillback, copper, and bocaccio rockfish are mature at age four, whereas female brown and black rockfish mature at slightly older ages, 6 and 7 years, respectively. Female canary rockfish mature, on average, at 14 years, and age of maturity is not known for yelloweye in Puget Sound.

Depending on the species, spawning seasons range from winter to summer and all rockfish bear live young. Black, bocaccio, and canary rockfish release their young during the winter, whereas copper, quillback, and brown rockfish release young during the spring. Yelloweye rockfish release their young during June. For the

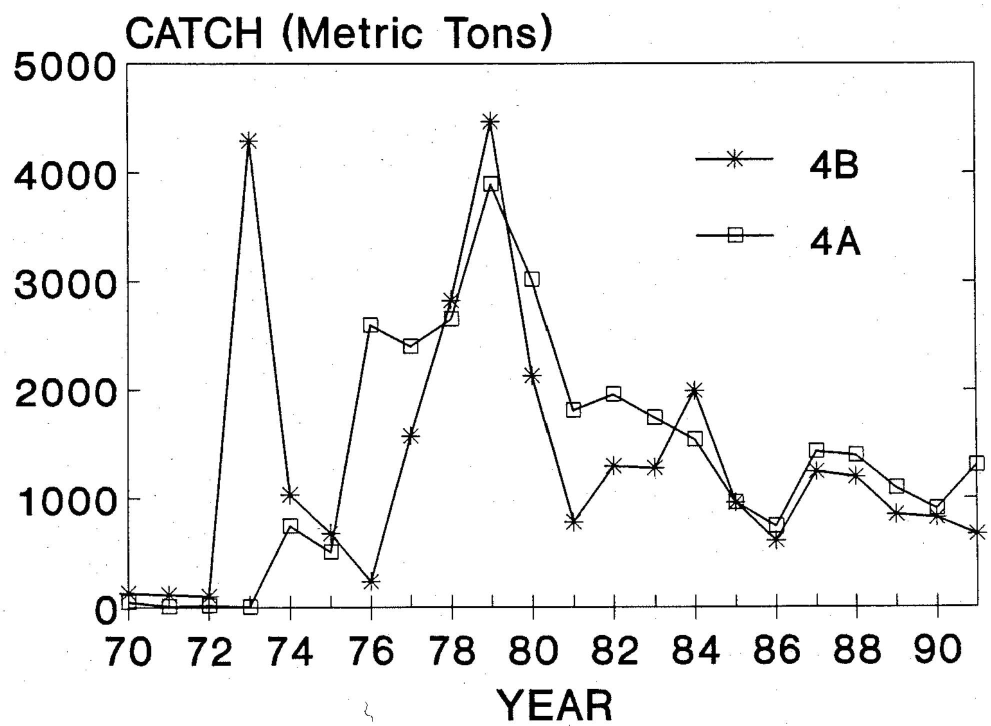

Figure 6. Dogfish catches in Area 4B (British Columbia) and Area 4A (Washington), 1970–1991.

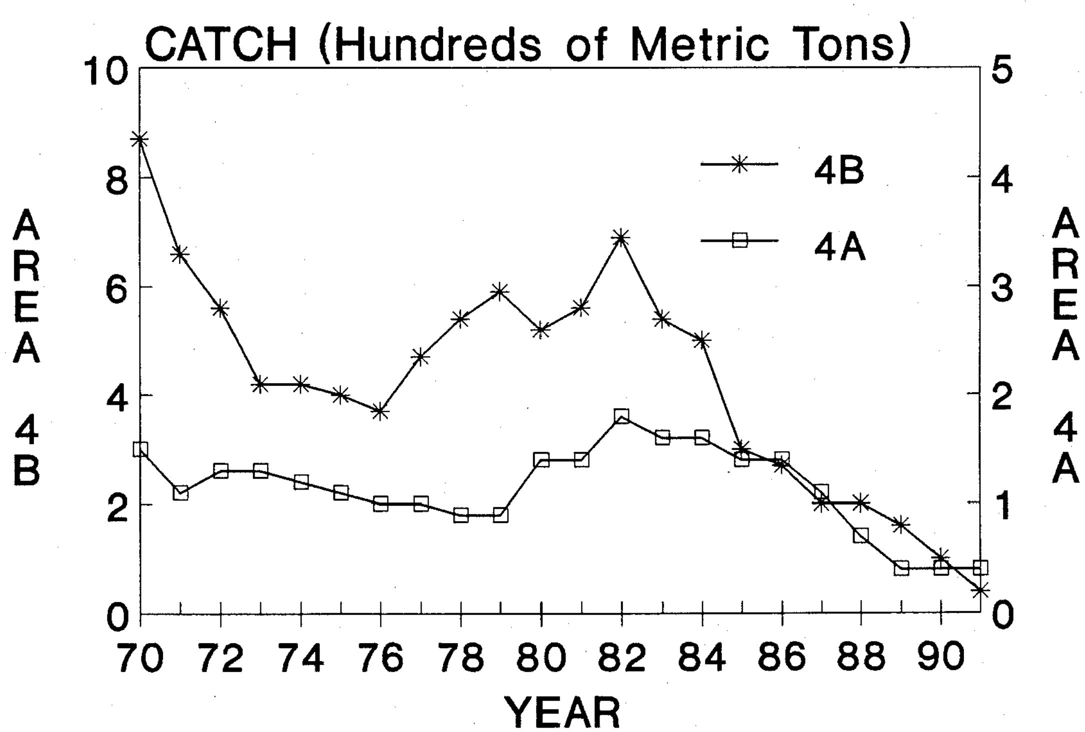

Figure 7. Lingcod catches in Area 4B (British Columbia) and Area 4A (Washington), 1970–1991.

Georgia Basin, locations where live young are released and the duration of the pelagic phase for juveniles prior to their recruitment to adult or transitional habitats are not known.

Distribution and Migration

Copper, quillback, and brown rockfish are generally found in shallow water, near kelp or rocky habitat, whereas canary and yelloweye rockfish occupy rocky habitat at depths greater than 37 m. Bocaccio occur in localized areas characterized by steep dropoffs to 90 m, and black and yellowtail rockfish form pelagic schools around kelp or rocky habitats.

Tagging information indicates that adult copper and quillback rockfish are very sedentary and show a high degree of homing in displacement experiments. Habitat quality also appears to be a significant factor affecting their movements. These species move seasonally, perhaps to take advantage of seasonally suitable habitats. For example, in late fall when kelp dies back, rockfish leave low relief reefs perhaps because the shelter and prey associated with the kelp is no longer available. In contrast, there appears to be little seasonal movement from high-relief reefs (Matthews 1990a,b).

Population Status

In Puget Sound (Area 4A), rockfish abundance is considered to be at a low level. Although catches (Figure 8) have been relatively constant at about 200 tonnes annually for the past decade, effort, particularly by sport fishers, has increased. Catch rates and sizes of rockfish in recreational fisheries have declined consistently for several years, especially around the San Juan Islands and in southern Puget Sound. The extent to which catches are being sustained by anglers fishing in new areas and/or targeting additional species is not known. Commercial harvests of rockfish have been increasingly restricted over the past few years, and more restrictive sport fishing regulations are being proposed for 1994.

In the Strait of Georgia (Area 4B), the stock condition for inshore rockfish is poor (Yamanaka and Richards 1994). Catches (Figure 8) increased almost continuously from a low of 60 tonnes in 1974 to a peak of 688 tonnes in 1986, but stabilized around 600 tonnes through 1991. Since 1986, increasingly restrictive regulations were implemented for the commercial and sport fisheries and catches were reduced to 300 tonnes by 1993 (Yamanaka and Richards 1994).

Rockfish are harvested in nearly every commercial and recreational fishery for groundfish in the Georgia Basin. In Areas 4A and 4B, all rockfish species are managed as a unit, primarily because each fishery harvests several species and they are difficult to identify. Although only limited information is available on the species composition of rockfish catches, quillback and copper rockfish comprise the majority in Area 4A, but yelloweye is also an important species in Area 4B.

In general, rockfish populations are more vulnerable to overharvest and take longer to recover than many other marine species. Although populations are less influenced by environmental conditions, they are difficult to manage properly for several reasons: they are harvested in mixed-species fisheries, they are very sedentary in relatively shallow water, which makes them relatively easy targets for anglers and divers, and they grow so slowly and mature at older ages.

English Sole

Life History

English sole *(Parophrys vetulus)* occur over flat bottom, mainly at shallow depths during the summer and up to 125 m during the winter. They feed on bottom-dwelling invertebrates. Males seldom appear in commercial landings because only a small percentage grow to marketable size (30 cm). Most females weigh less than 1.4 kg and few exceed 50 cm in length. Females usually mature at three years of age and spawn pelagic eggs at depths generally between 20 and 90 m during midwinter. The eggs are buoyant and rise to the sea surface. Larvae carried to sandy intertidal areas metamorphose and settle to the bottom. By late summer, they move to subtidal waters and eventually move to adult depths as they grow over the next two or three years (Ketchen et al.).

Distribution and Migration

Tagging data indicate that many subpopulations exist, with relatively little mixing in the Georgia Basin. In the Strait of Georgia (Area 4B), at least three stocks exist: one between Parksville and Comox, another in waters

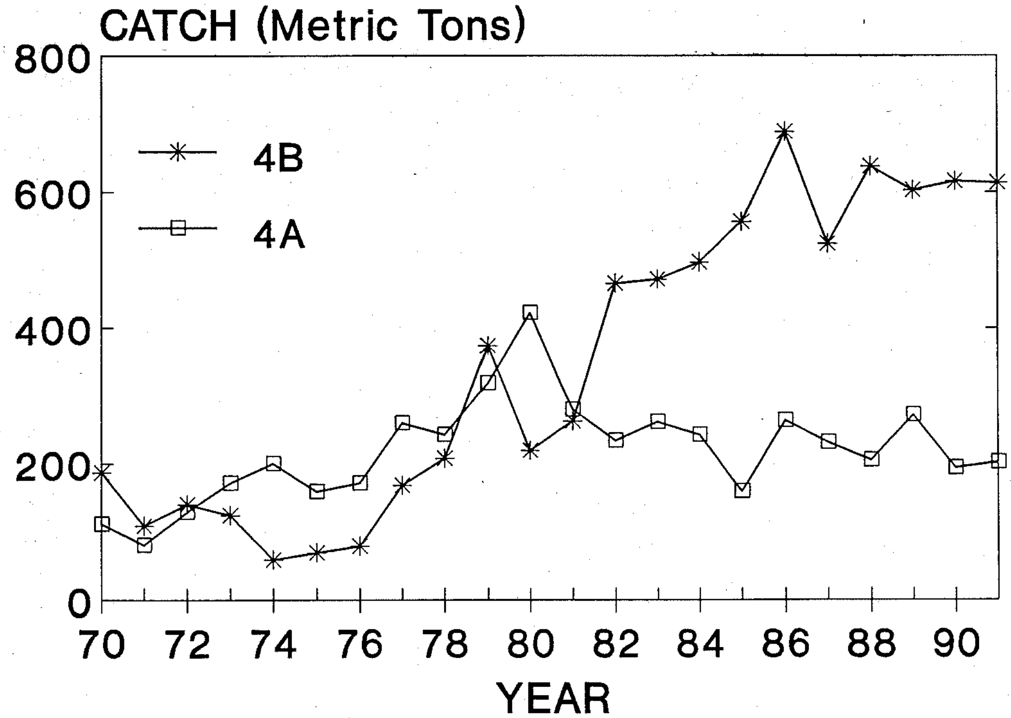

Figure 8. Rockfish catches in Area 4B (British Columbia) and Area 4A (Washington), 1970–1991.

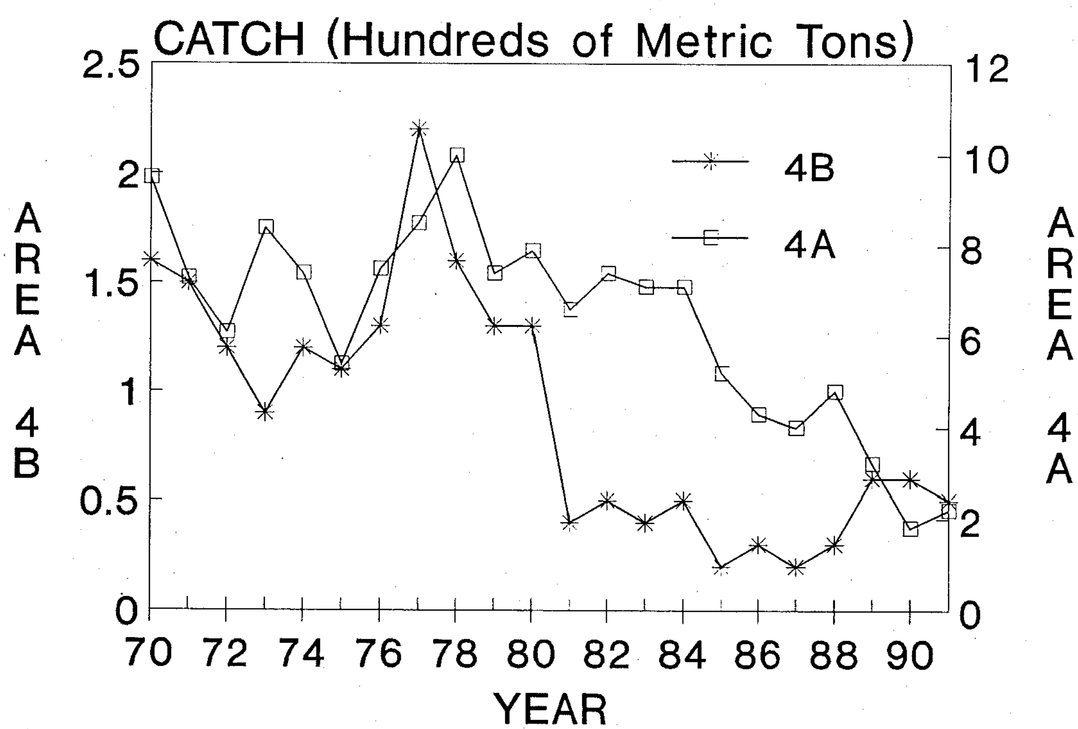

Figure 9. English sole catches in Area 4B (British Columbia) and Area 4A (Washington), 1970–1991.

among the Gulf Islands from Nanaimo to Sidney, and a third from Burrard Inlet south into northern Washington waters. A fourth, highly migratory stock is believed to enter the Strait of Georgia in the summer and return to the open coast in late fall (Ketchen et al. 1983). Displacement experiments in central Puget Sound showed significant homing by English sole and that fish not displaced during tagging remained essentially at their original capture location (Day 1976). English sole also make seasonal migrations associated with spawning.

Population Status

English sole are harvested nearly exclusively in commercial bottom trawl fisheries. In the Strait of Georgia (Area 4B), fisheries are at a low level (Figure 9) with little need for regulation. Most harvests occur in relatively undeveloped areas and have been lower than in earlier years; populations are thought to be at average levels (Fargo 1994).

At present, English sole populations in Area 4A appear to be relatively healthy and in stable condition, with some localized exceptions like Discovery Bay and Bellingham Bay. Based on commercial catches and catch rates, English sole abundance in Discovery Bay is at an extremely low level, and abundance in Bellingham Bay may also be low. Recent declines in harvest in Area 4A (Figure 9) are mainly attributable to increasingly restrictive regulations since the early 1980s. In 1989, all of Puget Sound south of Port Townsend was closed to bottom trawling, so essentially no English sole are harvested from this area. Consequently, populations are thought to be in good condition. However, reproductive success has been shown to be impaired by chemical contaminants, which have been measured in English sole in urban bays or those with pulp mills. A time-series of abundance information is not available for small or unfished areas, such as the urban bays, and therefore, the effects of chemical contaminants on fish populations in the bays are not known, but likely detrimental.

HUMAN-INDUCED THREATS

In Puget Sound causes of the declines in many marine fish populations are not well understood and a variety of factors likely contributed to the current low levels of abundance for most species. Overall, fishery harvests probably were the primary factor through the early 1980s, but they have continuously diminished to very low levels and may no longer be a significant factor for some species. As fishery harvests were reduced, predation by marine mammals grew and it may be preventing some populations, such as lingcod and Puget Sound hake, from rebuilding to former levels. Environmental factors also contribute to natural variations in abundance, and for some species, particularly gadids, environmental conditions have been unfavorable for several years and may be a significant factor in their low abundances. For example, a lengthy period of warm water temperatures during the winter has likely reduced survival of young cod and other gadids. Loss of eelgrass beds and degradation of critical nearshore habitat contributed to declines in herring and probably to most other marine fishes. In addition, competition for space and food, such as with the large releases of cultured salmon, is an unknown, but possibly significant factor.

In British Columbia, many of the same factors are operating on the populations but likely the fishery-induced effects are paramount. Most of the groundfish fisheries are of currently marginal viability, although the hake fishery continues at a significant level due to the large available biomass. Little is known about the susceptibility of most groundfish species to pollutants and urbanization in coastal areas of British Columbia. The large migratory herring stocks suffered drastic declines in the 1960s due to high exploitation levels and it is largely because of the conservative harvesting levels adopted with the beginning of the roe fishery that stocks have rebuilt to historical levels. The Georgia Basin also supports a multitude of small, apparently resident herring stocks that provide bait for the salmon sports fishery. These stocks occur primarily in southern Johnstone Strait and the Gulf Islands and because of their small size and localized spawning habits are particularly susceptible to habitat losses through urbanization. They could easily be extirpated before their loss is realized. Consequently, it is also very difficult to determine sustainable harvesting levels for them (Schweigert and Linekin 1990).

Much of the coastal habitat within the British Columbia portion of the Georgia Basin remains relatively pristine. Pacific herring home to the same spawning areas each year similarly to Pacific salmon. Consequently, they are subject to the same kinds of spawning

habitat disturbances or destruction as salmon. There is evidence that herring no longer spawn in a number of traditional locations throughout the Strait of Georgia. Many of these sites have been altered by urbanization apparently rendering them unsuitable as spawning sites. Similar effects are evident for the major urban centers in Puget Sound (Chapman et al. 1941; Williams 1959). Projected population increases throughout the Georgia Basin can be expected to increase the impacts on foreshore areas including many of the important herring spawning areas. Any large scale destruction of spawning habitat would significantly decrease herring production and as the base of the food chain would have impacts on all levels of the Georgia Basin ecosystem.

Other factors may also contribute to the declines in marine fish abundance, but they have not been evaluated in the Georgia Basin. Because fish toxics is the subject of another paper in these proceedings, we will only briefly mention them here. Chemical contaminants in fish tissues reduce reproductive success in laboratory studies on English sole, and microlayer contaminants reduce larval survival. Larvae of many marine fish species die from consuming phytoplankton that produce paralytic shellfish poisoning (Nishitani et al. 1988; Matter 1994). Therefore, the recent resurgence in time and area of phytoplankton that causes paralytic shellfish poisoning in Puget Sound may be a factor in marine fish declines (Nishitani et al. 1988), although this has not been studied in the Georgia Basin. In general, the information on fish abundance is not sufficiently specific in time and location to evaluate the effects of fish toxics.

CONCLUSIONS AND RECOMMENDATIONS

Fishing and other pressures on marine fishes have increased over the past decade and will continue to rise as the population and the popularity of fishing for marine fishes grows. Marine fish resources in Puget Sound have seriously declined and harvests are at their lowest level in over 55 years. Data used to assess marine fish populations come mainly from the fisheries, so information on populations has declined as severely as the fisheries. Over the past decade, more restrictive fishing regulations to reduce harvests and promote rebuilding have been implemented every year; however, populations so far have failed to recover. In the Strait of Georgia, marine fish populations, except lingcod and rockfish, are larger and in better condition. More restrictive fishing regulations have also been implemented to promote rebuilding of the lingcod and rockfish resources throughout the Georgia Basin.

The important scientific questions facing fisheries managers in trying to cope with such drastic population declines and stock rebuilding relate to developing a better understanding of the relative importance of biotic and abiotic effects on population abundance. Progress must be made in identifying the critical stages in the life history of various fish species and how sensitive they are to environmental variability. Fisheries biologists are increasingly focusing on the juvenile phases for many marine species in the inshore areas when they are particularly susceptible to predation. Unfortunately, very little is known about these stages in the life cycle of most marine species or even how they utilize much of the littoral zone. Anthropogenic effects resulting from population growth and urban sprawl tend also to be most significant in this area of the marine environment. The most desirable areas for human habitation and development are the waterfront areas in bays and coves, often at river mouths or estuaries transforming them into marinas, log dumps, and industrial or condominium developments, while destroying the eelgrass beds and associated algae that provide both cover and forage to juvenile fishes of many species. Unfortunately, these impacts are insidious, being small in scale but cumulative in their effects, until eventually much of the natural historic productive potential of the area has been lost through no single readily identifiable cause.

To mitigate some of the effects of development, one approach that is gaining in popularity is the use of marine ecological reserves as a fisheries management tool to preserve and enhance natural productivity for many species (Dugan and Davis 1993). As a component of the establishment of such reserves, detailed inventories of existing intertidal and subtidal habitats could be developed to provide a baseline of existing resources that require preservation. Some progress in this area has already occurred. British Columbia has established 11 ecological reserves of which four exist in the Strait of Georgia, ranging in size from 35.0 to 343.3 ha. Another completely marine reserve has also been proposed for Agamemnon Channel in Jervis Inlet. In addition, of 49 coastal marine parks, 31 exist within the Strait of Georgia and another ten existing marine parks are being expanded. In Puget Sound, a few small marine

reserves have been established around the San Juan Islands for research purposes, and the state is beginning to establish a series of underwater preserves and parks where harvesting is prohibited.

Existing information on the success of marine reserves in enhancing temperate fish populations is encouraging, but some generic questions relating to the optimum number, size, and distribution of reserves relative to the location of harvesting areas require further study (Davis 1989; Roberts and Polunin 1991; Dugan and Davis 1993). Research studies should be aimed at addressing these questions for the Georgia Basin. A component of this research should focus on the importance or various inshore ecotypes to marine fish production.

A better appreciation of the importance of abiotic factors on stock abundance is critical to evaluating the impact of anthropogenic effects on the Georgia Basin ecosystem. Recent decades have seen incremental advances in our understanding of climatic effects such as El Niño on the temperate marine environment. However, ongoing collection of time series of species abundance data are necessary to understand these effects on the biological systems. Comprehensive and standardized monitoring systems to census a representative sampling of the 200 species in the Georgia Basin annually or biannually, rather than focusing only on the commercially important stocks, should be instituted. While questions of defining indicators of ecosystem health or wellness are difficult to address without defining a clear set of societal goals for environmental quality, long-term changes in species composition or abundance would signal dramatic changes in ecosystem health or viability. A monitoring program, augmented by an endowment fund to support graduate student research related to understanding the effects of long-term environmental variability on recruitment and interspecific trophodynamics in the Georgia Basin marine ecosystem, will provide a better basis for evaluating the impacts of population growth on the Georgia Basin marine environment in the coming decades.

Another recommended priority is increased public awareness and understanding of the conditions of and factors affecting marine fish populations in the Georgia Basin. The human population surrounding the Georgia Basin is expected to increase dramatically over the next decade and most of these newcomers will have little understanding of marine resource needs or of their impacts on these resources. An improved understanding by the public may help shape their expectations about future productivity and the likelihood of populations rebuilding to historic high levels, given the habitat loss and degradation that has already occurred. Increased public awareness and understanding also may lead to greater stewardship activities. In addition, those involved in growth management planning should be provided with better information and in a useful format so that they may make the best decisions possible.

In summary, we have a limited understanding of the anthropogenic influences on fish populations in the Georgia Basin and we recommend five actions to begin to safeguard our resources for the future. These five actions include:

- increasing interjurisdictional cooperation and collaboration;
- implementing an integrated, long-term monitoring program;
- evaluating the potential of marine reserves for fish protection and preservation;
- improving other habitat protection and restoration efforts; and
- increasing public awareness of marine resource needs.

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DISCUSSION

Andrea Copping *(Panel)*: Cyreis I'm left with the impression that more Washington, or specifically Puget Sound, fish stocks are in trouble than those in B.C. Is this a fair assessment, or this an artifact of the data?

Cyreis Schmitt: I think we have seen more depressed stocks in Washington than in British Columbia. Obviously my knowledge of B.C. stocks is fairly cursory, most of my work having been done in Puget Sound, but it seems fairly clear that the stocks are larger, and can sustain higher fishing pressures than our stocks in Puget Sound — even when they're healthy. There is perhaps less intense fishing on B.C. stocks because of other resources, lower population and also the way they are managed. I think what led to some of the overfishing in Puget Sound was not knowing when a stock was in trouble until it was too late. Often the information comes in two or three years after the event. You see a decline and you don't know whether it's natural variation causing things to be depressed somewhat, so you are hesitant to make a change that would restrict harvest unnecessarily. The tendency is to wait until things are really bad, and then it is too hard to call a halt to the situation.

Andrea Copping *(Panel)*: Does that hold true for the salmonids as well the marine fish?

Cyreis Schmitt: I really don't have a sense for salmonids. They are so complex, there are so many jurisdictions, and the habitat-side is also more important. Stream, freshwater habitat problems, the mixing of stocks offshore and the various jurisdictions — Alaska, Canada, Washington, tribal people — make for a complex management system.

Chris Garrett *(Panel)*: I noticed you didn't mention mackerel. Is that something that is under-utilized or just intermittent?

Cyreis Schmitt: Mackerel rarely come into Puget Sound proper. They were in abundance, relatively speaking, this past year. We had unusually warm water temperatures and some people did try and take advantage of their unusual occurrence in the Sound. But they are not typically a significant part of the Puget Sound or Strait of Georgia populations.

Chris Garrett *(Panel)*: Are there other under-utilized species? Do we, for example, make the most of the herring we catch?

Cyreis Schmitt: I think herring is one that everyone wants to see maintained at it's maximum productivity level because it is so important to all the other species. I think when herring are caught for human consumption, you're taking fish that are important for food for salmon, birds, marine mammals and other resources. So herring, I think, would be one that people would not like to see any additional removal for human consumption. There may be others — smelt could be one — that might offer increased opportunities for harvesting. I think smelt is currently being evaluated for its potential and also for its potential risk. It spawns in the intertidal zone on graveled beaches, so all the shoreline development you see, bulkheads etc., could harm that species. I think we're trying to go slowly, at least in Washington waters.

Chris Garrett *(Panel)*: But do we make the most of the herring? I don't really know what we do with it. Is a lot just caught for roe, and the rest ground up for meal or what?

Cyreis Schmitt: In Washington the primary fishery is as bait for salmon and as spawn-on-kelp. In the spawn-on-kelp fishery, the adults are released, presumably unharmed, so they can come back and spawn again. I believe in Canada the primary fishery is for roe.

Jake Schweigert: I'll just add to that. The harvest of herring in Canada is strictly for the roe market; there's virtually no demand for food. Part of the issue is that Pacific herring tends to be a lot smaller than the Atlantic herring, so most of the food market niche is filled by imported Atlantic herring. Also, the market in Japan is relatively limited and the management system within B.C. focuses on trying to provide the highest value product for that market, so you are just targeting on a limited niche. We limit the catch to 20% of the forecast stock in any area, and that is enough to fill the Japanese demand.

Cyreis Schmitt: I think also there is a general feeling among the people who live in Puget Sound and surrounding area that they would like to see commercial fishing stopped entirely, and the resource utilized for recreation purposes, as hook and line and taking a fish home to eat, as a maintenance of the ecosystem and the marine environment for non consumptive enjoyment.

So I think there's sort of a bias against new commercial ventures in those waters.

Bruce McCain *(Panel)*: Have you noticed in cases where stocks have been depleted in Puget Sound, for example the cod, if there is an accompanying decrease in important prey organisms?

Cyreis Schmitt: We haven't looked at prey species at all. We're not even able really to monitor cod to any great degree. It's an important area, but we haven't been able to look at it. We were trying to identify prey species of rock fishes and their habitat requirements, but that work has also been cut for budgetary reasons recently.

Dave Nysewander *(Washington Department of Wildlife)*: You didn't mention too much about forage fish or sandlance. I wondered how you visualize our need for monitoring at the food chain base.

Cyreis Schmitt: Sandlance is probably as important as herring in the food chain, and is probably also prey to a wide variety of species, and has been fairly abundant. I know that there were some limited attempts at monitoring its abundance about 10 years ago, but they were unsuccessful in finding a method of assessing abundance, and we haven't spent much effort since that time.

Ken Warheit *(Washington Department of Wildlife)*: Do you think any of the stocks in Washington State are at a critical point where they are so low that a single acute event — such as any kind of toxic spill, an oil spill for example — will be fatal to the population?

Cyreis Schmitt: Yes I do. In my opinion, southern Puget Sound cod, or almost any of the populations in southern Puget Sound, might be wiped out if we were to have a large oil spill, in the order of the *Exxon Valdez*. Many of the small resident populations south of Port Townsend have been hit the hardest through fishing, and have shown the greatest declines. I think those are particularly vulnerable. For example, our whiting population spawns only in one bay that we know of. If something catastrophic were to happen in that one embayment, although there would be a few juveniles in other parts of the area that could replenish it over time, I think that they are in critical condition.

Ken Warheit *(Washington Department of Wildlife)*: What about herring?

Cyreis Schmitt: There's a large migratory population north of Cherry Point, but then there are a whole bunch of small stocks in southern Puget Sound that seem to utilize different areas from year to year. In overall abundance they seem to remain stable. I suppose again that if we had a Sound-wide catastrophic event, that could have a similar impact.

Jake Schweigert: There's an ongoing debate among the herring biologists about what constitutes a genetically discrete stock. I think there's enough evidence that herring spawn in a number of these little bays and inlets are somehow discreet in that they spawn at different times, and there tends to be differences in age structure and size at age. So there is some sort of difference in productivity between different populations which may or may not be genetic. But certainly there is a concern that if you lose one they may not re-establish themselves.

Martin Keeley *(Friends of Boundary Bay)*: I have a comment and a question. I have several friends who are fishers, or fishermen, whichever you choose, on the Canadian side. I think you can predict stocks crashing if you listen to them. One of my particular close friends last year fitted-out his herring boat with sonar because he could no longer see which direction the herring shoals were coming from. With sonar he could pick them up quicker than the other fishing boats and get there faster. It's his contention that herring stocks are falling rapidly and that this is an indication. My second point is, I have another friend on the US side whose biggest bug there is that they have to throw back the incidental catch, and the single-species fishing and monitoring seems somewhat archaic when we think in terms of ecosystems. I wondered when you were doing your studies and your planning and your numbers whether in fact you are taking into consideration the incidental catch which just gets thrown overboard, because if the fishermen are caught with it on board they get fined?

Cyreis Schmitt: For the majority we're not taking into account incidental catch. I believe on the Canadian side incidental catch was estimated for a few species. In Washington, particularly for gadids, the fishing has generally occurred on spawning stocks. When they are aggregated during spawning those species make up over 90% of the catch, so the incidental catch has not been considered harmful to other stocks. When they are

harvesting hake they are not getting lingcod, rockfish or flatfish, although there is a troll fishery that does take mixed species. In Washington the species thrown back are usually shellfish and invertebrates. Generally now the single operator, small mom-and-pop kind of operation, is being phased out. So I think that in a few years, maybe 5 or 10, we probably will not see those fisheries in Puget Sound any longer.

Dave Somers *(Biologist for The Tulalip Tribes)*: I just have a comment, in case there is any optimism left about Washington fisheries. Regarding the salmon stocks or the number of stocks listed as healthy, the report that generated that information defined healthy stocks as stocks that were not imminently in danger of being listed as threatened or endangered under our Endangered Species Act. So in fact, a number of those stocks have no harvestable surplus. While in the biological classification they are self sustaining, they are not necessarily commercially harvestable any more.

John Azar *(Ministry of Environment, Lands and Parks)*: With the predicted increase in the number of people out in boats, and given the catches and what you know about the populations, can you speculate on what stocks might be like with twice as many people fishing recreationally?

Cyreis Schmitt: I think that depends on what we do now, and how successful we are in persuading local governments to incorporate habitat protection measures. For example, King County just this last week considered requiring farmers to fence along streams that had salmon in them. As cows go through the streams they damage the stream bank and also introduce urine and other matter into rivers which is harmful for fish. The Council, after hearing all the testimony, and it was quite heated testimony, did decide to pass it. The King County Executive on the other hand vetoed it. The Council then overrode this veto and we have a new King County Executive whom I expect may go ahead and pass this. That's the kind of debate we are facing now. It is no longer a decision that a biologist is going to make, or that a director is going to make. It takes all the people out there to make those decisions.

Status, Trends and Potential Threats Related to Birds in the Strait of Georgia, Puget Sound and Juan de Fuca Strait

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ABSTRACT

Systematic censuses or inventories of bird populations in British Columbia and Washington have emphasized: (1) numbers and productivity at breeding colonies; and (2) overwintering populations utilizing various marine habitats. Populations of urban Canada Geese, Glaucous-winged Gulls, Caspian Terns, Pelagic and Double-crested cormorants, Bald Eagles, Peregrine Falcons, and Osprey have increased. Species of concern because of low numbers or habitat loss include Marbled Murrelets and Harlequin Ducks. Washington's depressed Common Murre population is also of concern. Wintering populations of birds tend to be much larger than the summer breeding populations. Species diversity is also greater during winter due to an influx of waterfowl and marine birds.

The Canadian Wildlife Service has used eggs from Great Blue Herons and cormorants to monitor trends of environmental contaminants in the Strait of Georgia since 1977. Levels of PCBs, DDE, dieldrin, heptachlor epoxide, PCDFs and PCDDs have fallen. Based on results from monitoring contaminants in several waterfowl species, a health advisory regarding the consumption of livers from Western Grebes and Common Mergansers was issued in 1990. A limited number of studies have been conducted on contaminant concentrations in birds in Washington's inland marine waters. Samples with the highest contaminant concentrations and eggshell thinning were associated with urban and industrial centers and agricultural areas.

Birds are at risk in the marine environment due to commercial fisheries, oil and hazardous materials spills, human disturbance, habitat loss, degradation of water quality, and contaminants from point and non-point sources. Indicator species should be selected that are most vulnerable and represent the various niches in the marine ecosystem.

INTRODUCTION

International borders obviously pose no barrier to the movement of marine and water birds in Puget Sound and the Strait of Georgia. The magnitude of the northerly spring and southerly fall migration is well known. The region is located on the Pacific flyway between Alaska or other northern breeding grounds and winter-Alaska or other northern breeding grounds and wintering areas to the south. Common Murres *(Uria aalge)* leave the Washington and Oregon outer coasts, starting late in the summer, and move into the inner waters of British Columbia and Washington for the winter. Some species migrate to the north from southern breeding areas. Heermann's Gulls *(Larus heermanni)* migrate from Mexico to the San Juan Islands and surrounding areas in June and July, where they are abundant during the summer. Some species breed inland and then winter on marine waters. Canadian biologists recently captured Harlequin Ducks *(Histrionicus histrionicus)* during the winter in the Strait of Georgia that included ducks that bred in Washington and Montana (I. Goudie, pers. comm.). Birds associated with the marine waters are an important natural resource shared between Washington and British Columbia. This paper primarily focuses on marine birds; however, some information also is presented for other species.

PAST AND ONGOING POPULATION MONITORING EFFORTS

Systematic censuses or inventories of marine bird populations have either quantified birds at breeding colonies or sites, or have examined at-sea distribution, whereas bird populations utilize a range of marine habitats during other portions of the year. Most effort has historically been directed at colonies or breeding sites as birds concentrate at certain locations, often returning to these same sites annually. Censuses of at-sea distribution are now receiving increasing attention, as birds feed, experience mortality, and spend a large proportion of their lives away from colonies or breeding sites.

Historically, monitoring of game species received more emphasis than nongame species. However, this has changed somewhat in recent years with oil spills, the U.S. Endangered Species Act, and increasing public concern for the protection of ecosystems and their components.

WASHINGTON

Manuwal and Campbell (1979) described the status and distribution of breeding seabirds in Washington. This was followed by Speich and Wahl (1989), who comprehensively catalogued observations and bird numbers from all known colonies of most marine bird species in Washington. Great Blue Heron *(Ardea herodias)* colonies were the principal exception.

The Marine Ecosystem Analysis (MESA) during 1978–79 (Wahl et al. 1981), involved a variety of surveys that attempted to examine throughout the year the numbers and distribution of all marine birds associated with Juan de Fuca Strait, the San Juan Islands, and northern waters of Washington. This was the first attempt in Washington to determine the habitat use and distribution of all marine bird species over all seasons, and it has served as a baseline for later programs to build upon.

There are a number of ongoing efforts presently monitoring different facets of bird populations in Puget Sound. One of these is the collaboration between Washington Department of Wildlife (WDW) and the Puget Sound Water Quality Authority (PSWQA) for studies of marine birds and mammals. It is being undertaken as part of the long-term monitoring for the Puget Sound Ambient Monitoring Program (PSAMP) and was initiated in 1991–92. Aerial and boat surveys, described by Nysewander et al. (1993b), are being conducted during summer (July) and winter (December–February). Starting in 1992, all of greater Puget Sound was surveyed, including marine areas adjacent to the international border. These surveys include low and high density sampling strata, a system of replicate counts, and densities mapped as small as two minutes of latitude/longitude. The use of the Global Positioning System has allowed greater resolution than was previously available. These recent survey data, along with most of the MESA data, have been included in a database, which is then being made available for mapping by CAMRIS (a patented GIS system). A survey specifically targeting wintering shorebird populations in Puget Sound is also being conducted for PSAMP.

Other ongoing efforts have focused on specific sites or species. Long-term studies at colonies are being conducted by US Fish and Wildlife Service (USFWS), with the most intensive work taking place at Smith and Protection islands by Ulrich Wilson. Murre numbers

and productivity at Tatoosh Island continue to be monitored by Julia Parrish working out of the Institute of Environmental Studies at the University of Washington. Annual winter waterfowl surveys, coordinated between the USFWS and WDW, are the primary inventory for monitoring populations of waterfowl during migration and on wintering grounds in Washington.

Data have also been gathered periodically by WDW Game and Nongame programs on current distribution and breeding population estimates of certain species commonly associated with Washington state marine habitats. These species include Bald Eagles, Peregrine Falcons, Great Blue Herons, Marbled Murrelets *(Brachyramphus marmoratus)*, Harlequin Ducks, and eight other species of dabbling and diving ducks.

British Columbia

Campbell (1976) and Manuwal and Campbell (1979) described the status and distribution of breeding seabirds along the Washington and British Columbia coasts. Vermeer et al. (1983) produced an atlas of distribution and densities of marine birds for British Columbia. The proceedings of a symposium sponsored by the Pacific Northwest Bird and Mammal Society and the Canadian Wildlife Service (CWS) in 1987 (Vermeer and Butler 1989) describe the physical and biological environment of the Strait of Georgia, the feeding ecology, populations and breeding ecology of marine and shoreline birds, and the populations and ecology of wintering birds.

The symposium publication (Vermeer and Butler 1989) compares breeding numbers over time at various colonies for Glaucous-winged Gulls *(Larus glaucescens)*, Double-crested Cormorants *(Phalacrocorax auritus)*, Pelagic Cormorants *(P. pelagicus)*, and Pigeon Guillemots *(Cepphus columba)*, and includes information on the Great Blue Heron, Black Oystercatcher *(Haematopus bachmani)*, sea ducks, and Bald Eagle *(Haliaeetus leucocephalus)*.

The Canadian data on at-sea distribution of marine birds have been gathered by varying methods that have resulted in different data sets:

- Numbers per linear kilometer, as in the 1983 atlas (Vermeer et al. 1983) which gives relative densities of populations over large geographical areas;
- Monthly means of maximum numbers counted on certain beaches in the Strait of Georgia; and
- Actual densities (numbers of birds per area surveyed) at fjords like Saanich and Jervis Inlets (Morgan 1989; Vermeer 1989a).

Although these data provide some information on the seasonal composition and distribution of marine birds and waterfowl, they have not been repeated over a number of years. Consequently, it is not possible to determine population trends.

PRESENT STATUS, DISTRIBUTION AND TRENDS

Wintering bird populations in the inner marine waters of Washington and the Strait of Georgia tend to be much larger than the summer breeding populations. Species diversity also increases greatly during the winter. However, the summer populations should not be ignored, as there are species of specific concern such as the Marbled Murrelet and Harlequin Duck. Reproductive success is crucial to a species' survival, which is why breeding populations are monitored. The following summaries describe breeding populations, and at-sea composition and distribution of birds associated with the marine waters.

Breeding Population Levels

Washington

Eighteen species of marine birds, consisting of at least 303,000 birds, were estimated to breed within the marine shoreline habitats of Washington in 1989, with over 78% of these along the outer coastal waters of Washington (Speich and Wahl 1989). Close to 22% bred in the inner waters, with 16% found at Protection Island alone. The major breeding species in the inner waters were Rhinoceros Auklet (*Cerorhinca monocerata*; 36,804 birds), Glaucous-winged Gull (19,200 birds), Pigeon Guillemot (3500 birds), Pelagic Cormorant (2238 birds), and Double-crested Cormorant (1100 birds). Significant proportions of the populations of Black Oystercatcher (120 birds) and Marbled Murrelet (at least half of the 5000) also were found in these inner waters (Speich et al. 1992b). The Marbled Murrelet numbers are largely based on older estimates and an updated estimate is needed.

Speich and Wahl (1989) documented the following distribution and numbers of the more numerous species:

- Two of the three main Rhinoceros Auklet colonies in the state occurred in greater Puget Sound, at Protection Island and Smith Island (34,216 and 2588 breeding birds respectively). These two colonies contain 60% of the state's breeding population for this species.
- Over half of the state's breeding population of Glaucous-winged Gulls occurred in greater Puget Sound, with Protection Island alone supporting 30% of the state's breeding numbers.
- Approximately 82% of the state's known breeding numbers of Pigeon Guillemot were recorded in the inner marine waters. Protection Island again contained a large contingent of this species with 30% of the state's breeders found there.
- Approximately 33% of the state's Double-crested Cormorants bred in inner marine waters, primarily at three islands at the southern end of Rosario Strait. Pelagic Cormorants bred at Protection Island (18% of state total) and at other locations, primarily in the San Juan Islands (28%).

Accurate population counts of Marbled Murrelets are lacking, but numbers have been greatly reduced. As a result, in 1992 Marbled Murrelets were listed federally as a threatened species in Washington, Oregon and California due to low numbers and loss of nesting habitat. Marbled Murrelets are currently experiencing very low recruitment rates (Strong et al. 1993) and nest predation may be having significant impacts on the population (Nelson et al. 1992).

Washington's Common Murre population is also of concern. Although they are coastal breeders, they utilize the inner marine waters for significant proportions of the year. The numbers of Common Murres breeding on Washington's coast have decreased from approximately 30,000 during 1979/82 to 565 in 1993. In addition to a reduced population size, they failed to reproduce in 1993 and possibly in 1992 (U. Wilson, unpub. data). Because of their depressed population, any additional mortality incurred from unnatural causes in the inner marine waters is cause for concern. Increases in breeding numbers of Caspian Terns *(Sterna caspia)* and Ring-billed Gulls *(Larus delawarensis)* in Washington marine waters have been primarily occurring on the outer coast estuaries of Grays Harbor and Willapa Bay. These species have also been increasing in recent years on the inner waters of Washington, and in 1992 a colony of 600 nesting Caspian Terns was established at Everett (Tweit and Johnson 1992). A substantial non-breeding population of Caspian Terns also is present throughout the bays and estuaries of Puget Sound (T. Wahl, pers. obs.). Non-breeding Ring-billed Gulls are now considered common in Puget Sound in the summer, but breeding has not been documented.

Resident Canada Geese *(Branta canadensis)* were uncommon 30 years ago in the Puget Sound area. Christmas bird count data in the Bellingham area have shown that numbers of Canada Geese doubled between 1988 and 1993 to well over 1,000. The expanding goose population in the greater Seattle area has become such a problem that the United States Department of Agriculture Animal Damage Control (ADC) program has relocated over 4200 Canada Geese since 1990, and has initiated a study to evaluate egg oiling to reduce hatching (Cummings et al., unpub. report).

Since 1986, USFWS Nisqually National Refuge (NWR) biologists have conducted annual breeding bird surveys of marine birds in the San Juan Islands and Protection and Smith islands. Refuge data (U. Wilson and M. McMinn, pers. comm.) suggest the following:

- Pigeon Guillemots appear to have a stable population;
- Although Rhinoceros Auklets appear to have a stable breeding population, there have been only three surveys since 1976; consequently, comments about population levels are suspect;
- Black Oystercatchers have a relatively stable breeding population; and
- Double-crested Cormorants appear to have increased slightly while the Pelagic Cormorant numbers have remained relatively steady.Cormorant colonies, however, have shifted back and forth between the San Juan Islands and Protection and Smith islands because of human disturbance.

The breeding population of Glaucous-winged Gulls on Protection Island increased by approximately 4%

annually during the early 1980's (Galusha et al. 1987). Since the late 1980's the population has remained stable (J. Galusha, unpub. data.). Exact counts are not available for Smith Island; however, Glaucous-winged Gulls are now nesting in greater numbers on the periphery of the island and in other locations that were not occupied in 1974 (U. Wilson, pers. comm.). Glaucous-winged Gulls nesting in urban areas also have increased in recent years (Eddy 1982; Wahl, pers. obs.).

Tufted Puffins *(Fratercula cirrhata)* nesting on Protection and Smith islands and the San Juan Islands declined from 1066 historically, to 74 in 1989 (U. Wilson, unpubl. report). Their numbers have been consistently low for the last 20 years at most sites in the eastern Juan de Fuca Strait and San Juan Islands (Speich and Wahl 1989). Concern has been expressed about the declining puffin population on Protection Island; in 1993 only 13 pairs nested there (U. Wilson, pers. comm.).

Watson and McAllister (1992) summarized population trends from WDW data for five diurnal raptor species in Washington. Increases were noted for the three species most strongly associated with marine waters. Bald Eagle populations have increased dramatically with occupied nesting territories increasing from 114 in 1975 to 459 in 1992. The new territories were established primarily along marine coastlines. Peregrine Falcons *(Falco peregrinus)* increased from a statewide total of four territories in 1980 to 23 in 1992, the San Juan Island portion growing from one territory in 1980 to nine in 1992. Osprey *(Pandion haliaetus)* nesting territories statewide have increased by 220%, from 168 in 1984 to 373 territories in 1989; much of this increase took place in the greater Puget Sound area.

British Columbia

In 1988, the total breeding population of seabirds found in the relatively sheltered waters of the Strait of Georgia was estimated at 36,522 birds (Vermeer 1989b), whereas the outer coast of British Columbia supported 5,228,200 breeders. Species richness was considerably lower in the Strait of Georgia with seven species breeding there, compared to fifteen species nesting along the outer coast. Four species dominated these inland breeders: Glaucous-winged Gulls (26,000 birds), Pelagic Cormorants (4700 birds), Double-crested Cormorants (4000 birds), and Pigeon Guillemots (1800 birds). Rhinoceros Auklets, Tufted Puffins, and Brandt's Cormorants *(Phalacrocorax penicillatus)* had very low breeding numbers.

The breeding population of Glaucous-winged Gulls in these inner waters doubled between 1960 and 1986, with almost half of the population found on three islands: Great Chain, Mandarte, and Mitlenatch islands. The population increase may be related to an abundant supply of human refuse on which these gulls feed (Vermeer 1983; Butler et al. 1980; Vermeer and Devito 1989). Roof-nesting gulls are rapidly colonizing the urban waterfront along the Strait of Georgia and becoming a nuisance (Vermeer et al. 1988). Also, this species has recently invaded the traditional American Black Oystercatcher nesting habitat and may be negatively impacting the oystercatchers (Vermeer et al. 1989a).

Populations of breeding Pelagic and Double-crested cormorants increased between 1960 and 1987. Pelagic Cormorant nests numbered 953 (1960), 2149 (1975), 2448 (1983), and 2356 (1987), suggesting the increase has now levelled off. Double-crested Cormorant nests rose from 203 (1960) to 671 (1975), 1606 (1983), and 1981 (1987). Although cormorants may now have fully recovered from times when they were persecuted, repeated monitoring is required (Vermeer et al. 1989b).

Two sites, Mandarte and Mitlenatch islands, support nearly half of the breeding population of Pigeon Guillemots within the Strait of Georgia. Unfortunately, differences in survey methods have made it impossible to evaluate the population trends (Emms and Morgan 1989).

There are 26 species of shoreline birds that breed in the Strait of Georgia (Butler and Verbeek 1989). Mallard *(Anas platyrhynchos)*, Gadwall *(A. strepera)*, Cinnamon Teal *(A. cyanoptera)*, and Blue-winged Teal *(A. discors)* are the most numerous breeders. The single major threat to shoreline birds is habitat destruction. The nesting duck populations are not large, and little information exists on their breeding ecology in the Strait of Georgia.

Canada Geese are presently a widespread and abundant nesting species. They did not nest around the Strait of Georgia before 1940. Small numbers were released in 1967 around the lower Fraser River valley and today the population in the same area is estimated to be between 8000 and 10,000 birds (Butler and Verbeek 1989).

The Bald Eagle population within the Gulf Islands increased approximately 30% between 1974 and 1987, with 97 occupied nests and 293 adult eagles seen in 1987 (Vermeer et al. 1989c). The increase in numbers may reflect the growth of the Glaucous-winged Gull population. Studies of prey remains beneath eagle nesting trees showed that Glaucous-winged Gulls were the most frequent taken prey (35%)(Vermeer et al. 1989c).

Pelagic and Nearshore Distribution

Washington Aerial Surveys

Data on marine bird distribution in the inner marine waters are available from the 1992 summer and the 1992–93 winter aerial surveys conducted by PSAMP-WDW (Nysewander et al. in prep.). These surveys cover most shoreline or nearshore waters (high density strata) and a proportion of the offshore waters (low density strata). A systematic comparison has not yet been made, but the patterns appear similar to those reported by Wahl et al. (1981). These data, although preliminary, are presented here to give a general idea of bird distribution, species composition and relative numbers.

Summer 1992 Survey

The summer surveys recorded the following:

- gull and tern flocks generally distributed along shorelines, with feeding flocks of certain species, such as Heermann's Gull, concentrating in the northern two-thirds of Washington's inner marine waters;
- feeding flocks of alcids such as Common Murres and Rhinoceros Auklets in deeper waters in the northern two-thirds of Puget Sound;
- moulting/feeding flocks of ducks along shores and river deltas; and
- other marine birds including cormorants, Pigeon Guillemots, and Great Blue Herons seen along shorelines.

Gulls and terns accounted for 72% of the total of 117,633 birds observed in July 1992. Four species dominated this group: Glaucous-winged Gulls (46%), Bonaparte's Gull (*Larus philadelphia*; 22.2%), Heermann's Gull (19.2%), and California Gull (*L. californicus*; 9.3%). Glaucous-winged Gulls were the only resident breeder. Large numbers of Bonaparte's and California gulls migrate into Puget Sound during July–August. Ring-billed Gulls and Western/Glaucous-winged Gull intergrades were also present, but were not numerous. Caspian Terns were the most common tern during most of the summer. Concentrations of Common Terns migrate through during July and August.

Alcids comprised 11.2% (13,188 individuals) of all birds observed in July 1992. Three species, Common Murre (44.3%), Rhinoceros Auklet (31.6%), and Pigeon Guillemot (23.3%) constituted practically all alcids identified to species. Common Murres and Rhinoceros Auklets were mostly seen in deeper waters in the northern two-thirds of greater Puget Sound. Common Murres feed in tide rips and channels. Rhinoceros Auklets were found in waters near their breeding sites and frequented the same foraging habitat as murres. Pigeon Guillemots were widely distributed along shorelines near breeding sites.

Ducks and geese comprised 7.7% of all birds seen. Scoters, almost entirely Surf Scoters *(Melanitta perspicillata)*, comprised 77.7% of the waterfowl identified to species. Significant numbers of mergansers (12.2%), primarily Common Mergansers *(Mergus merganser)*, Mallards (11.0%), and Canada Geese (6.5%) were also present. Small numbers of Harlequin Ducks and unidentified species of goldeneyes were observed.

Other species of birds that accounted for the 7.4% of the identified species included three species of cormorants, Northwestern Crows *(Corvus caurinus)*, six species of wading birds (including Great Blue Herons), Western Grebes *(Aechmophorus occidentalis)*, loons, Belted Kingfishers *(Ceryle alcyon)*, Bald Eagles, and Ospreys.

Winter 1992–93 Survey

The winter pattern of bird distribution differed numerically and geographically from the summer pattern. A total of 620,082 birds were counted during winter compared to the 117,633 seen on similar transects in the summer. The distribution changed in the following ways:

- larger numbers of birds used southern Puget Sound in winter than in summer;
- waterfowl increased along shorelines and near river deltas, with certain estuaries including the Skagit

River delta and Padilla Bay containing large numbers of waterfowl and geese; and

- grebes and loons migrated into the Sound and used protected waters (deeper waters with low currents) in southern Puget Sound, the Bainbridge Island area, the Whidbey/Camano Island area, Bellingham and Padilla/Samish Bay areas, and portions of the San Juan Islands and the Point Roberts/Boundary Bay area.

The PSAMP surveys are best suited for estimates of marine birds. They do, however, include counts of geese and dabbling ducks which move back and forth between marine and inland habitats. Because PSAMP surveys do not include inland areas, geese and dabbling duck counts are incomplete.

Ducks, Geese and Swans: The numbers of waterfowl using Puget Sound increased dramatically in the winter and comprised 68.2% of all birds. Diving ducks, which include both bay and seaducks, comprised 32% (135,174 individuals) of all waterfowl counted. Scoters made up 50.1% of all diving ducks observed and the percent of scoters identified by species was as follows: Surf Scoters (64.9%), White-winged Scoter (*Melanitta fusca*; 32.9%), and Black Scoter (*M. nigra*; 2.2%). Buffleheads (*Bucephala albeola*; 16.7%) and the two goldeneye species (11.4%) were the next most numerous diving duck species. Other species of diving ducks observed in decreasing order of abundance were the two scaup species, the three merganser species, Ruddy Duck *(Oxyura jamaicensis)*, Harlequin Duck, Canvasback *(Aythya valisineria)*, and Oldsquaw *(Clangula hyemalis)*. The number of Harlequin Ducks seen during the winter was 4–5 times the number recorded on the same transects in the summer, supporting the conclusion that Harlequin Ducks migrate into the inner marine waters of Washington in the winter.

Overall, the dabbling ducks comprised 56.7% of all waterfowl counted on winter surveys. Of those dabbling ducks identified to species, four species comprised almost 100%: American Wigeon (*Anas americana*; 54.9%), Mallard (33.1%), Northern Pintail (*A. acuta*; 10.2%), and Green-winged Teal (*A. crecca*; 1.8%). A few Gadwall were also noted.

Geese and swans comprised 11.3% of all waterfowl observed on the winter aerial transects. The counts included 862 unidentified swans, 91 Trumpeter Swans *(Cygnus columbianus)*, 438 Tundra Swans *(C. columbianus)*, and 506 Canada Geese.

Other surveys in Washington since 1970 (Kraege 1990; WDW unpub. data) have documented the following trends for wintering populations of dabbling and diving ducks, geese and swans. The population of dabbling ducks has varied from year to year. The overall trend was stable until the late 1980's when numbers increased 100–200%, possibly as a result of feeding programs and management actions. Diving duck estimates have also varied annually with an overall downward trend since 1978 (Kraege 1990), although the trend is not statistically significant. Trumpeter Swans have been increasing over the last 15 years in Washington, with numbers doubling in certain areas (Kraege, pers. comm.). Brant *(Branta bernicula)* population estimates were as low as 3,000 when hunting was closed in 1981. When hunting was reopened in Washington in 1987, the population was 16,000 and has ranged between 10,000 and 14,000 since then. Numbers of Snow Geese *(Chen caerulescens)*, which move back and forth between the Fraser River delta and the Skagit River delta vicinity, are summarized in the British Columbia section of this paper.

Alcids and unidentified seabirds (which probably included many alcids), comprised 1.3% (8,333 individuals) of all birds encountered. The numbers were about half of those recorded during summer transects and alcids were distributed throughout all of Puget Sound. The species composition changed from the summer. Few Rhinoceros Auklets and Pigeon Guillemots were seen. Ancient Murrelets *(Synthliboramphus antiquus)*, which were not present in the summer, were seen primarily in Juan de Fuca Strait. Common Murres were the predominant species by far, constituting 82.7% of all alcids identified to species. Marbled Murrelet numbers increased from those seen in the summer, suggesting that murrelets migrate into portions of Puget Sound during winter. This species was also seen in areas such as southern Hood Canal where they were not observed during the summer.

Loons and Grebes: Large, highly aggregated concentrations of Western Grebes (over 35,000 seen on transects) dominated this group. In total, loons and grebes accounted for 5.9% of all birds seen. Four other grebe species, Horned *(Podiceps auritus)*, Red-necked *(P. grisegena)*, Eared *(P. nigricollis)* and Pied-billed *(Podilymbus podiceps)* were also present. Although Western Grebes comprised 97.9% of all grebes identi-

fied to species, this may in part be an artifact due to aerial surveys underestimating the smaller dispersed grebe species, such as Horned and Red-necked grebes.

Three loon species constituted 0.3% (1,632 individuals) of all birds surveyed. The Red-throated Loon (*Gavia stellata*; 46.4%) was the most abundant species identified, followed by the Common Loon (*G. immer*; 33.2%) and the Pacific Loon (*G. pacifica*; 20.4%). Loons, which often dove upon the approach of the plane, may have been underestimated.

Gulls accounted for 9.4% (58,026 individuals) of all birds seen. The species composition differed significantly from the summer. Heermann's Gulls had left and Bonaparte's and California gulls were present only in low numbers. However, Mew *(Larus canus)*, Western *(L. occidentalis)*, and Herring *(L. argentatus)* gulls increased in numbers. Ring-billed Gulls were seen in fresh, brackish, or estuarine waters. Glaucous-winged Gulls and Mew Gulls comprised 51.9% and 25.3%, respectively, of the gulls surveyed. Although not distinguishable from Herring Gulls during aerial surveys, Thayer's Gulls *(Larus thayeri)* are the third most abundant gull species in Puget Sound during the winter (Wahl, Pers. Obs.).

Shorebirds were censused in November-December, 1992, by a PSAMP-funded survey specifically targeting winter resident shorebirds (Evenson 1993). A total of 60,626 shorebirds, representing 17 species, were counted. Skagit Bay had the highest count with 32% of the total numbers for the entire Puget Sound region. Dunlin *(Calidris alpina)* was by far the most abundant species, comprising 93% of the shorebirds observed, followed by Western Sandpiper (*C. mauri*; 3%), Sanderling (*C. alba*; 1%), Killdeer (*Charadrius vociferus*; 1%), and Black-bellied Plover (*Pluvialis squatarola*; 1%).

Cormorants accounted for 0.7% (4777) of all birds counted. Double-crested Cormorants comprised 95.0% of the identified cormorants with Pelagic and Brandt's cormorant dividing up the remainder. It should be noted that Double-crested Cormorants are the easiest to identify on the aerial survey and a larger percentage of the other two species was probably included in the unidentified cormorant category. Winter counts of cormorants exceeded (by 64%) the number observed on the same transects during the summer.

British Columbia

Most of the Canadian data on at-sea or pelagic distribution of marine birds are focused around either migrating or wintering distributions (Vermeer and Butler 1989; Vermeer et al. 1983). The distribution patterns discussed in the following section will concentrate primarily on the winter concentrations.

The winter pattern of marine bird distribution in the inner marine waters of British Columbia changes from summer distribution in a similar fashion to that described for Washington state. Large influxes of waterfowl, diving birds, and wading birds swell the wintering numbers at estuaries like the Fraser River delta and beaches as found at Boundary Bay.

The maximum number of birds, using monthly averages from October to March, was nearly 118,000 in eight estuaries and about 105,000 on three beaches (Butler et al. 1989). These figures are the basis for an estimate of 400,000–500,000 water birds that pass through and utilize all of these estuaries and beaches. The Fraser River estuary and the Boundary Bay beach contained 69.2% and 92.6% of the totals found on estuaries and beaches, respectively, with high numbers of waterfowl, wading birds, and gulls. The Cowichan River estuary hosts large populations of divers, especially Western Grebes. Two other marine habitats in the Strait of Georgia — rocky coastlines and pelagic waters — support smaller numbers than the estuaries and beaches, but these habitats are important for species like Barrow's Goldeneye *(Bucephala islandica)*, Pacific Loon, Harlequin Duck, and Red-breasted Merganser *(Mergus merganser)*.

Diving Ducks: Surf Scoters were the most numerous and widely distributed diving duck species, with higher numbers along the mainland coast than along the Vancouver Island side of the Strait of Georgia. White-winged Scoters were occasionally common near certain estuaries. Black Scoters were the least common scoter, but were nevertheless abundant at certain locations. Bufflehead were the most abundant diving duck in sheltered waters of southern British Columbia. Barrow's Goldeneye was the most common goldeneye species in the fjords, whereas Common Goldeneyes *(Bucephala clangula)* were numerous in estuaries. Red-breasted Mergansers were the second most abundant diving duck in areas like Saanich Inlet (Morgan 1989)

and coastal shores, while Common Mergansers were seen more in estuaries (Vermeer et al. 1983). Harlequin Ducks were mostly concentrated along the east side of Vancouver Island. Included in these groups were birds from Washington and Montana (I. Goudie, pers. comm.). Greater Scaup *(Aythya marila)* were numerous at Boundary Bay and along the east coast of Vancouver Island.

Dabbling Ducks: American Wigeon and Mallard were the most numerous dabblers seen in estuaries. Maximum counts at the Fraser River estuary, which contained 74.5% of waterfowl found in eight estuaries, tallied 62,000 American Wigeons and 50,000 Mallards (Vermeer et al. 1983).

Geese and swans are primarily birds of estuaries and adjacent fields and marshes, except for Brant, which are usually found in association with eelgrass beds. A maximum of approximately 8300 Brant per day were seen during aerial surveys of Brant staging-areas in the Strait of Georgia, held weekly from March 14 to May 15, 1990 (Nygren 1990). On the basis of this survey, it was calculated that 23,700 Brant moved through the Strait of Georgia in spring. During the survey most Brant (up to 4300 birds per census) were observed in the Qualicum-Parksville area on the east coast of Vancouver Island. However, during a survey in April 1993 of the area between the B.C. Ferry terminal and the Roberts Bank coalport terminal at Tsawwassen, up to 7000 per census were counted. It is suggested that this particular location may be the largest staging-area for Brant in the Strait of Georgia (K. Vermeer, unpubl. data). Although few censuses have been conducted between the terminals at Tsawwassen, the Brant population has undoubtedly increased over the years. Vermeer and Levings (1977) reported that a total of 2000 to 3000 Brant were seen in the Fraser River estuary in spring during the 1970's, of which the large majority occurred in Boundary Bay. Nygren (1990) reported only a maximum of 1000 Brant between the terminals during his surveys in 1990. The eelgrass beds between the terminals have continuously grown since the terminals were built, expanding the feeding habitat for Brant.

Canada Geese are common residents in most Strait of Georgia estuaries. Although no systematic censuses of that species have been conducted in the Strait of Georgia, the Canada Goose population undoubtedly has increased there. The species was introduced into the Fraser Valley in the late 1960's and early 1970's to provide a harvestable surplus in areas open to hunting and to provide wildlife viewing opportunities throughout the valley. Urbanization, high fecundity and survival, diminution of hunting, and exploitation of vacant habitat in urban areas, have led to a rapid increase in the Canada Goose population (Breault and McKelvey 1991). Wintering populations of the species have doubled in the Fraser Valley from 1977 to 1988. The number of Canada Geese in cities and towns bordering the Strait of Georgia are also growing, resulting in geese becoming a nuisance and a health hazard in city parks. Also, nesting Canada Geese have joined nesting seabirds on some islands in the Strait during the last decade. For instance, Mandarte Island has now a dozen nesting pairs of geese where none nested before.

One of the largest goose populations in the Strait of Georgia is that of the Snow Geese. Up to 35,000 birds per census have been observed in tidal marshes of the Fraser River in 1993 (S. Boyd, pers. comm.). In winter, these Snow Geese move between the Fraser and Skagit river estuaries. The total Snow Goose population at those two estuaries consisted of 52,000 birds in 1993. The Snow Goose population at the Fraser River estuary has increased about three-fold since the mid 1970s (S. Boyd, pers. comm.).

Of the swans, the Trumpeter Swan is the most widespread and numerous. They are concentrated in tidal marshes of the Fraser River (up to 1,000 birds per census) and in the Comox-Courtenay area (up to 750 birds per census). The Trumpeter Swan population in the Strait of Georgia has increased an average of 7% per year over the last two decades. However, in the Fraser River estuary the population has increased an average of 15% per year over the same time period (S. Boyd, pers. comm.). The Tundra Swan is less common than the Trumpeter Swan; the Mute Swan *(C. olor)*, a resident and introduced species, is the least common. The largest concentration of Mute Swans (up to 100 birds per census) is found in the Cowichan River estuary (K. Vermeer, unpubl. data).

Alcids: The Common Murre is the most abundant and widespread alcid along exposed shores and open water. Marbled Murrelets are also common in fjords and sheltered waters (Vermeer et al. 1983). Pigeon Guillemots are regularly seen in low numbers in the nearshore habitat. Low numbers of Rhinoceros Auklets are occa-

sionally seen wintering in the Strait of Georgia. Relatively high numbers of Ancient Murrelets can be found off James and Sidney Island in the southern Gulf Islands during the winter (K. Morgan, pers. comm.), whereas Rhinoceros Auklets are common there during summer. K. Vermeer has seen that population increase from an absence of Rhinoceros Auklets in the early 1960's to about 1000 birds in the 1990's. Most of those Rhinoceros Auklets probably originate from nesting colonies in Washington.

Loons and Grebes: Western Grebes are the most numerous species in this group. Christmas count totals of this species range from 9000 to 31,000. Their flocks are distributed from Boundary Bay north throughout coastal areas of the Strait of Georgia, with concentrations in the Gulf Islands and at the mouths of estuaries.

Gulls are among the most numerous residents in estuaries during winter. A year-long survey in 1989 indicated that gulls made up 31.1%, 34.5%, 23.5% and 87.9% of the waterbird composition of the Chemainus, Cowichan, Courtenay and Nanaimo river estuaries, on the east coast of Vancouver Island, respectively (K. Vermeer, unpubl. data). The most numerous species was the Glaucous-winged Gull. For instance, 29,000 Glaucous-winged Gulls were counted in the Nanaimo River estuary on January 25, 1988. The Nanaimo River estuary may represent only an important resting place for Glaucous-winged Gulls as few were observed feeding. Instead the gulls moved between the estuary and the nearby Nanaimo garbage dump. On the Fraser River estuary, Glaucous-winged Gulls were also most numerous nearest to the Greater Vancouver landfill, where up to 44,000 Glaucous-winged Gulls were counted on December 19, 1989 (K. Vermeer, unpubl. data).

Glaucous-winged Gulls have become a nuisance at certain landfill sites (Vermeer and Irons 1991). For example, the greater Victoria regional dump is the largest refuse landfill on Vancouver Island. In 1987, in response to complaints that Glaucous-winged Gulls were dropping large amounts of garbage into nearby Prospect Lake, the Capital Regional District installed parallel overhead wires across the active landfill site. The feeding activity of gulls there was consequently much reduced. Only a few Glaucous-winged Gulls visit the active landfill site now, by walking to it beneath the wires. The program has one drawback: it costs approximately $10,000 a year to maintain the wiring system, as garbage trucks frequently snap wires.

Other species which commonly visit Strait of Georgia estuaries are Thayer's and Mew gulls. Thayer's Gull is also common at landfills (9600 birds were counted on the Greater Vancouver landfill on 29 October 1989), whereas Mew Gulls have not been seen there (K. Vermeer, unpubl. data). Mew Gulls tend to prefer estuaries, mudflats and tidally active areas.

An abundant migrant in both spring and fall, the Bonaparte's Gull, frequents estuaries, kelp beds and areas with strong currents. Up to 10,000 Bonaparte's Gulls have been counted in a single census in Active Pass in September.

California Gulls chiefly visit estuaries in spring, late summer and fall, but are most numerous in August and September. They are also common at landfills (7000 birds were counted on the Greater Vancouver landfill on August 22, 1990, K. Vermeer, unpubl. data). Ring-billed Gulls are most common in estuaries during summer and fall.

Shorebirds: The Fraser River estuary supports one of the largest wintering and migrant shorebird populations in the Strait of Georgia. Most of the wintering population consists of Dunlins. Butler and Vermeer (in press) observed a peak number of 62,000 Dunlins in the Fraser River estuary in November 1992. Western Sandpipers are the most numerous spring migrants. Butler and Vermeer (in press) estimated that there were between 500,000 to 1 million of these sandpipers in that estuary during late April, 1992. The third most numerous shorebird in the Fraser River estuary is perhaps the Black-bellied Plover, which is seen there throughout the year. Butler and Vermeer (in press) observed 2,300 Black-bellied Plovers in April, 1992. Other common shorebirds found in the Fraser River estuary are golden plovers (*Pluvialis* spp.), Greater Yellowlegs *(Tringa melanoleuca)*, Spotted Sandpipers *(Actitus macularia)*, Whimbrels *(Numenius phaeopus)*, Black Turnstones *(Arenaria melanocephala)*, Sanderlings, Least Sandpipers *(Calidris minutilla)*, Short-billed *(Limnodromus griseus)* and Long-billed Dowitchers *(L. scolopaceus)*, Common Snipe *(Gallinago gallinago)* and Killdeer (Butler and Campbell 1987).

Cormorants: Three species of cormorants visit the Strait of Georgia waters: Brandt's, Double-crested and Pelagic

cormorants. Thousands of Brandt's Cormorants visit tidally active waters, such as Active and Porlier Passes in the Gulf Islands in the winter (Vermeer 1983). They generally congregate to feed upon spawning Pacific herring in March (Vermeer 1981). Most of the visiting Brandt's Cormorants probably originate from nesting colonies in Oregon. Double-crested Cormorants are most numerous in estuaries, where they are chiefly seen loafing on booms and pilings, whereas Pelagic Cormorants are found in various marine habitats.

CONTAMINANT MONITORING

Washington

Limited research has been conducted on contaminant concentrations and impacts to birds associated with Puget Sound's marine waters. Calambokidis et al. (1991) provided a summary of toxic contaminant studies for birds in the Puget Sound area. They concluded that existing research was insufficient to adequately assess the impacts of contaminants on birds. The various studies and their results are discussed below. All organic concentrations are reported in wet weight and inorganic data are reported in dry weight.

Great Blue Heron eggs and tissues from the general Puget Sound area were collected in 1981 and 1982 (Riley et al. 1983; Blus et al. 1985; Fitzner et al. 1988) in 1984 (Calambokidis et al. 1985; Speich et al. 1992a) and in 1988 (Kendall et al. 1990; Norman 1992; and Block 1992). Polychlorinated biphenyl (PCB) levels in eggs collected in 1982 from Fort Lewis at a colony close to south Puget Sound (1.61–7.33 ppm, Fitzner et al. 1988) were similar to levels in eggs collected in 1988 (Block 1992) from the Tacoma area (1.8–5.1 ppm) and Nisqually NWR in south Puget Sound (0.77–6.2). Speich et al. (1992a) found the highest average concentrations of PCBs in eggs from Seattle (15.56 ppm) and Tacoma (5.46 ppm), which are the most industrially developed areas in Puget Sound. Generally, low total DDT concentrations were measured in eggs from all the studies, with the highest (at Fort Lewis) being 2.4 ppm (Fitzner et al. 1988). Speich et al. (1992a) observed significant eggshell thinning (to 13%) in Great Blue Heron eggs from heronries near agricultural areas at Samish Island and March Point. Samples from near urban-industrial areas showed less thinning (average 5–7%). Concentrations of trace elements measured in Great Blue Heron eggs from 1981 and 1988 were considered below toxic levels (Fitzner et al. 1988; Block 1992).

Several studies have examined the impact of contaminants on Glaucous-winged Gulls populations in Puget Sound, Washington (WDW 1980; Riley et al. 1983; Calambokidis et al. 1985; Fry et al. 1987; Speich et al. 1992a). Eggshells of Glaucous-winged Gulls sampled in 1984 from colonies in or near urban-industrial areas exhibited significant thinning of 8 to 10% (Calambokidis et al. 1985, Speich et al. 1992a). Total DDT concentrations were highest in Seattle (1.19 ppm), however they do not account for the amount of thinning observed. Speich et al. (1992a) also found average concentrations of PCBs highest in the Glaucous-winged Gull eggs from the Seattle and Tacoma areas (4.63 and 2.91 ppm, respectively) compared to Smith Island in Juan de Fuca Strait (1.36 ppm). Concentrations of PCBs were highest in gulls collected in 1982 from Commencement Bay and lowest in gulls from the control site on Protection Island in Juan de Fuca Strait (Riley et al. 1983). Mercury and lead were significantly higher in gulls from the Seattle and Tacoma areas, while selenium was higher in gulls from Juan de Fuca Strait (Riley et al. 1983). Signs of reproductive failure were not evident in any of the studies.

Due to poor production and abandonment of Double-crested Cormorants at the Colville Island colony in the San Juan Islands NWR, Henny et al. (1989) collected eggs for contaminant analyses in 1984. Protection Island NWR was used as a reference site. No difference in eggshell thickness from the pre-1947 value was observed at either location. Concentrations of DDE, PCBs, mercury and selenium in the eggs from both colonies were below established critical levels associated with health problems. Henny et al. (1989) concluded that human disturbance, not contaminants, were probably impacting the Colville Island colony. Pelagic Cormorants eggs collected in 1984 from Smith Island also did not show significant eggshell thinning (Speich et al. 1992a).

Pigeon Guillemot eggshells were collected from Puget Sound in 1975 (Oakley 1976) and 1984 (Calambokidis et al. 1985; Speich et al. 1992a). The mean eggshell thickness of eggs from both studies was not significantly different from eggs collected prior to 1947 in the Pacific Northwest (Speich et al. 1992a). PCBs and total DDT concentrations were measured in the eggs collected in

1975, with levels of PCBs ranging from 2.7 to 23.4 ppm. The higher concentrations were found in eggs from Seattle, Everett, and one location in southern Puget Sound. The DDT concentrations ranged from 0.1 to 2.6 ppm, with the highest also in the Seattle and Everett areas (Oakley 1976). One egg collected in 1982 near Seattle also had high PCB concentrations with 11.3 ppm (Riley et al. 1983).

Henny et al. (1990) measured contaminants in Western Grebes from the Tacoma area and found that levels of mercury, arsenic, PCBs, DDE, and chlordanes significantly increased during their wintering period. Contaminant concentrations, however, were below those reported to cause adverse impacts. Selenium, cadmium, mercury, copper, manganese, zinc, aluminum, lead, PCBs and DDE were accumulated by Surf Scoters that winter in the Tacoma and Seattle areas (Henny et al. 1991). While only mercury and lead significantly increased while the birds were in Puget Sound, the mean selenium concentration (43.4 ppm) in scoters from the Tacoma area increased above levels associated with health problems.

Limited contaminant data are available for wintering shorebirds. Samples have been collected at Samish Bay and two sites at the southern end of Puget Sound. Shick et al. (1987) and Custer and Myers (1990) reported that levels of organochlorines in wintering shorebirds (Dunlin, Black-bellied Plover, and Western Sandpiper) appeared to be declining and were below those known to cause adverse impacts to the shorebirds or their falcon predators. However, spring migrant shorebirds from Washington's coast contained both low and very high DDE residues (up to 417 ppm; Shick et al. 1987). Elevated selenium concentrations (29.9 and 26.9 ppm) were reported in pooled liver samples of Black-bellied Plovers from Samish Bay and southern Puget Sound, respectively (Custer and Myers 1990).

The USFWS and WDW began a study in 1992 evaluating potential contaminant impacts on nesting Hood Canal Bald Eagles. Total PCBs ranged from 7.9 ppm to 24.8 ppm, which is above the level known to negatively impact birds (Mahaffy et al., in prep). Further evaluations of the food chain are needed. Low levels of trace elements have been found in Bald Eagle eggs and blood (Wiemeyer et al. 1989; Mahaffy et al., in prep). Levels measured are below those known to cause biological effects.

As part of the PSAMP, the USFWS is beginning to implement a long-term monitoring program of birds. At this time Pigeon Guillemots and Surf Scoters are being evaluated as potential monitoring species. Nesting boxes have been placed at various locations for use by Pigeon Guillemots. Depending on success of the nesting-box project, guillemots may be monitored for contaminants, nest productivity and general chick growth rates.

British Columbia

Contaminant studies were initiated because of the concern for the health and well-being of resident and migratory birds; the health of those that might hunt and consume contaminated birds or eggs; and as indicators of environmental quality. Since 1973, the CWS has used eggs from Great Blue Herons and Double-crested and Pelagic cormorants to study long-term trends of environmental contaminants around the Strait of Georgia. In addition to annual egg collections at selected locations, samples are archived in the tissue bank at the National Wildlife Research Centre in Ottawa so they will be available for future analyses if needed. In general since 1973, several toxic chlorinated hydrocarbons, including PCBs, DDE, dieldrin, and heptachlor epoxide, have fallen in estuarine and coastal areas of the Strait of Georgia to levels below those known to cause health problems. Results of the contaminant studies on birds in the Strait of Georgia area are discussed below.

The CWS has used eggs from Great Blue Herons to follow trends of environmental contaminants since 1977. Detailed discussions of the heron research are presented in Elliott et al. (1989a), Whitehead (1989), and Whitehead et al., (1992). Samples have been collected from 24 different colonies located throughout the area. Mean PCB levels (sum of congeners) in eggs decreased significantly from 7.71 ppm in 1977 to 1.72 ppm in 1993. Mean DDE levels also fell from 2.01 to 1.622 ppm in 1993 (P. Whitehead, unpub. data). The highest mean level of PCBs, DDE, dieldrin, and heptachlor epoxide were found in eggs from the colony on the University of British Columbia Endowment Lands by the Fraser River Delta. Elevated levels were also found at colonies in Stanley Park near Burrard Inlet and at Tillicum Mall, on the Saanich Peninsula.

Great Blue Herons nesting near a pulp mill at Crofton failed to fledge chicks in 1987 and 1988 (Elliott et al.

1988 and 1989a, Moul et al. 1989). Eggs salvaged from the Crofton nests showed that 2,3,7,8-tetrachlorodibenzo-*p*-dioxin (TCDD) levels were about three times higher in 1987 (geometric mean 210 ppt) than in 1986 (geometric mean 66 ppt)(Elliott et al. 1989a). Polychlorinated dibenzodioxin (PCDD) and polychlorinated dibenzofuran (PCDF) contamination could not be directly linked to the breeding failures. Studies showed a number of sublethal effects, correlated with PCDD/PCDF contamination, including induction of hepatic enzymes, edema and depressed growth in heron chicks (Bellward et al. 1990; Hart et al. 1991). In 1988, the nearby pulp mill in Crofton began introducing process changes to eliminate PCDDs and PCDFs in its effluent. By 1991, TCDD levels had fallen dramatically to 16.4 ppt in heron eggs (Whitehead et al. 1992). This decline indicates a rapid cleansing of PCDDs and PCDFs from the food chain. None of the sublethal effects seen in chicks in 1988 were present in chicks examined in 1991 (Sanderson et al., in press).

Contaminant trends in Double-crested and Pelagic cormorants have been followed since 1973 and 1985, respectively (Elliott et at. 1989b; Whitehead et al. 1990b). Eggs from Double-crested Cormorants have been sampled at seven colonies located throughout the south Strait of Georgia area, and eggs from Pelagic Cormorants have been sampled at nine study area colonies. PCBs and DDE in Double-crested Cormorant eggs from Mandarte Island decreased from 6.17 ppm and 4.07 ppm, respectively, in 1970 (Ohlendorf et al. 1978) to 2.57 and 0.914, respectively in 1992 (P. Whitehead, unpub. data). Similar findings were observed in Pelagic Cormorant eggs with PCBs and DDE decreasing from 3.45 ppm and 1.49 ppm, respectively, in 1973 (Elliott et al. 1989b) to 0.71 and 0.16, respectively, in 1989 (P. Whitehead, unpub. data).

Dioxin levels in eggs from Double-crested Cormorants at the Crofton colony have been recorded since 1987. Concentrations of 2,3,7,8-TCDD declined from 71.8 ppt in 1987 to 8.2 ppt in 1992 (P. Whitehead unpub. data). In 1988–1990, PCDDs and PCDFs were measured in Double-crested Cormorant eggs from Howe Sound. The major PCDD and PCDF congeners identified in the cormorant eggs were 1,2,3,6,7,8-hexachlorodibenzo-*p*-dioxin (HxCDD) >1,2,3,7,8-pentachlorodibenzo-*p*-dioxin (PnCDD) >TCDD >2,3,4,7,8-pentachlorodibenzofuran (PnCDF), with the exception of 1989 when TCDD >PnCDD (Whitehead et al. 1990b). Residue levels declined by more that 50% between 1988 and 1989, while the 1990 residues were relatively unchanged from the 1989 levels.

In 1988, the CWS expanded its contaminants program to include diving ducks and grebes that winter in Howe Sound, which receives effluent from two bleached kraft mills. Species included Common Goldeneye, Surf Scoter, Harlequin Duck, Oldsquaw, Western Grebe and Common Merganser (Whitehead et al. 1990b). Concentrations of TCDD and 2,3,7,8-tetrachlorodibenzofuran (TCDF) ranged up to 46 ppt and 163.0 ppt, respectively, with the fish-eating species being the most contaminated. TCDF was the only contaminant found in all samples analyzed. A health advisory regarding the consumption of livers from Western Grebes and Common Mergansers was issued in 1990.

In 1989, eight estuarine bird species were collected from the Somass River estuary on the west coast of Vancouver Island, downstream from a pulp and paper mill (Whitehead et al. 1990a; Vermeer et al. 1993). Although this study was outside the Strait of Georgia, the findings underscore the need for similar work at locations within the Strait of Georgia and in Washington. The species included Horned, Red-necked and Western grebes; Bufflehead; Barrow's Goldeneye; Surf Scoter; Greater Scaup; and Common Merganser. All of the birds contained PCDD and PCDF residues. Red-necked and Western grebes had the highest concentrations of HxCDD (910 ppt and 249 ppt, respectively) and PnCDD (170 ppt and 385 ppt, respectively). Highest TCDD concentrations (117 ppt) were in Western Grebes. In April 1990, Health and Welfare Canada assessed the health risks to persons that might eat the liver of these birds. They issued an advisory relating to consumption of the livers of the Common Merganser, Surf Scoter, and Western Grebe. High dioxin levels were also observed in surficial sediments and *Corophium* amphipods. Although there is only limited information on the sensitivity of birds to TCDD-like toxicity, it was concluded that the residue concentrations in food items in the Somass River estuary may be high enough to affect health in some bird species.

Vermeer and Peakall (1979) evaluated trace metals in Surf Scoters and Greater Scaup from the Fraser River Delta Intertidal area to determine if they were impacted

by discharged wastes. Trace metals in samples of their major prey items were also analyzed. Significant differences of mercury, silver, copper, lead, and zinc concentrations between the species and among different sites were observed. However, they were below concentrations reported to cause adverse impacts.

ADDITIONAL CONCERNS AND THREATS

Many human activities, including oil spills, intrusion disturbances (by both humans and dogs), entanglement in marine debris and fishing gear, and hunting, negatively impact resident and migratory birds. More serious, but less obvious, are the indirect threats related to human population growth and development, which include the contamination and reduction of food supplies and the degradation and destruction of critical habitat (PSWQA 1992a)

The region's growing and sprawling population poses a great threat to the health of Puget Sound and the Strait of Georgia (Butler and Vermeer 1989; PSWQA 1992b). Extraordinary population growth and related development has occurred in all areas of the region. Development is encroaching upon the most sensitive of the region's remaining habitats (PSWQA 1992b). In the Puget Sound region, approximately 70% of the tidally influenced emergent wetlands have been lost to diking, dredging, and filling (Washington State Department of Ecology 1989). Over 75% of the marshes of the Fraser River delta (Butler and Campbell 1987) and about 32% of the former estuarine marshland on Vancouver Island (Campbell-Prentice and Boyd 1988) now lie behind dikes.

Population increases have also brought a tremendous increase in recreational boating and flying, fishing, and diving. This has caused disturbance at colonies, roosts, and foraging areas.

The estimated risk for a large oil spill (>1,000 barrels) to occur in the area between southern British Columbia and northern Washington is once every 1.3 years (Burger 1992). Birds most likely to be directly affected by spills are species that spend nearly all their time on the water surface (such as Common Murres, grebes, and loons), breeding populations of alcids, and wintering diving ducks. Ducks (especially seaducks), geese, and shorebirds, which feed in the intertidal zone, may be hardest hit indirectly through destruction of their feeding habitat (Vermeer and Vermeer 1975; Speich and Wahl 1989). Spills in locations with large concentrations of birds would be particularly destructive. External oiling often causes loss of buoyancy and insulation, resulting in the bird drowning or dying of hypothermia. Toxic effects can result from the ingestion of oil through preening feathers or eating contaminated food (Hartung and Hunt 1966). The sublethal effects of oil ingestion include increased mortality from predation, starvation, and disease (Albers 1991). Mortality of embryos can result when eggs are oiled, especially during the early stages of incubation (Albers 1991). Experienced breeders are lost and reproductive success at impacted colonies can be altered by delayed breeding and below-normal reproductive success (Nysewander, et al. 1993a).

Various species of seabirds are known to be at risk due to net fisheries. Gillnet fisheries are believed to pose the highest hazard, but birds are also lost to purse seines and other types of net fisheries. Gillnets are commonly used to catch salmon in Washington and they have long been recognized as a significant source of mortality for seabirds (King et al. 1979; Ainley et al. 1981; Carter and Sealy 1984; Takekawa et al. 1990; DeGange et al. 1993). Gillnet fishing seasons overlap the arrival of wintering bird populations. Direct observations of certain fisheries, and reports of large numbers of dead birds on beaches, suggest the main species involved in net entanglement are Common Murres, Western Grebes and Marbled Murrelets, with Rhinoceros Auklets and various cormorant species also impacted (Troutman et al. 1991).

Carter and Sealy (1984) estimated that a gillnet fishery in Barkley Sound, British Columbia, killed over 7.8% of a post-breeding Marbled Murrelet flock during 1980. In 1993, the Canadian Wildlife Service counted 1100 dead seabirds (90% adult Common Murres) on beaches in or near Boundary Bay (Kaiser 1993). The carcasses showed evidence of drowning due to entanglement in gillnets. The only suspected source was the gillnet salmon fishery in U.S. waters off Point Roberts and the nearby San Juan Islands. The nesting population of Common Murres in Washington is currently at very low levels and there is concern regarding gillnet mortalities and their adverse effects on the population (Wilson 1991).

There are several factors that restrict the ability to recognize trends and the severity of threats to bird populations:

- Bird populations exhibit great natural variability.
- Populations of birds breeding elsewhere but wintering in marine waters may be affected by factors (i.e. drought or loss of habitat) unrelated to what is occurring in the marine ecosystem.
- There may be natural cyclical effects (e.g. ENSO) related to weather patterns, or unrelated to other known factors.
- It may be difficult to obtain enough replicate counts of a highly variable population to determine whether a change is significant.
- The actual effects of incidents such as oil spills are difficult to ascertain because the origins of the affected bird populations are frequently unknown.

For these reasons it is important to systematically gather data that permits the identification of population trends. It should also be recognized that there will be a degree of uncertainty associated with monitoring. It generally will not be possible to wait until 'statistically significant' trends are identified before taking action, because populations or sub-populations may have already been impacted to such a degree that they will be slow to recover or will not recover in the immediate future. It is also important to identify and address situations where several factors may impact a species simultaneously (for example, Common Murres abandoning a colony prematurely when an ENSO event causes a lack of food, and resulting in higher mortality from gillnet fisheries when the birds move into wintering areas earlier than normal).

RECOMMENDATIONS

Birds associated with marine waters are an important natural resource shared between Washington and British Columbia. Whenever possible, resource information and management efforts should be coordinated. The following recommendations identify important information/data gaps and resource management needs. Recommendations are grouped into four general categories: marine bird population monitoring/studies; prey base analyses; environmental contaminants; and human-marine bird interactions. The recommendations are neither prioritized, nor are they all-inclusive.

1. Marine bird population monitoring/studies: Current monitoring efforts need to be continued and/or increased to address data gaps and improve the analysis of status and trend information. The collection of year-round information, including both breeding and wintering surveys, is crucial.
    - Continue or expand the monitoring of populations of marine birds during all seasons.
    - Conduct special surveys for species of concern, such as Marbled Murrelet and Harlequin Duck, that may not be adequately surveyed in existing monitoring programs.
    - Identify inland marine water areas that are highly utilized by summer populations of sub-adults/non-breeders. These areas may be critical for the long-term well-being of certain species, as inland waters often harbor large numbers of nonbreeders. These areas should be considered for habitat preservation and/or management activities.
2. Prey base analyses:
    - Where unknown, identify diets of marine birds to support prey base management recommendations by fishery resource agencies.
    - Evaluate the interaction of hydrographic features (tides, currents, upwelling, etc.) on the distribution of wintering concentrations of both marine birds and their forage fish or prey items. Identify prime feeding areas related to physical/hydrographic features.
    - Expand existing baseline data on the distribution, timing, and movement of non-commercial forage fish (prey) in marine waters.
    - Evaluate adequacy of the prey base for marine birds and the role of fisheries management in addressing the sufficiency of that prey base. The relative productivity of the inner marine waters and the outer coastal waters should be considered.
3. Environmental Contaminants:
    - Develop and implement a long-term program to monitor contaminant levels in fish-eating birds as

ecosystem indicators throughout Puget Sound, Juan de Fuca Strait and the Strait of Georgia.

- Develop and implement a research program to identify and determine the source of contaminants that are bioconcentrated in bird species at the top of the marine foodchain.
- Develop and implement a program to determine the impact of sublethal levels of contaminants and other health stressors on bird species at the top of the marine foodchain.
- Develop and implement a program to measure contaminant levels in game species to establish the potential impact on human health.

4. Human-marine bird interactions:
   - Evaluate the loss of essential habitats due to human development and other activities. Estuarine habitats, in particular, are among the most threatened by human development and contaminants. Identify habitats of immediate concern; develop recommendations to reduce habitat loss rate and/or protect important habitats.
   - Identify and protect nesting colonies where human disturbance is a problem.
   - Continue existing monitoring of impacts to seabirds by net fisheries. Develop recommendations to reduce bird mortalities.
   - Evaluate direct (i.e., drowning, shooting, etc.) and indirect (i.e., degradation/loss of habitat, water quality and food) impacts of mariculture on marine birds. Develop management practices and/or recommendations to reduce impacts.
   - Address the impacts of Glaucous-winged Gulls on the following: colonial nesting seabirds; as nuisance factors on roofs of buildings and at landfills; safety risks at airports; and as vectors in the dispersal of organisms harmful to human health.
   - Evaluate the use of habitat and population restoration techniques (e.g. social stimulation; release of captive-reared birds; nest-boxes; translocation of Tufted Puffins to Protection Island) for the assisted recovery of declining species or populations.

To turn these and other recommendations into actions, a working group of scientists and resource managers from British Columbia and Washington should be formed. Topics that the workgroup should address include coordination of studies and monitoring efforts, development of implementation strategies, identification of priorities, and funding opportunities.

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DISCUSSION

ANDREA COPPING *(Panel)*: Mary, given that so many of these birds are migratory — and migrate a very long ways — is the health and the toxic body burden of these animals really a good indicator of environmental stresses and the environmental condition of our ecosystem here in British Columbia and Washington?

MARY MAHAFFY: That's why it's hard to select birds to monitor long term. You have to be careful with the selection. Cormorants and herons are resident species, so you can see what they have picked up here. We have to study scoters to see how long they stay here. Guillemots are another resident bird. But for a shore bird that's gone to Latin America, you probably wouldn't want to say the contaminant was related to pollution here.

BRUCE MCCAIN *(Panel)*: You talked about eggshell-thinning as one possible sublethal effect of contaminant exposure. Have you identified any other types of sublethal effects that might be measured as indicators of the contamination?

PHILIP WHITEHEAD *(Canadian Wildlife Service)*: The differences we saw were in the developing embryos. Specifically we found elevated enzyme activity in the livers of the more contaminated birds. The chicks were of a smaller size than they were in colonies where dioxin levels were lower. There were two or three sublethal effects like that, but they didn't appear to affect the productivity in the colonies. The colonies seem to be fledging the normal number of young, so they didn't have a long-term impact.

CURTIS EBBESMEYER *(Panel)*: In physical oceanography we have a few benchmark sites in the northwest that we can go back to as being correlative with a wide range of other phenomena. Is there a benchmark bird?

MARY MAHAFFY: Well, aside from herons in B.C., guillemots are one that we may be doing in Washington. The big thing is going to be if they start using the nest boxes so that we can actually monitor them. We need to find one that is right there, that each year we can count on being there, that's a key thing.

LAURIE MACBRIDE *(Save Georgia Strait Alliance)*: Martin Keeley from Friends of Boundary Bay couldn't be here this morning and asked me to bring up the issue of the common murre kill which I'm glad you covered. But the question is, since obviously this population is getting so low that it cannot stand another kill of the magnitude that happened last year, is anything being done, other than more studies, to replace the monofilament nets that are used by Washington State fishers with the braided nylon nets of the type BC fishers use, because the BC fishers have had much lower levels of bird kill?

MARY MAHAFFY: People are starting to look at the difference of net or gear makes. One question is that if the net fisheries are occurring at night, are the birds going to notice a difference between the monofilament versus the other heavier nets. I guess is something that does need to be looked at, and part of the monitoring that is being done. The overall coverage of 1% or 2% wasn't enough for Fish and Wildlife Service to come out and say, okay we know this is the kill and we know therefore that in these areas we need to make sure that there aren't fisheries.

LAURIE MACBRIDE *(Save Georgia Strait Alliance)*: I guess that Martin's concern is that with the population in the area at less than 3000 now, and the 1000 that were washed up, with likely three times that number washed out to sea, that's the end of the entire population if there is yet one more kill of that magnitude.

MARY MAHAFFY: It is a great concern.

DAVE NYSEWANDER: You're right, there is a concern about Washington State birds, but we also have a great influx of other birds that come in; 70,000 to 100,000 birds from Oregon move into this area, so we have a hard time separating out the different bird populations that move in. But that is part of the equation you need to keep.

I might also mention on species for monitoring purposes, you mentioned the guillamots and contaminants. We tend to have three, because they look at different niches. One would be the fish-eating diving birds like rhinos or murres. Loons and grebes tend to use a different niche and we have large populations that use both British Columbia and Washington in the winter. The third is diving ducks of some sort, sea ducks, harlequin ducks, whatever. So if I had to select certain

species it's hard to pick one that will look at all these different niches, but you could take, say, three suites of species.

Ken Warheit *(Washington Department of Wildlife)*: This is pretty much a follow-up question to the one that was just asked, and comments made by Dave Nysewander. First of all, concerning the influx of birds coming in from other areas. I'm right now heading up a project that's using morphometric techniques to determine the area of origin of common murres coming into the State of Washington. We're looking at birds from Alaska, British Columbia, Washington, Oregon, and California, so hopefully we'll get some results from that in the spring.

Secondly, concerning the net fisheries, I want to emphasize one point to the Panel, and I mentioned this in my brief to the Panel, that in the State of California they have estimated between 70,000 and 75,000 common murres have been taken in the net fisheries. They have also estimated that that has had a significant impact on the population. Now we don't know if that's happening in Washington, but we certainly know that there are birds being caught in the net fisheries, and that there is a tremendous overlap between the areas where they forage and where the commercial fisheries are, so that's something that we definitely need to look at.

Dave Kalman *(University of Washington)*: My question really has to do with a monitoring-strategy issue. It seems that we're still playing out a lot of the pesticide use that occurred in the 60s and early 70s. I'm wondering about organophosphate pesticides, and in particular I am wondering about exposures that would occur because of agricultural activity in non-nesting areas where bird population, or bird census data, will not help you to assess effects. An example might be the Skagit although I only have a superficial knowledge of it, but I am aware that there's a lot of organophosphate spraying and a major flyway for bird populations. Does the monitoring program have any element that would let you see these kinds of health impacts?

Mary Mahaffy: Right now as far as the birds go in Washington, we still haven't set this up. Especially in the Midwest, there have been impacts shown because of the organophosphates, and it is something that we do need to look at. There is concern about what the birds are bringing in, and if they are impacted by contaminants in agricultural areas.

Philip Whitehead *(Canadian Wildlife Service)*: Just a comment for BC. We don't have a monitoring program *per se* for organophosphates or carbon-based pesticides. These chemicals don't persist in tissues, so it's rather hard to construct a program that looks at long-term trends and things like that. We do have a network set up where we can, we can respond to impacts on bird populations or bird kills, identify the compound, and then perhaps take action to have these compounds regulated in some way.

Brett Betts *(Washington Department of Ecology)*: Mary, I wonder if there has been any kind of study on trying to make that a stronger link between sediments, contaminated shellfish, and fish and birds.

Philip Whitehead: We have found that the herons remain around the nesting colonies year-round and they forage in the same area pretty well year-round, so we view the herons as indicators of particular sites and very specific areas. And with regard to the pulp mills and at Crofton for example, the fact that the dioxin levels went down very rapidly at Crofton shortly after the mill implemented clean-up procedures, indicated to us not only were the heron of course cleaned up, but because they accumulate these compounds from the fish that they eat, then clearly the fish had cleaned up as well. We were confident that at least part of that food chain in that system had been cleansed of dioxins.

Chuck Kenney *(US Fish and Wildlife)*: I was going to try to talk a little bit about the sediment residue relationship that the question that came up. It's very difficult to evaluate residue uptake from sediment. I'll give you a couple examples. We looked at western grebes in Commencement Bay, which is one of the most contaminated parts of Puget Sound. We looked at surf scoters in the same bay, the same year. The difference for example in cadmium uptake in that particular area was a 50-fold difference, just because of different food habits. The sediment was the same, they ate different things.

Another example in relation to two different species of mollusc in the same area, essentially collected from the same rock, one had 30 ppm cadmium, the other had 3 or 4 ppm. So each species is different, they accumulate at different rates, so it's very difficult to make that sediment-to-bioavailability of what that bird is actually in-taking in that particular area.

Chris Garrett *(Panel)*: As a Panel member I wonder which of these problems could the populations recover from in a few years — if we were to get smart and clean up our act a bit as humans — and which are things that would be irreversible, and so would have long-term threats to the populations? I mean should we focus on the longer term ones?

Mary Mahaffy: Seems like always the long-term ones are the ones you're definitely concerned with. If there were a spill, certain species would be impacted more than others. If all the Washington nesting birds were caught in a spill, the recruitment rate to the colony, differences with the reproduction, all those things would take a long time to bounce back.

Chris Garrett *(Panel)*: But they would bounce back I guess. I mean if we try and project say where we'll be in 20 years time, will we look back and say, 'Oh it was that terrible spill in 1994 which was the end of some population', or will we look back and say, 'Well there was that awful spill in 1994, but the birds have recovered by now, but on the other hand the estuaries have all gone'?

Mary Mahaffy: It depends on what the spill was. Was the prey-base totally affected — that's a key thing — the birds have to have something to eat. There have been differences in Alaska with the recovery of the birds up there from the spill.

Tom Pedersen *(Panel)*: The common murre decline in Puget Sound, which is shocking, what has that been attributed to? Is there one single cause, or is it a whole raft of things, or is there one major pressure that has caused that steep decline?

Mary Mahaffy: Well the initial decline occurred after an El Niño year and there's just been a real slow recovery to the population from that, and there have been several years when the birds haven't been able to breed. Or they've maybe left the colony area because things aren't quite right there, and they haven't been counted. Maybe if we get some real normal years, we'll see different numbers there.

Dave Nysewander: It's a combination of factors like the California situation Ken mentioned. It was a combination of three factors, El Niño, oil spills and gillnet fisheries.

Tom Pedersen *(Panel)*: If I was to ask you to give me your best impression as to what percentage of that decline was due to the El Niño and what percentage was due to the gillnet fishery what would you say?

Ken Warheit *(Washington Department of Wildlife)*: Let me add to what Dave was saying. The impact of the '83 El Niño may have been two-fold, not only reducing the births, but severe El Niños kills adults as well. It depends if there is no food anywhere, then you can have population decline not only due to the fact they didn't reproduce, but because adults have died. The problem that we are having in Washington right now is that we had an oil spill, and then we've had two El Niño years, so we have difficulty seeing what's going on due to the oil spill and what's a result of the El Niño effect. So we have to be able to tease those things apart.

When you talk about the common murre and some of the diving ducks, after the populations have declined and in fact if they become locally extinct, it is difficult for them to return to certain areas because they are incredibly philopatric, that means they return to natal areas. So if you have wiped out an entire colony, you don't have a source by which that colony can be repopulated, unless the young from other areas are moving out, which tends to be rare.

Tom Pedersen *(Panel)*: Well I understand that it's very complicated, but I would still like someone to tell me about the fishery, this gillnet fishing problem. Is this a big effect?

Ken Warheit *(Washington Department of Wildlife)*: There haven't been big efforts in the State of Washington to examine what is the injury to the population. We know that birds are being taken, and we know that there's an overlap between where the birds forage and the commercial fisheries. What we need to go out and find out is what the impact to the population is. If we find out the same results that they found in California, then we can make a statement that the gillnet fisheries or the seine fisheries is injuring X% of the population, but we don't have an answer for that right now. We need to gather more information for that.

Dave Nysewander: In Prince William Sound they didn't find too much impact with gillnet mortalities. So there is a mixture, depending probably on when these fisheries occur, what type of gear they are using, a lot of different factors, and the areas. It's hard to generalize at the moment until here is a lot more information. And there has been some information gathered, but it's

minimal and then what has been given in some cases has not been released.

Laurie MacBride *(Save Georgia Strait Alliance)*: I don't think it's an issue of shutting down a fishery, and I as an ex-commercial fisher, would be the last to argue for that. I think it's a matter of what type of gear is used, and the point that I was trying to make on behalf of Martin Keeley was that the braided nylon fishing nets used in BC have a much lower kill-rate than the monofilament nets used in Washington State. And therefore should we not be urging a switch-over to braided nylon since the common murre population is obviously in very serious trouble?

Status of Marine Mammals in the Strait of Georgia, Puget Sound and the Juan de Fuca Strait and Potential Human Impacts

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ABSTRACT

Nine species of marine mammals commonly occupy the transboundary waters of British Columbia and Washington (BC/WA). Individuals of all species move across this international border. Of the four pinniped species common to these waters, harbour seals are the most numerous and the only one that breeds in the transboundary area. Approximately 27,000 harbour seals occur in the transboundary area, and the population has been increasing at 5–15% per year. Elephant seals are found in the transboundary area in small numbers, and their occurrence in the area has increased in recent years. The number of California sea lions in the area increased in the 1980s and appears to have stabilized. While declining through most of its range, the number of Steller sea lions which use this area appears to be stable, although well below historical levels. Of the five cetacean species common to the waters, harbour and Dall's porpoise are the most abundant and number in the several thousands. Harbour porpoise numbers in some areas have declined since the 1940s, though little data are available to assess current trends in populations of these two species. Two populations of killer whales utilize the transboundary area. The 'resident' population is growing and is currently larger than it was prior to a live-capture program in the 60s and 70s. Over 20,000 gray whales migrate past the entrance to Juan de Fuca Strait and some individuals spend prolonged periods feeding during the spring and summer in BC/WA waters. A small number of minke whales use this area for feeding, primarily during the spring, summer, and fall.

Marine mammals are vulnerable to human activities in the BC/WA transboundary waters. High concentrations of contaminants, especially chlorinated hydrocarbons and some metals, have been identified in these animals. Highest concentrations of contaminants have been found in harbour seals (from southern Puget Sound), harbour porpoise and killer whales. Determination of the impacts of these contaminants on marine mammals in these waters has been inconclusive, though in other areas contaminant exposure has been linked to reproductive failure and immunosuppression. Marine mammals are killed incidental to commercial fishing operations, particularly harbour porpoise and Dall's porpoise. Information to assess human impacts on most marine mammals and to adequately evaluate their current status is extremely limited.

INTRODUCTION

The transboundary waters of British Columbia and Washington, including Puget Sound, the Strait of Georgia, and Juan de Fuca Strait, are used by a variety of marine mammals for feeding and breeding (Osborne et al. 1988; Everitt et al. 1980). Despite the cross-border movement of marine mammals, management of marine mammals has largely been conducted independently within each country due to legal and logistical constraints. The status of management of marine mammals is of great interest to many people for many reasons. Populations of many marine mammals species were severely depleted by human exploitation prior to their legal protection. Today, many people feel a strong emotional attachment to marine mammals, though to some fishermen, marine mammals are viewed as competition for limited fish resources.

A variety of human activities potentially impact marine mammal species in the transboundary waters. Pinnipeds and odontocetes (toothed cetaceans) are especially vulnerable to the impacts of stable environmental contaminants because they feed high on the food chain. Extremely high concentrations of contaminants have been found in tissues of marine mammals in the transboundary area (Calambokidis et al. 1984, 1991a). Marine mammals are also vulnerable to mortality incidental to commercial fishing activities and to human disturbance in the transboundary area.

In this report we summarize what is known about the status of marine mammals that occur in the transboundary area, examine potential human impacts on marine mammals, and make research recommendations. Place names mentioned in the text are shown in Figure 1.

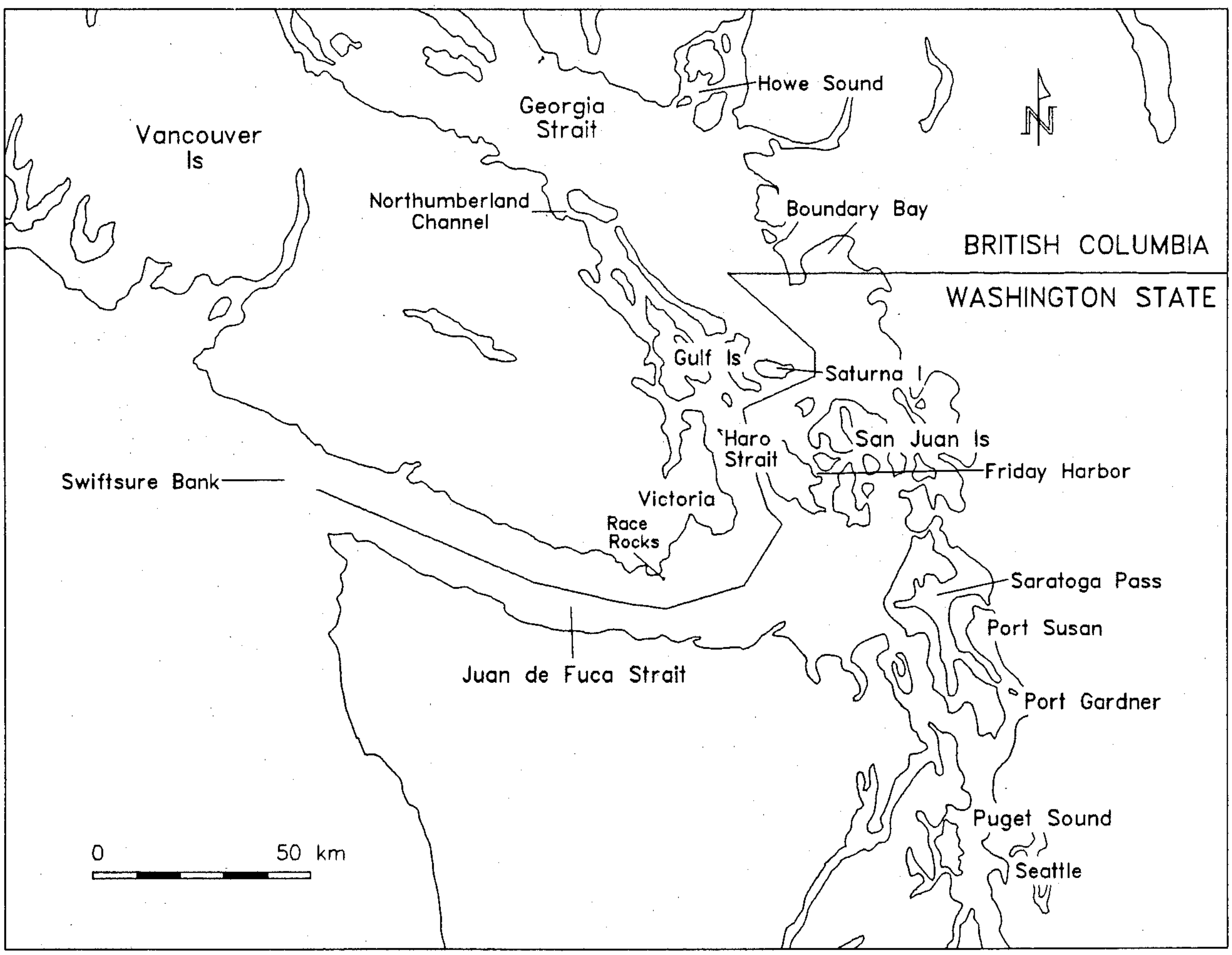

Figure 1. Map of trans-boundary area showing place names mentioned in text.

SPECIES ACCOUNTS

Harbour Seals *(Phoca vitulina)*

Harbour seals are the most abundant marine mammal in the transboundary area; they breed and occur year-round in these waters (Osborne et al. 1988). They use numerous rocks, beaches and log booms throughout the area to haul out to rest, give birth and nurse their young (Scheffer and Slipp 1944; Osborne et al. 1988; Olesiuk et al. 1990a; Huber et al. 1993). Harbour seals were killed under bounty and other control programs in both British Columbia and Washington State due to purported predation on commercial fish species (Scheffer and Slipp 1944; Newby 1973a; Bigg 1969). Harbour seals, like other marine mammals, have been protected since 1970 in British Columbia and 1971 in Washington State (by state law prior to protection in 1972 under the U.S. Marine Mammal Protection Act).

Harbour seal abundance has been increasing at an average annual rate of 12.5% in British Columbia (Olesiuk et al. 1990a) and generally between 5% to 15% for most sites in Washington State (Calambokidis et al. 1979, 1985; Jeffries 1985; S.J. Jeffries and H.R. Huber pers. comm.). In recent years, numbers may have stabilized or decreased in northern Hood Canal (Evenson and Calambokidis 1993). Absolute abundance estimates of harbour seals have been made for the transboundary area although methodologies to correct counts have varied somewhat between British Columbia (Olesiuk et al. 1990a) and Washington (Huber et al. 1993). The abundance of harbour seals in the Strait of Georgia was estimated at 15,810 for 1988 (Olesiuk et al. 1990a) and 11,800 for Juan de Fuca Strait, San Juan Islands, and the embayments just north of Puget Sound in 1992 (Huber et al. 1993). Continued monitoring of harbour seal numbers as well as aspects of their biology and human impacts in the transboundary area is underway.

Harbour seals are considered non-migratory, but long-distance movements among sites in the North Pacific have been documented (Scheffer and Slipp 1944; Pitcher and McAllister 1981; Brown and Mate 1983; Jeffries 1986; Huber et al. 1993). Radio tagging of harbour seals in the San Juan Islands, Gulf Islands, and Boundary Bay demonstrated extensive movements of harbour seals among sites in this area, with many animals documented moving across the international border (Huber et al. 1993).

Conflicts between the growing populations of humans and harbour seals have increased. Harbour seals are opportunistic foragers and feed in the transboundary area on a wide variety of fish species and to a more limited degree on cephalopods and crustaceans (Scheffer and Slipp 1944; Fisher 1952; Spalding 1964; Everitt et al. 1981; Calambokidis et al. 1978, 1989; Olesiuk 1993). Primary prey species within the Strait of Georgia are hake and herring (Olesiuk 1993). Conflicts with commercial fisheries include predation on commercially valuable fish, removal or damage of fish caught in gillnets, and damage to gear. In rare circumstances, particularly due to loss of salmon breeding habitat and overfishing, harbour seals may have a serious impact on some salmon runs (Bigg et al. 1990a). Harbour seals have also been implicated with closure of commercial shellfish beds near some haul-out areas in Puget Sound due to high concentrations of fecal coliform contamination (Calambokidis et al. 1989). Harbour seals are the primary prey of transient killer whales in this area with large numbers taken at some haul-out sites, such as Race Rocks (Baird and Dill 1994).

California Sea Lion *(Zalophus californianus)*

California sea lions breed on islands off Baja, Mexico and southern California with primarily males migrating north to feed in the transboundary area (Everitt et al. 1980). The breeding population in southern California has been increasing at about 5% a year (DeMaster et al. 1982). California sea lion occurrence in the transboundary area increased sharply in the late 1970s and early 1980s (Everitt et al. 1980; Bigg 1985; Steiger and Calambokidis 1986). Counts of California sea lions in the transboundary area totalled just under 3,000 by the mid-1980s (Bigg 1985; Gearin et al. 1986). In recent years the number of sea lions has stabilized or decreased in some portions of the transboundary area (Gearin et al. 1988).

California sea lions are present in the transboundary area from late August to June of each year (Everitt et al. 1980; Bigg 1985; Steiger and Calambokidis 1986; P. Gearin pers. comm.). They leave and enter the area through Juan de Fuca Strait, for migrations to and from their breeding grounds in California (Calambokidis et al. 1987). California sea lions use numerous locations to raft in the water or to haul out (Everitt et al. 1980; Bigg 1985; Gearin et al. 1988). Although these sites some-

times change over time, areas of concentration in recent years have included Race Rocks and Northumberland Channel in British Columbia and Port Gardner in Puget Sound. They can also be found in small numbers throughout all marine areas and into major rivers.

California sea lions come to the transboundary area primarily to feed. Primary prey of California sea lions in the study area include hake, walleye pollock, herring, and spiny dogfish (Everitt et al. 1981; Gearin et al. 1988; Olesiuk and Bigg 1988). California sea lion predation on steelhead trout and coho salmon at the Ballard Locks in Seattle has become a major concern since the mid-1980s (Gearin et al. 1986, 1988). Predation rates on this already small run have been high enough to endanger the survival of the steelhead run. Attempts to reduce the predation through seal bombs, underwater sounds, nets, and relocation of animals have so far been unsuccessful. Continued research on the status of this species and ways to reduce predation on steelhead is underway. Within the transboundary area both California and Steller sea lions are occasionally eaten by transient killer whales (Bigg et al.. 1987; Baird and Dill 1994).

Steller (Northern) Sea Lion
(Eumetopias jubatus)

Steller sea lions are year-round residents in British Columbia, and seasonal visitors to Washington State. Within B.C. they breed only in the central and northern parts of the province (Bigg 1988), and are largely seasonal visitors to the transboundary area (Everitt et al. 1980). Steller sea lions are currently listed as threatened in the U.S. (Marine Mammal Commission 1991), but are not listed as endangered or threatened in Canadian waters (Bigg 1988). Populations in Alaska and California have declined by over 50% in the last 30 years (Loughlin et al. 1992), while the population in British Columbia appears to be stable, but at levels far below the original levels which existed prior to intensive culling programs (Bigg 1988).

Within the transboundary area, other than an occasional animal seen between June and August, Steller sea lions move into the area in September, and depart in May. The majority of Steller sea lions within this area appear to be males, with females remaining closer to their breeding colonies. High numbers of Steller sea lions (of both sexes) are seen on the northern Washington coast with peak numbers from August to March (P. Gearin pers. comm.). The majority of sea lions appear to enter the transboundary area through Juan de Fuca Strait, thus peak numbers occur earlier in the season at haul-out sites in this area. Steller sea lions can be predictably found at about 10 haul-out or rafting sites within the transboundary area, usually intermixed with numbers of California sea lions (Bigg 1988; Everitt et al. 1980; Osborne et al. 1988). They also range in small numbers throughout the study area. Numbers within the transboundary area may surpass a thousand individuals during the winter.

Within British Columbia and Washington, Steller sea lions have been recorded eating octopus, squid, lamprey, skate, spiny dogfish, ratfish, herring, eulachon, hake, rockfish, halibut, lingcod and salmon (Pike 1958; Spalding 1964). Salmon only makes up a few percent of their diet (Olesiuk and Bigg 1988). In Alaska, Steller sea lions have occasionally been recorded feeding on harbour seals and on northern fur seal young (Gentry and Johnson 1980; Pitcher and Fay 1982).

Little research has been undertaken on this species in the transboundary area, other than periodic surveys of animals hauled out (Steiger and Calambokidis 1986; Bigg 1988; Gearin et al. 1988), and regular counts of numbers at Race Rocks, one of the larger haul-out sites within the transboundary area (Baird unpubl. data).

Northern Elephant Seal
(Mirounga angustirostris)

Northern elephant seals are found within the transboundary area in small numbers year-round (Baird 1990, and unpubl. data), although they do not breed there. This species is abundant and increasing within its range in the eastern North Pacific (Campbell 1987). Adult animals congregate around several breeding colonies in California and Mexico during the winter; but even during this time small numbers of juveniles and sub-adults are found in Juan de Fuca Strait and surrounding areas. The transboundary area is used by elephant seals both to feed and to haul-out. Small numbers of juveniles haul out throughout this area for periods of over a month to moult. Haul-out areas in the transboundary region are not as predictable as for the other species of pinnipeds found there. Only one site (Race Rocks, at the southern tip of Vancouver Island) has been identified as a regular haul-out area for ele-

phant seals (primarily juveniles), where they have been observed with harbour seals or sea lions (Baird unpubl. data). In recent years up to four elephant seals have simultaneously used this site for extended periods (up to several months). Adult elephant seals can be found foraging in deeper water (typically greater than 100 m) throughout the transboundary area, although few records are available for the central and northern Strait of Georgia. While no estimate of population size within the transboundary area is available, the number of elephant seals using this area appears to be increasing (Baird unpubl. data; Everitt et al. 1980).

No diet studies have been conducted on northern elephant seals within the transboundary area; knowledge of prey is based on a few anecdotal observations of feeding elephant seals and from studies in more southerly parts of their range. Elephant seals have occasionally been observed eating spiny dogfish at the surface in local waters (e.g., Osborne et al. 1988). Studies on feeding habits off California and Oregon indicate that they feed on a wide variety of prey, both within the water column and bottom dwelling organisms. These include shrimp, pelagic red crabs, numerous species of squid and octopi, tunicates, skates, rays, sharks, ratfish, lamprey and bony fish, such as hake and rockfish (Antonelis et al. 1987; Condit and LeBoeuf 1984).

Juvenile elephant seals are often mistaken for large harbour seals (Everitt et al. 1980). As they are easily approachable on beaches and often appear sick to an uninformed observer (in comparison to normal harbour seal behaviour), such confusion has resulted in the accidental killing of several animals around southern Vancouver Island in the last five years (Baird 1990, unpubl.). Elephant seals are occasionally killed due to entanglement in gillnets. One other occasional source of mortality for elephant seals in the transboundary area is predation by transient killer whales (Baird and Dill 1994). In the transboundary area research has been limited to monitoring hauled animals for tags and moulting status, and examining some strandings.

Harbour Porpoise *(Phocoena phocoena)*

Harbour porpoise are common in coastal waters of the North Pacific and occur year-round and breed in the transboundary area (Osborne et al. 1988). They are considered vulnerable to human activities, and populations in several other portions of their range have declined or been eliminated (Wolff 1981; Otterlind 1976; Prescott and Fiorelli 1980; Leatherwood and Reeves 1983).

Abundance estimates of harbour porpoise for Juan de Fuca Strait and San Juan Island area in 1991 were approximately 3,300 (Calambokidis et al. 1993a). Densities of harbour porpoise were similar in Juan de Fuca Strait and the San Juan Island area but both were lower than in coastal waters of Oregon and southern Washington (Calambokidis et al. 1992b). Harbour porpoise along the coast use primarily near-shore waters shallower than 100 m, but the depth-associated distribution pattern is not as clear in Juan de Fuca Strait and San Juan Islands (Calambokidis et al. 1992b). Harbour porpoise were once considered common in southern Puget Sound (Scheffer and Slipp 1948) but are now rarely seen (Everitt et al. 1980; Calambokidis et al. 1985, 1992b). Reasons for their decline in Puget Sound and other areas are not known, although pollutant effects, avoidance of heavy vessel traffic, and mortality due to entanglement have all been suggested as possible reasons. Additional research is currently underway to further examine harbour porpoise occurrence in Puget Sound. Anecdotal evidence also suggests that harbour porpoise populations in southern British Columbia have decreased since the early part of this century.

Harbour porpoise feed on a variety of smaller fish and squid. Harbour porpoise entangled in gillnets along the northern Washington coast were feeding primarily on herring, squid, smelt, and gadoids (Gearin and Johnson 1990). Treacy (1985) found mostly small schooling fish and squid in the stomachs of seven harbour porpoise found dead near the Columbia River.

An unusually large number of harbour and Dall's porpoise were found dead on southern Vancouver Island in 1993, but the cause of this mortality has not been determined (Baird et al. 1993a). Small numbers of both harbour and Dall's porpoise are eaten by killer whales in the transboundary area (Baird and Dill 1994).

Little information exists on harbour porpoise movements and stock structure in the transboundary area. This is an important concern because of the localized nature of some of the fishery-related mortality. Although it is suspected that harbour porpoise in some areas make extensive migrations (based on seasonal shifts in distribution), no evidence exists for migrations

in the transboundary area. Significant differences in the pollutant ratios of harbour porpoise along the U.S. west coast suggest that harbour porpoise populations may be somewhat discrete (Calambokidis and Barlow 1991).

Dall's Porpoise *(Phocoenoides dalli)*

Dall's porpoise occur year-round and breed in deeper waters (>50 m) of the transboundary area (Baird and Guenther 1991; Everitt et al. 1980; Osborne et al. 1988). Dall's porpoise are not considered depleted and are widely distributed throughout the North Pacific with an estimated abundance of over 1,590,000, though this figure may be overestimated due to vessel attraction (Hobbs and Lerczak 1993). Only limited research has been conducted on this species in the transboundary area.

Dall's porpoise abundance has not been determined for all the transboundary area, though estimates are available for some regions. Estimated abundances were 3,015 for Juan de Fuca Strait and 133 for the San Juan Islands area (Calambokidis et al. unpubl. data). Green et al. (1992) estimated an abundance of 2,149 Dall's porpoise in the waters off Oregon and Washington out to 185 km, but this estimate is probably low because it was not corrected for missed animals. Although Dall's porpoise are killed incidental to fishing operations in the transboundary area, there are no data on population trends or the impact that this is having on the population.

The degree of movement of Dall's porpoise in the transboundary area is not known. The year-round presence of Dall's porpoise in many areas may be indicative of resident animals or it could reflect the presence of different groups moving through the area. In Puget Sound, Dall's porpoise were seen year-round, but the low resighting rate of photographically identified individuals suggested interchange with other sites (Miller 1990). Densities of Dall's porpoise off the coasts of Oregon and Washington were not significantly different by season, although there was a seasonal shift in distribution with higher densities offshore in winter and spring and inshore in summer and fall (Green et al. 1992).

Dall's porpoise feed primarily on squid and small schooling fish (Jefferson 1988). Thirteen Dall's porpoise collected off Washington, including one off Juan de Fuca Strait, had been feeding on squid, capelin, eulachon, and righteye flounder (Stroud et al. 1981).

Killer Whale *(Orcinus orca)*

Two sympatric populations of killer whales are found within the transboundary area. These populations can be discriminated based on diet; one specializes on marine mammal prey (termed 'transient') and one specializes on fish prey (termed 'resident'). In addition to differences in diet, numerous other differences exist between transient and resident killer whales. These include differences in habitat use, surfacing patterns, vocalizations, group size, and social structure (Baird et al. 1992; Baird and Dill 1994; Bigg et al. 1987; Heimlich-Boran 1988; Morton 1990). Differences in external morphology (Baird and Stacey 1988; Bain 1989; Bigg et al. 1987) and mitochondrial DNA (Stevens et al. 1989; Hoelzel and Dover 1991) imply that these populations are reproductively isolated, and may in fact be incipient species (Baird et al. 1992). While a potential third form (termed 'offshore' killer whales) has also been recorded within the transboundary area (Walters et al. 1992), they have only been seen on one occasion and are not considered in detail here.

Both residents and transients are seen year-round and breed within the transboundary area, and can be predictably encountered in some areas at certain times of the year. Individuals of both forms have long-ranging movements (e.g., one pod of transient killer whales has a documented range of 140,000 km2), and thus regularly leave the transboundary area. Resident killer whales appear to be subdivided into two distinct populations in British Columbia; only one of which crosses the international border between Washington State and British Columbia, while the other ranges from the central Strait of Georgia north as far as southeastern Alaska (Bigg et al. 1976, 1987). This northern population (termed 'northern residents') numbers over 200 individuals, but as the centre of the range of these individuals lies outside of the transboundary area, our focus will be on southern residents and transients. The southern resident population numbers 96 individuals (ca. 1993). This population has been increasing 1.3 to 2.0% per year since live-capture of this species was stopped in 1977, and is now larger than the population size prior to the beginning of the live-capture program in 1962 (Olesiuk et al. 1990b). The range of the south-

ern resident population overlaps with the northern resident population by approximately 125 km on both the east and west coasts of Vancouver Island, but the core of the southern resident range lies within the waters of Haro Strait, the southern Strait of Georgia and eastern Juan de Fuca Strait. The population size for transient killer whales in BC/WA is unknown, but numbers at least 160 animals. New adult individuals are regularly discovered, so the total population size is probably much greater. No information is available on population trends however. To date, over 85 individual transients have been documented in the transboundary area, and additional individuals are documented in this area yearly (Baird unpubl.; M.A. Bigg unpubl. data; Baird and Dill 1994; Bigg et al. 1987).

The majority of prey recorded for resident killer whales have been salmon (Bigg et al. 1990b), but observations of prey taken are limited to those brought to the surface. Stomach contents from stranded animals implies that bottom fish are also regularly taken. Transient killer whales within the study area have been recorded feeding on both species of porpoises, both species of sea lions, elephant seals and several species of sea birds. By far the most important prey taken in this area is harbour seals however, comprising 96% of 136 marine mammals kills observed between 1986 and 1993 around southern Vancouver Island (Baird and Dill 1994).

Intensive research on this species has been undertaken in the transboundary area since the mid-1970s. In fact, the resident population is one of the most well-studied populations of cetaceans in the world. Ongoing research includes year-round monitoring of movements, photo-identification studies to monitor births and deaths in the populations, and behavioral studies.

Gray Whale *(Eschrichtius robustus)*

Over 20,000 gray whales migrate past Juan de Fuca Strait en route between their breeding grounds in Baja, Mexico and their primary feeding grounds in the Bering Sea (Buckland et al. 1993; Rice and Wolman 1971). Commercial hunting for gray whales reduced their numbers to under 2,000 earlier in the century. The eastern Pacific stock of gray whales has made a strong recovery since that time and is now thought to be close to its historical abundance. The U.S. National Marine Fisheries Service has recently recommended that the gray whale be removed from the endangered species list. The Korean stock of gray whales, in the western North Pacific, has not been so fortunate, however, and remains at precariously low levels (Rice and Wolman 1971).

Sightings of gray whales have been made in the transboundary area in all months of the year (Flaherty 1983), but most sightings in recent years have been in spring and summer (Calambokidis et al. 1992a). During and following the migration of gray whales past Washington and British Columbia in the spring, a small number of gray whales enter the transboundary area and spend extended periods feeding. Photographically identified individual gray whales have stayed for up to 4 months (Calambokidis et al. 1987, 1991c, 1992a) in these waters and some have returned for at least 4 consecutive years (Calambokidis et al. 1993b, in prep.). A number of gray whales have been identified feeding on both sides of the BC/WA boundary. Studies of the abundance and movements of gray whales in the transboundary area using photographic identification is continuing. Gray whales feeding for extended periods through the spring and summer in areas south of the Bering Sea have also been found off northern California (Mallonee 1991), Oregon (Sumich 1984), and along the west coast of Vancouver Island (Darling 1984).

Throughout the transboundary area, gray whales primarily use shallow areas close to shore for feeding. Gray whales feed primarily on amphipods and crustaceans that they capture by filtering water and sediment from the bottom (Nirini 1984). Prey types identified for gray whales in the transboundary area include ghost shrimp around Port Susan and Saratoga Pass (Weitkamp et al. 1992), and mysids (Murison et al. 1984) and ampeliscid amphipods (Oliver et al. 1984) along the west coast of Vancouver Island.

Varying numbers of gray whales wash up dead each year in the transboundary area, primarily in spring and summer. Starting in 1984, there has been concern and controversy regarding the role of pollutants in these deaths (Fouty 1984; Malins et al. 1984; Calambokidis 1992; Varanasi et al. 1993). Gray whales' ingestion of bottom sediments during feeding potentially exposes them to elevated concentrations of contaminants that occur in the upper layers of sediment in contaminated areas. Many of the animals that died in Puget Sound and Juan de Fuca Strait had very low fat reserves and were likely in poor nutritional condition (Varanasi et al. 1993). Causes of death of gray whales stranded in

Washington and British Columbia have included gillnet entanglements, boat collisions, and killer whale attacks (Baird et al. in press; Geiger and Jeffries 1983; Calambokidis et al. unpubl. data).

Minke Whale *(Balaenoptera acutorostrata)*

Minke whales have been reported from the transboundary area year-round (Everitt et al. 1980; Baird unpubl. data), although the majority of records are from March through November. World-wide, minke whales appear to be the most abundant species of baleen whale (U.S. Department of Commerce 1988). Population size and trends in the eastern North Pacific remain unknown however. Thirty individuals were photographically identified from the transboundary area around the San Juan Islands over a ten year period, and individual whales appeared to exhibit high site-fidelity, with many re-sightings of individuals in specific areas both within and between years (Dorsey et al. 1990). Population size within the transboundary area is unknown, but up to 19 individuals were photo-identified from around the San Juan Islands in a single year (Dorsey et al. 1990). Minke whales appear to be more common around the San Juan Islands than in other parts of the transboundary area, but little research effort has been extended in most other areas (particularly the Strait of Georgia and western Juan de Fuca Strait).

The transboundary area appears to function primarily for feeding; calving and mating in this species presumably occurs during the winter in lower latitudes. Most minke whales seen within the transboundary area are adults or subadults; the presence of calves has only been confirmed with two stranded animals (R. Osborne pers. comm.). Individual whales within the area seem to differ in foraging techniques, with some individuals primarily engaging in lunge-feeding, and others feeding in association with birds (Hoelzel et al. 1989). Feeding around the San Juan Islands appears to be concentrated in waters between 20–100 m in depth over submarine slopes with moderate inclines (Hoelzel et al. 1989). Regular sightings of travelling minke whales at East Point, Saturna Island, imply that some areas in The Strait of Georgia must be frequently used for feeding (Baird unpubl.). Two prey species have been identified in association with feeding minke whales in this area; juvenile herring and juvenile sandlance (Hoelzel et al. 1989).

Current research on this species within the transboundary area is limited to the collation of sighting records by the Marine Mammal Research Group in B.C. and by The Whale Museum in Washington State, and opportunistic photographic identification of individuals in the area around the southern tip of Vancouver Island and the San Juan Islands (e.g., Osborne et al. 1988; Dorsey et al. 1990).

Other Species

At least 16 additional species of marine mammals have been recorded within Juan de Fuca Strait, Puget Sound and the Strait of Georgia. Sea otters *(Enhydra lutris)* occur just outside the transboundary area on the northern Washington coast and the northwest coast of Vancouver Island, but a few sightings have been made inside Juan de Fuca Strait (Calambokidis et al. 1987; Jameson et al. 1986; Nagorsen 1986). The northern fur seal *(Callorhinus ursinus)*, typically an offshore species in this area, is an occasional visitor to these waters, usually with one or two records per year. Two species of baleen whale (right, *Eubalaena glacialis*, and fin, *Balaenoptera physalus*) were likely once seen occasionally in these areas until their populations were seriously depleted by commercial whaling, and they are no longer found here accept accidentally.

Humpback whales *(Megaptera novaeangliae)* were once considered common to the transboundary area including Puget Sound and the Strait of Georgia (Scheffer and Slipp 1948; Pike and MacAskie 1969). Though catch data from early years are not complete, several thousand humpback whales were killed primarily during summer months from 1905 to 1965 from whaling stations on the west coast of Vancouver Island (Pike and MacAskie 1969) and 1,933 were taken from 1911 to 1925 from a whaling station on the Washington coast (Scheffer and Slipp 1948). A smaller number of humpback whales were also taken commercially in the Strait of Georgia in two periods, from 1866–1873, and 1907–1908 (Merilees 1985). Sightings in the transboundary area are now uncommon, although a few humpback whales have entered and spent prolonged periods in these waters in recent years (Calambokidis and Steiger 1990). Humpback whales are regularly seen during summer months at Swiftsure Bank at the mouth of Juan de Fuca Strait (Calambokidis et al. unpubl. data).

Seven species of toothed whales have only been recorded in these waters as stranded animals. These include common dolphin *(Delphinus delphis)*, striped dolphin

(Stenella coeruleoalba), bottlenose dolphin *(Tursiops truncatus)*, Cuvier's beaked whale *(Ziphius cavirostris)*, a beaked whale of the genus *Mesoplodon*, Baird's beaked whale *(Berardius bairdii)*, and pygmy sperm whale *(Kogia brevirostris)* (Baird et al. 1993b, 1994; Osborne et al. 1988; Ferrero and Tsunoda 1989). Four additional species of toothed whales have been found in this area. Risso's dolphins *(Grampus griseus)* have been recorded in these inshore waters, but the last documented sighting was in 1977 (Baird and Stacey 1991). There are several sightings and one stranding record of short-finned pilot whales *(Globicephala macrorhynchus)* within the transboundary area within the last 20 years, but this species is very rare in this area (Baird and Stacey 1993). Besides a single record from Washington State in 1937, false killer whales *(Pseudorca crassidens)* were first regularly seen in this area in 1987 (Stacey and Baird 1991a). Since 1990, a lone false killer whale has been repeatedly seen in the transboundary area, generally ranging from Howe Sound in the north to southern Puget Sound. Pacific white-sided dolphins *(Lagenorhynchus obliquidens)* are occasionally seen in the northernmost part of the Strait of Georgia and in western Juan de Fuca Strait, but are generally only rare visitors to the transboundary area (Stacey and Baird 1991b).

HUMAN IMPACTS

Pollutant Impacts

A variety of contaminant types including chlorinated hydrocarbons, heavy metals and other trace elements, and petroleum hydrocarbons potentially impact marine mammals (see Risebrough 1978; Addison 1989; Wagemann and Muir 1984; Calambokidis et al. 1991a, for reviews). Some of the potential impacts are direct and fairly obvious, such as the mortality of sea otters from exposure to petroleum hydrocarbons after oil spills. Other potential effects are indirect and harder to measure. Determination of cause and effect relationships between problems and contaminants is extremely difficult without controlled experiments. Within the transboundary area there has been disagreement among researchers regarding the potential association between gray whale deaths and contaminants (Calambokidis 1992; Fouty 1984; Malins et al. 1984; Varanasi et al. 1993).

Extremely high concentrations of contaminants have been found in marine mammals from different parts of the world which has made these contaminants a primary concern. Coastal marine mammals that feed high on the food chain near contaminated areas, such as many pinnipeds and coastal odontocetes, have the highest concentrations. Among a number of species of marine mammals examined in the transboundary area, highest concentrations of chlorinated hydrocarbons have been found in harbour seals, harbour porpoise, and killer whales (Calambokidis et al. 1984, 1990, 1991b; Varanasi et al. 1993; Baird et al. 1993a; Muir et al. 1991). Concentrations in harbour seals have been highest in southern Puget Sound and have declined from the 1970s to 1991 (Calambokidis et al. 1985, 1991b)

Chlorinated hydrocarbons have been linked with a variety of problems in marine mammals. Premature births in California sea lions have been associated with elevated concentrations of DDT (DeLong et al. 1973; Gilmartin et al. 1976), and PCBs have been implicated in reproductive failure in ringed seals in the Baltic (Helle et al. 1976) and harbour seals in the Wadden Sea (Reijnders 1980, 1986). Recent studies have also implicated chlorinated hydrocarbons with reduced immune response in harbour seals (Brouwer et al. 1989; de Swart et al. 1993; Ross et al. 1993).

Although high concentrations of contaminants have been found in marine mammals from the transboundary area, evidence for their association with dysfunctions has been inconclusive or circumstantial. Newby (1973b) reported high rates of premature births and birth defects in harbour seals from southern Puget Sound in the early 1970s and suggested these were associated with contaminants. Studies since then have shown that PCB concentrations and the incidence of reproductive problems declined subsequently and that concentrations in the 1970s were similar to those reported to cause reproductive problems in other areas (Calambokidis et al. 1988, 1991a; Steiger et al. 1989). High concentrations of aluminum, once suggested as a potential cause of mortality in gray whales in Puget Sound, were not significantly different between animals found in California, Washington, and Alaska, suggesting that these seemingly high concentrations may be 'normal' for gray whales (Varanasi et al. 1993). Although some of the highest concentrations of contaminants have been found in killer whales, it has been difficult to evaluate their potential impacts. Reproduc-

tive rates are generally not known for transient killer whales, which have the highest concentrations of chlorinated hydrocarbons (probably due to their feeding on other marine mammals). In the 1970s and 1980s unexpectedly low reproductive rates were observed in southern resident killer whales that occupy the transboundary area, but these are potentially attributable to other factors besides contaminants (Olesiuk et al. 1990b). Levels of mercury among the highest recorded for any cetacean world-wide have been found in two resident killer whales in B.C., although one was from the northern resident population, which is not exhibiting low reproductive rates (Langelier et al. 1990; Baird unpubl. data).

Disturbance Impacts

The high level of human activities on and near the water in the transboundary area has the potential of disturbing marine mammals. For two species, killer whales and harbour seals, research has been conducted on the rate and potential effects of disturbance.

Killer whales in the transboundary area are regularly approached by pleasure boats, whale watch boats (primarily operating out of Friday Harbour and Victoria), scientific researchers, and commercial transport vessels. The number of boats approaching killer whales in Haro Strait has increased dramatically since the late 1980s (Osborne 1991). No apparent shifts in distribution or behaviour, however, have been observed in this region (Osborne 1991). Kruse (1991) reported that northern resident killer whales in Johnstone Strait (northeast coast of Vancouver Island) increase their speed in the presence of boats, though Duffus and Dearden (1992) dispute her conclusions. A study of killer whale reactions to vessels in the transboundary area by R. Otis (unpubl.) has found no immediate changes in behaviour which correlate to the presence of boats (Phillips and Baird 1993).

Harbour seals are one of the most wary pinnipeds to approach while hauled out, and typically enter the water upon approach. Harbour seals instinctual fear while hauled out most likely stems from the history of hunting of seals by aboriginal peoples and by other land carnivores (see Steiger et al. 1989 for example). At several haul-out areas in the San Juan Islands in the summer of 1991 and 1992, harbour seals were disturbed 48% and 89% of the days surveyed (Suryan 1993). Powerboats engaged in 'seal watching' were the primary cause of disturbance. Calambokidis et al. (1991d) found that kayaks disturbed harbour seals in Puget Sound at a significantly greater distance than other boats. Potential impacts of disturbance include separation of mothers and pups, interruption of nursing, and abandonment of haul-out areas. Given the rate of increase of harbour seal populations in the transboundary area, the population impacts from the current rate of disturbance cannot be large.

Fishery Conflicts

Marine mammal conflicts with fisheries can be categorized as direct or indirect. Indirect or ecological interactions involve competition for resources which are also used by humans. Declines in the populations of many of the gadoid species in the transboundary area due to over-fishing (Schmitt et al. this volume) could easily impact the many marine mammal species that prey on these species. While indirect interactions could have potentially devastating effects on marine mammal populations, determining the precise impacts of such interactions is difficult, and our discussion will focus on direct interactions. Such interactions include entanglement or collision with fishing gear as well as shooting that may occur in association with sport and commercial fisheries and salmon farming.

Three of the four species of pinnipeds commonly found in the transboundary area (harbour seals, California sea lions and Steller sea lions) are occasionally shot by fishermen. All four species of pinnipeds are killed due to entanglement in gillnets in waters adjoining the transboundary area, although data from within this area is limited. In British Columbia, aquaculture operations can obtain licenses to shoot harbour seals and California sea lions which interfere, or are thought to interfere, with salmon farms. These three species also are occasionally hooked on sports fishing gear. While they appear able to break lines in almost all cases, lodged hooks and trailing gear may interfere with feeding or cause infection. No detailed information is available to determine the impacts of these types of direct interactions between pinnipeds and fisheries in this area, but they likely do not have a significant effect on populations.

Mortality of harbour porpoise in gillnets has been a major concern in many portions of their range (Diamond and Hanan 1986; Hanan et al. 1986; Young et al.

1993). Along the Washington coast, up to a hundred harbour porpoise have been killed annually in a tribal set-net fishery, but this mortality has been dramatically lower in recent years (Gearin et al. 1990, 1993). Both harbour and Dall's porpoise have been recorded killed in fishing operations in the transboundary area. Within this area, harbour porpoise have been caught in commercial salmon drift gillnet fisheries, Native American set gillnet fisheries, and Canadian government test and research fisheries (Baird and Guenther in press; Everitt et al. 1980; S. Osmek pers. comm.; Stacey et al. 1989). For this species, such entanglement can even occur in rivers; one animal was killed in a Canadian government test fishery for salmon approximately 55 km up the Fraser River (Guenther et al. 1993). Dall's porpoise in this area have been caught in commercial drift gillnet fisheries and bottom fish trawl fisheries (Baird et al. 1988; Everitt et al. 1980; Stacey et al. 1989). Both species are occasionally caught in the salmon seine fisheries in this area, but mortality of captured animals in these fisheries appears to be lower than for gillnets, as some animals can be released alive (Stacey et al. 1990). Porpoises are also occasionally hooked on lines from sport fishing operations, but it is not known whether these individuals are killed (Baird unpubl.). Other species are also occasionally caught in fishing gear in the transboundary area. In 1989, a live humpback whale was observed in the northern part of the Strait of Georgia entangled in a salmon drift gillnet (Langelier et al. 1990). No observer programs exist for any of the fisheries for this area, so no information is available on the levels of incidental mortality or their impacts on local populations.

Research Needs

Although some species of marine mammals have received considerable research attention (e.g., harbour seals, killer whales), research on other species within the transboundary area has been extremely limited. Of critical importance to the conservation and management of marine mammals within this area is more information, particularly that necessary for evaluating potential impacts of human activities. Important information includes:

- Estimates of population size (particularly for harbour porpoise, Dall's porpoise and minke whales) within the Canadian waters of the transboundary area. Virtually no research has been undertaken on these species in the Canadian waters of the transboundary area.
- Information is needed on trends in the populations of most marine mammal species in the study area. This is especially critical for harbour porpoise and Dall's porpoise, as they are regularly killed in fisheries. In the case of harbour porpoise, there is circumstantial evidence of long-term declines in some areas, but this needs to be verified.
- A better understanding is needed of the stock structure and movements of marine mammals in the transboundary area. Evaluating the impacts of mortality on a population is not possible without a better understanding of the geographic range of the stock affected.
- The level of harbour porpoise and Dall's porpoise incidental mortality in the various commercial, Native and research fisheries needs to be estimated. Natural causes of mortality in all species of marine mammals within the transboundary area should also be investigated, to examine the effects of viral or bacterial outbreaks, as well as biotoxins, on populations.
- Research is needed on pollutant levels and potential impacts on marine mammals. The research that has been conducted, although limited, has indicated very high concentrations of contaminants in some marine mammal species in the transboundary area. Relatively few samples, obtained from the occasional strandings, have been analyzed. Additional data from biopsies of live animals would allow better evaluation of contaminant concentrations and relationship to reproductive success and other parameters. Marine mammals provide a good method for examining overall trends of contaminants in a broad sector of the marine environment.
- Information is needed on the community ecology of marine mammals. This includes an examination of competition between marine mammals and commercial fisheries. No research has been conducted on the impacts on marine mammals of declines in some of their primary prey due to overfishing.

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DISCUSSION

Chris Garrett *(Panel)*: Is shipping or industrial noise a factor in disturbing migration patterns and feedings?

John Calambokidis: It's definitely known for offshore industry, and has been looked at in particular with two species: Baltic whales and gray whales. It has been demonstrated that, for example, gray whales do alter their migration routes in response to seismic exploration-type noise. That's been looked at, but the more low-level and the more common noise that might be generated in the transboundary area, whether or not there is an effect, is ambiguous.

Richard Beamish *(Panel)*: In your opinion what do you think the reason is for the dramatic increase in harbour seals? And it's still increasing isn't it?

John Calambokidis: Yes, but there is evidence in a few areas that the increase may be tapering off. For example, in northern Hood Canal where we have done some work related to the fecal coliform problem, we have in the last three or four years seen a stabilization and even slight decline in the number of harbour seals in that area. But that is one of the first areas to show that. In most other areas the evidence is that they are still increasing. These animals were reduced to very low numbers by commercial bounty, and since I was asked to have a speculative hat on here, I'll venture a little farther. I think in Puget Sound the populations were depressed and held down by pollution, because PCB levels were highest in the 1960s and 70s in harbour seals. The levels were of the same magnitude that has been shown to cause reproductive failure in harbour seals in experiments done in the Netherlands. High rates of premature births were seen in harbour seals in Puget Sound in the early 1970s. So I think in some areas like Puget Sound the population was kept low. Now with the decline in PCB levels, we're seeing recovery from a combination of those factors.

Richard Beamish *(Panel)*: But it's a dramatic increase, and it's not just in that area, it's throughout Puget Sound and the Strait of Georgia. So there are animals that are increasing where it's unlikely that was a problem.

John Calambokidis: Certainly the bounty was a factor, and the bounty just represents the tip of the iceberg in terms of how many animals were being killed throughout the transboundary area.

Richard Beamish *(Panel)*: Would it be fair to say that we don't know why harbour seals are increasing in abundance?

John Calambokidis: I think it is pretty clear actually. It doesn't seem ambiguous to me because we know it is a very flexible marine mammal that can feed on a wide variety of prey, and was subjected to a dramatic decrease in its population due to active human efforts - the bounty, dynamites of haul out areas - so their populations were dramatically reduced. So it isn't that surprising to me they'd be recovering once protected.

Tom Pedersen *(Panel)*: My question has to do with the gray whale problem or population. You pointed out that they are soft-bottom substrate feeders, and Robie Macdonald yesterday told us that fine-grained soft sediments tend to be the areas where contaminants are most concentrated. Is there any evidence whatsoever to draw a link between the nature of feeding activity of the gray whales, the high mortality you mentioned in Puget Sound where you said up to one third were going, and contamination and pollution uptake? And when you find these carcasses, are they routinely being analyzed for contaminants?

John Calambokidis: Starting in 1984 that issue has come up each time there's been a number of mortalities of gray whales in Puget Sound. There has been quite a bit of controversy about it, quite frankly several researchers have concluded that there is a direct link between the deaths of these gray whales and pollutants, but I don't find that very well founded. We've collected tissues, and a number of other researchers have collected tissues, from all the stranded gray whales. National Marine Fisheries Service, Environmental Conservation Division, has recently completed a study analysing those tissues, including some animals from California and Alaska. Generally the contaminant concentrations, for example chlorinated hydrocarbons, are fairly low compared to what is typically found in most marine mammals.

The other thing that came out of those analyses is that many of the animals that died due to unknown causes had extremely low levels of lipids in the blubber layer,

and our girth and blubber-thickness measurements suggested that a lot of these animals were emaciated, which reflects some sort of chronic problem that would predate their coming to the transboundary area. The lipid levels, which often were below 1 or 2% lipids in the blubber, suggest that these animals were in very poor nutritional condition. I can't rule out animals feeding in a few contaminated areas, but most of the areas these animals are feeding in do not have high concentrations in the sediment. There might be some impact, but it doesn't seem a likely link with most of the mortality.

Bruce McCain *(Panel)*: I'm interested in the decline of harbour porpoises in Puget Sound, and I didn't catch when you talked about them. Did you talk about where harbour porpoises breed? Do they migrate out of Puget Sound to do that?

John Calambokidis: No, there is evidence that harbour porpoise in some other areas go through migrations, but to the best of our knowledge — and it isn't very well studied in this area because they are hard to tag or trap — but the animals are here year-round, and we do see them with calves throughout the transboundary area in which harbour porpoise are seen. So they do breed, calve and appear to be here year-round. And it was thought, when they were in Puget Sound, that they were here year round and resident as well.

Bruce McCain *(Panel)*: Do you have a speculation on why the numbers declined so dramatically in Puget Sound?

John Calambokidis: No, I can just raise the three things that have been raised in other areas: gillnet entanglement, potential of disturbance, and pollution effects. But this predated the beginning of any focus of research on them, so all we have is — they were plentiful, and then when studies in the late 60s began again, they were gone. I think we're really left with speculation on that question.

Ben Kangasniemi *(Ministry of Environment, Lands and Parks)*: Can you mention what the harbour porpoise feeds on?

Robin Baird: From stomach contents of animals around southern Vancouver Island, it's primarily small schooling fish and squid, a lot of the fish that they are feeding on are very small bottom fish, blennies and needle fish, very small herring.

John Calambokidis: I would add on the mystery of harbour porpoise, Robin recently documented an unusual mortality last year of harbour and Dall's porpoise in the transboundary area on the south Vancouver Island coast. We haven't been able to attribute a cause, but there's also some unusual mortalities that have occurred with this species that we can't attribute even currently to what the source is.

Robie Macdonald *(Institute of Ocean Sciences)*: Has any connection been made on these mortalities or effects on these larger animals with the algal toxins we heard about yesterday?

John Calambokidis: I think the talk yesterday mentioned that there have been two major die-offs of marine mammals that have been linked to natural toxins. Bottlenose dolphins on the East Coast and humpback whales, one to a brevitoxin and another to a saxitoxin. We've tried to look at the presence of natural toxin in a few of the gray whales, particularly in the mid-1980s and weren't successful. Robin's tests on the harbour porpoise were inconclusive or negative.

Michael Coon *(Ministry of Agriculture, Fisheries and Food)*: Regarding gray whale mortalities, you mentioned the apparent poor nutritional status of some of the animals, and I wondered if there was an age relationship, did they tend to be older animals or very young animals. Are weakened animals on their migration to Alaska the ones stopping here.

John Calambokidis: No, if I had to speculate I think that we have two groups, One group comes back year after year, and the animals seem to be fairly healthy. The animals that have died have never been animals we had seen a previous year. Some of them not only have lower lipid levels, but have been stunted — animals that are physically mature, but their length is less than you would expect for a physically mature animal. So our general conclusion as the most likely reason we see higher mortality is that these are straggler animals, unhealthy, desperate to find an area to feed. But these are definitely separate from the first group. If you look at the total mortality, all of the strandings of gray whales from Mexico up to Alaska, the total number of animals dying is actually lower than you'd expect. In that sense it fits within what you'd expect to be some level of natural mortality.

Rick Thomson *(Institute of Ocean Sciences)*: We've had a fair amount of discussion about habitat loss in

Puget Sound, and one of the things that gray whales feed on is mysids associated with kelp beds. I'm wondering if there's a linkage here with the loss of habitat through that process in addition to bottom sediments.

JOHN CALAMBOKIDIS: Could be. Unfortunately I can't say we've done that much with food habits in the transboundary area. I think that's something that could be looked at more.

Toxic Chemicals and Fish Health in Puget Sound and the Strait of Georgia

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ABSTRACT

Exposure to anthropogenic contaminants in the marine environment has been associated with a variety of detrimental health effects in fish from urban areas in Puget Sound and Strait of Georgia. These include elevated levels of such chemicals as chlorinated and aromatic hydrocarbons in tissue and body fluids, elevated activities of hepatic xenobiotic metabolizing enzymes, binding of chemical carcinogens to DNA in liver, and pathological conditions such as liver disease. These conditions are more common in bottomfish from heavily polluted sites, but are also observed in fish from moderately contaminated sites with total aromatic hydrocarbon concentrations in sediment of approximately 1 ppm. Generally, however, fish from transboundary sites located in non-urban areas show minimal effects of contaminants. Transient species such as outmigrating juvenile salmon may also accumulate detectable levels of contaminants as they migrate through urban estuaries, and these contaminants may be linked to impaired growth and dysfunction of the immune system. The long-term impact that toxicopathic disease and reproductive impairment have on the survival and abundance of affected fish is not known, but preliminary population modeling studies suggest that contaminant-related declines in reproductive output may have the potential to reduce the growth rate of certain sub-populations of sole from contaminated areas. Sediment contaminant levels and disease prevalences in fish from heavily contaminated sites in Puget Sound are still among the highest in the nation, but appear to have declined in the last 10 to 15 years as a result of improvements in sewage treatment, regulation of toxic chemicals, and remediation efforts. However, as a consequence of increased urban development throughout the Pacific Northwest, the number of sites with sediment contaminant levels high enough to induce mild toxicopathic effects in fish may increase.

INTRODUCTION

Preserving the quality of the marine environment in Puget Sound and the Georgia Basin is a major concern of government officials and the general public in the State of Washington and British Columbia. Over the past fifteen years there have been many reports of environmental degradation in urban embayments in the Pacific Northwest, and continued population growth and industrial and urban development may further threaten the ecological health of marine communities in the region. While many types of marine organisms are affected by toxic contaminants in the environment, the impact of these chemicals on fish has been of particular concern due to the economic importance of these animals and the clear linkage between chemical contamination in fish and human health risk.

Studies in a variety of fish species from sites in United States, Europe, and Canada (reviewed in Harshbarger and Clark 1990; Hugget et al. 1992; and Vethaak and Rheinallt 1992) clearly demonstrate that anthropogenic chemicals have negative effects on fish health. Exposure to industrial pollutants such as aromatic and chlorinated hydrocarbons has been associated with a variety of effects in fish, including liver cancer, decreased reproductive success, impaired growth, and altered immune function. Considerably less is known about the effects of contaminant-associated disease on fish abundance, although there is some evidence that contaminant exposure and associated effects may increase mortality rates and depress population growth rates of fish from polluted areas (Barnthouse 1990; Baumann et al. 1991).

This paper will focus specifically on the effects of chemical pollution on the health of fish in Puget Sound, the Georgia Basin and the US/Canada transboundary area. Our current knowledge of toxicant exposure and associated biological effects in marine fish from this region will be reviewed and used to evaluate how conditions have changed since intensive sampling began in the 1970s. We will also discuss possible relationships between toxicant-associated disease in individual fish and changes in fish abundance. Finally, on the basis of current evidence we will attempt to provide some recommendations as to those types of impact which appear to be the most serious and are particularly in need of attention in future research and monitoring studies in the US/Canada transboundary region.

CURRENT RESEARCH ON FISH TOXICS

EFFECTS ON BOTTOMFISH

Exposure and Early Response

Sampling studies conducted by a variety of agencies including the National Marine Fisheries Service, the Puget Sound Water Quality Authority, and Environment Canada (Figure 1), indicate that industrial pollutants such as aromatic and chlorinated hydrocarbons and toxic elements are present at high concentrations at a number of sites in Puget Sound (Figure 2a, b) (Malins et al. 1984, 1985; Varanasi et al. 1989a; PSWQA 1990, 1991, 1992) and Vancouver Harbour (Figure 3) (Goyette et al. 1988; Goyette and Boyd 1989). These compounds are taken up by fish through the diet, the water column, or directly from bottom sediments (Varanasi and Stein 1991). Chlorinated compounds such as PCBs and pesticides are bioaccumulated (Stein et al. 1987, Varanasi et al. 1992), so exposure to these contaminants may be detected measuring their concentrations in tissues. Aromatic hydrocarbons, on the other hand, are rapidly metabolized and not retained in tissues (Varanasi et al. 1989b). However, exposure to aromatic hydrocarbons (AHs) can be detected measuring levels of metabolites of these compounds in bile (Krahn et al. 1984, 1987).

Elevated concentrations of environmental contaminants can be found in tissues or bile of bottomfish from a number of urban sites in Puget Sound (Malins et al. 1984, 1985; Krahn et al. 1987; Varanasi et al. 1989a; PSWQA 1990, 1991, 1992) and Vancouver Harbour (Goyette et al. 1988; Goyette and Boyd 1989) (Figure 3a, b). Elevated levels of PAH conjugated metabolites have also been reported in English sole *(Pleuronectes vetulus)* collected from areas in the vicinity of pulp mills in British Columbia, (Brand and Kusser 1993). In contrast to heavily urbanized areas, at relatively pristine areas along the US/Canada border near Vancouver Island and the San Juan Island, levels of chemical contaminants such as PCBs in English sole liver and muscle are near or below detection limits (Figure 4) (PSWQA 1992).

Fish from contaminated areas not only show elevated levels of chemicals in tissue and body fluids, but also show other physiological changes that are indicators of biological responses to contaminant exposure. These changes are often expressed first on the biochemical level. One of the earliest changes associated with exposure to contaminants is increased activity of cytochrome P450 associated enzymes in the liver, which are responsible for metabolism of aromatic hydrocarbons and a variety of other toxic compounds (Buhler and Williams 1989; Goksoyr and Forlin 1992). Binding of chemical carcinogens to DNA in liver (Gupta and Randerath 1988), which is thought to be an early genotoxic step in the process of carcinogenesis, has also been observed in several species of fish exposed to carcinogenic compounds such as benzo[a]pyrene (Shugart et al. 1989; Varanasi et al. 1989c; Sikka et al. 1990). Both of these types of biochemical alteration have been found in English sole, starry flounder *(Platichthys stellatus)*, and rock sole *(Lepidopsetta bilineata)* from several areas in Puget Sound with elevated sediment

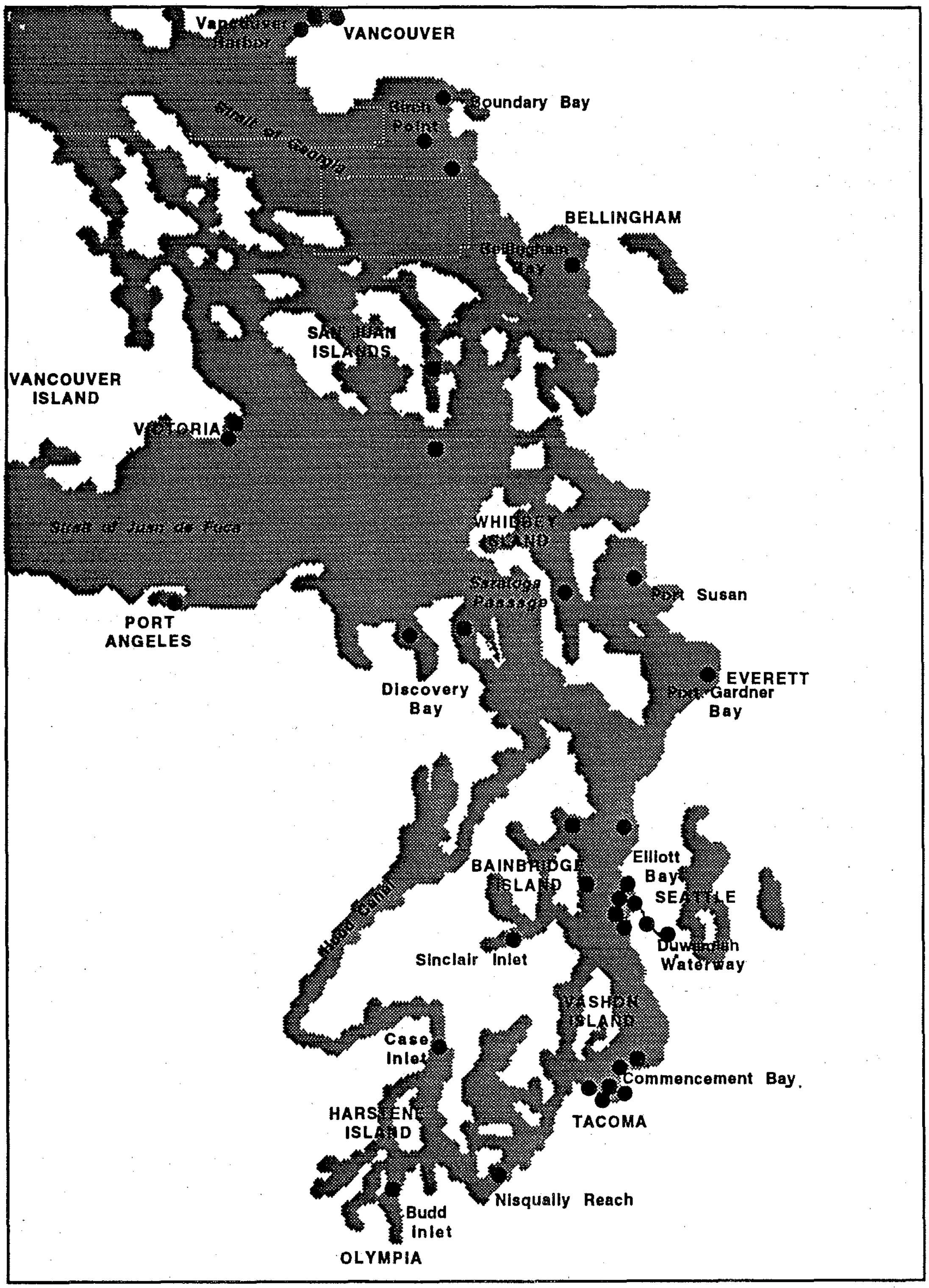

Figure 1. Map of Puget Sound and the Georgia Basin showing sites where fish and sediments have been sampled in biomonitoring studies conducted by the National Marine Fisheries Service, Puget Sound Water Quality Authority, and Environment Canada.

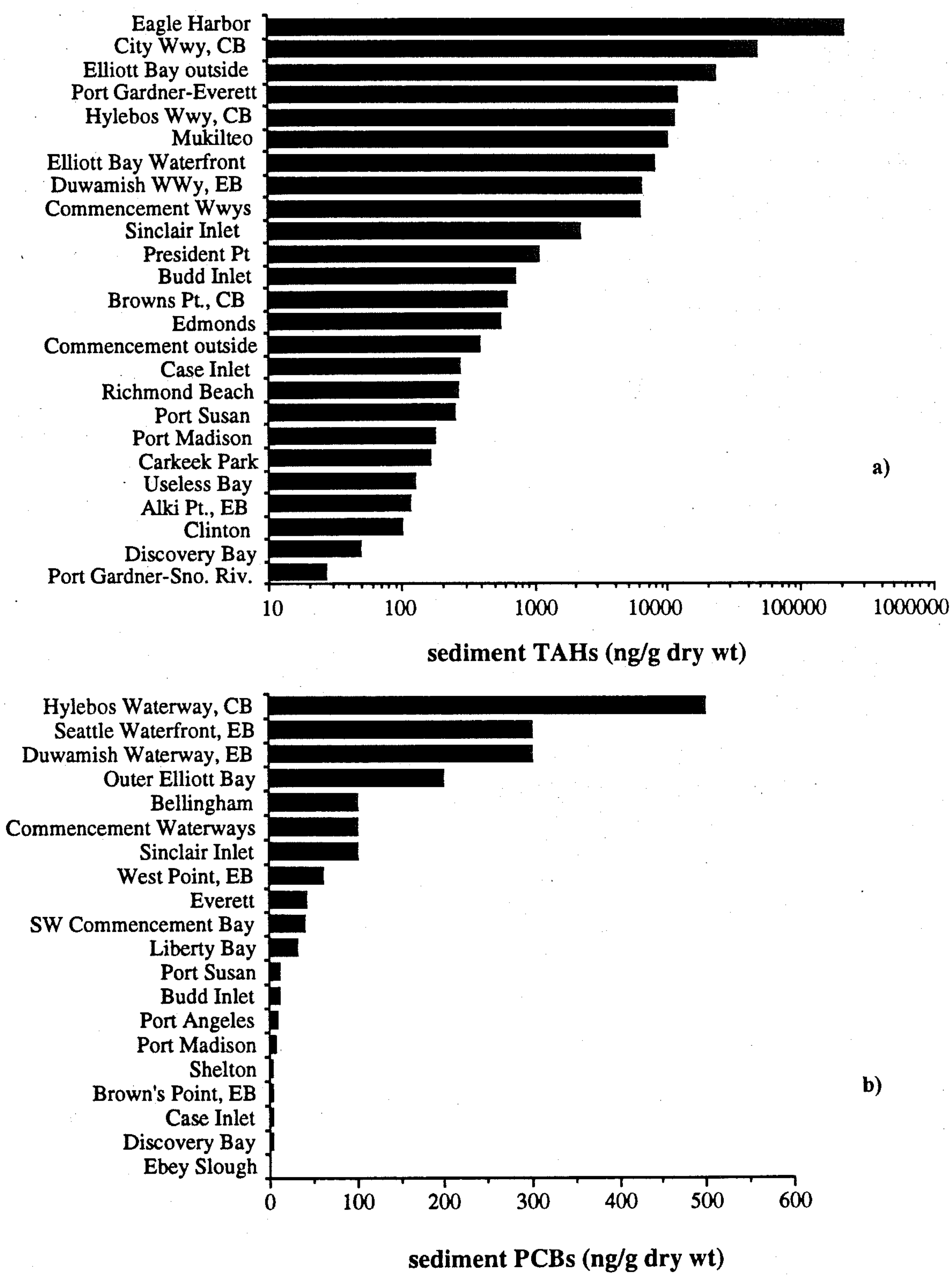

Figure 2. Concentrations of (a) aromatic hydrocarbons (ng/g dry weight) and (b) chlorinated hydrocarbons in sediments from sites in Puget Sound. EB = Elliott Bay; CB = Commencement Bay. Modified from Malins et al. 1984, 1987.

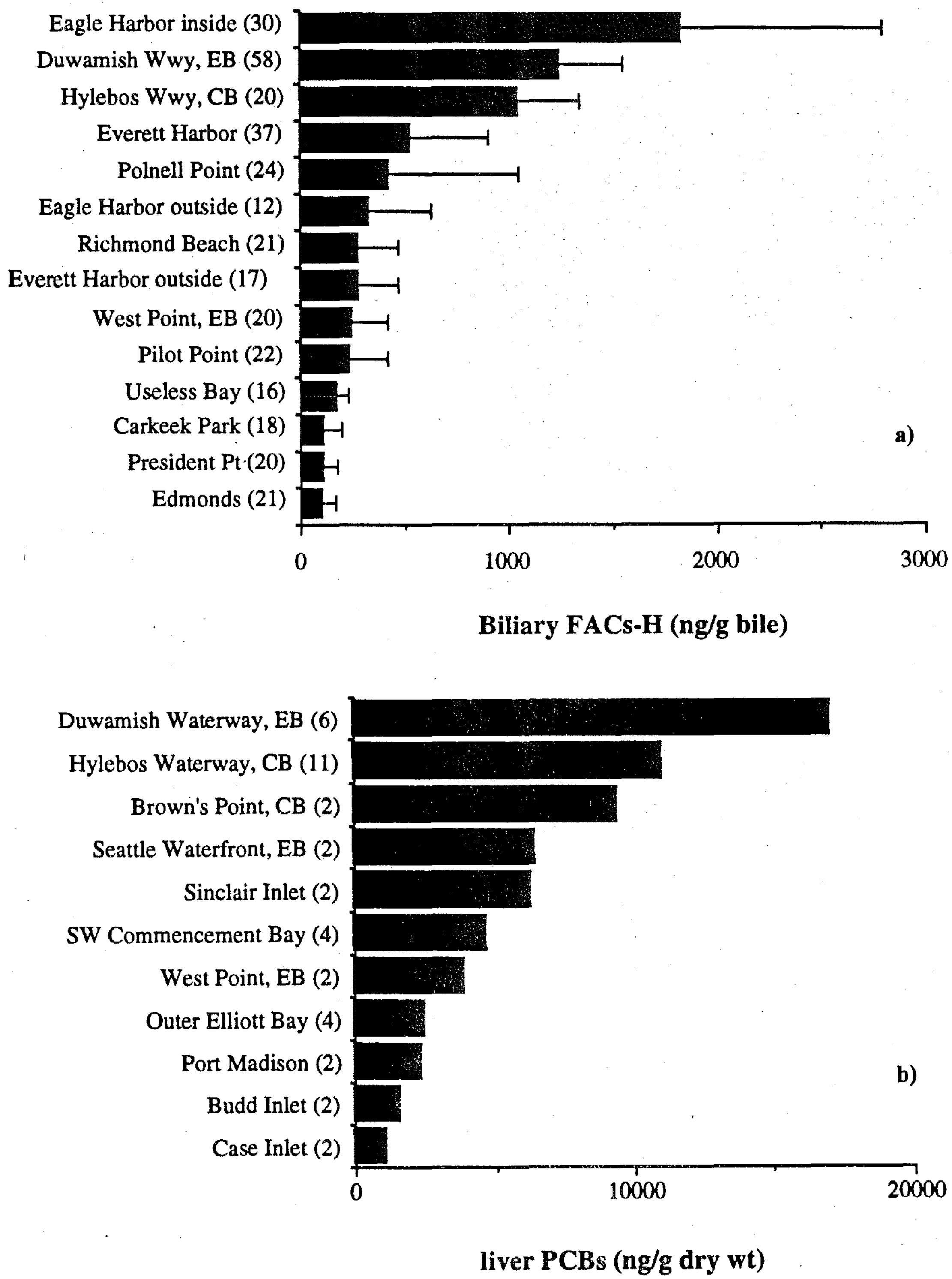

Figure 3. Concentrations of (a) fluorescent aromatic compounds (FACs) in bile (ng/g bile ± SD) and (b) polychlorinated biphenyls (PCBs) in liver tissue of English sole from sites in Puget Sound. The number of samples analyzed is indicated in parentheses. Bile samples were collected from individual fish, while PCB samples are composites of tissue collected from approximately 10 fish. Values reported are total PCBs in ng/g dry wt of tissue. Data from Malins et al. 1984, 1987; Krahn et al. 1984, Stein et al. 1992.

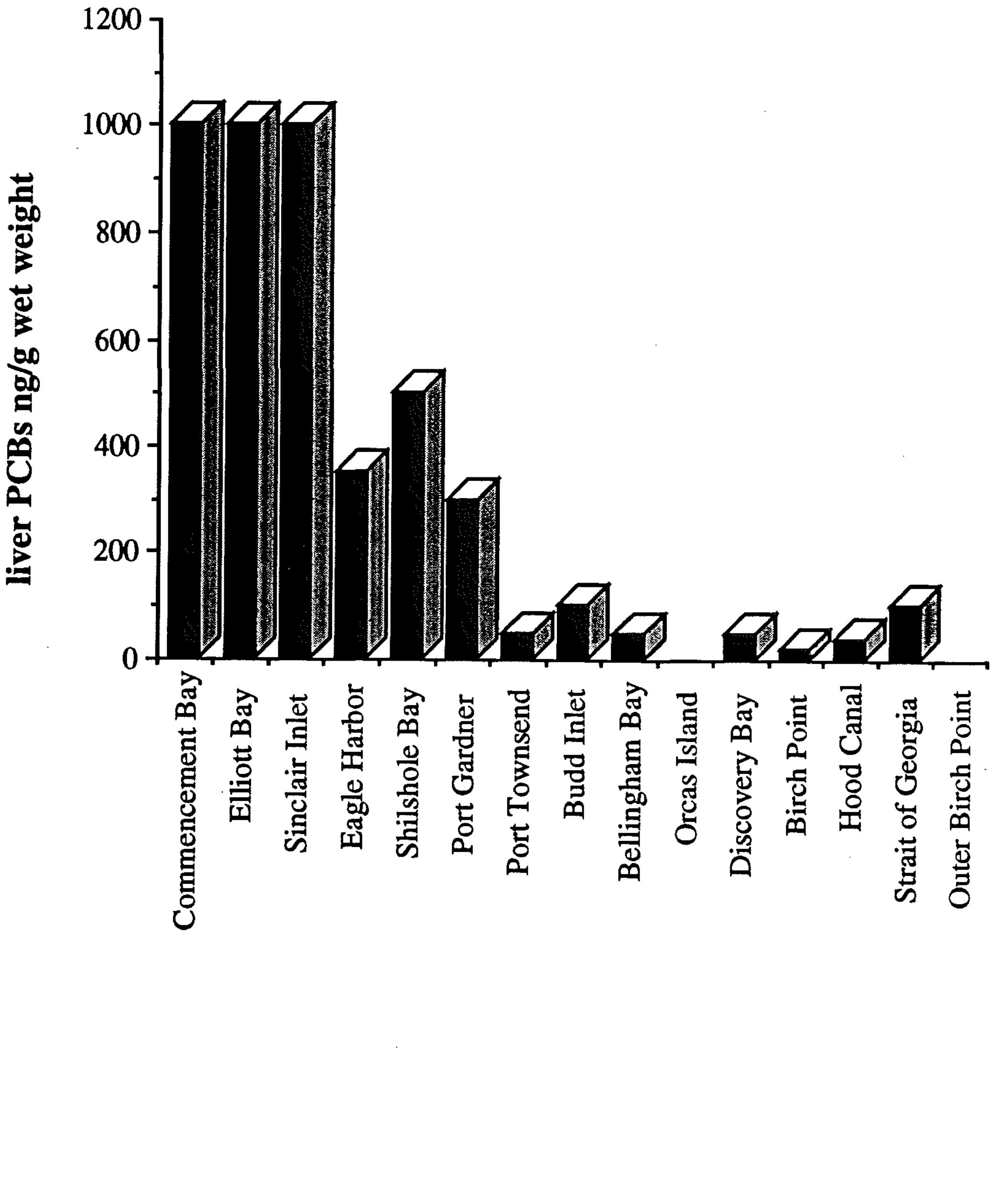

Figure 4. Concentrations of PCB 1260 in liver tissue (ng/g tissue wet weight) of English sole from sites in Puget Sound and at the US/Canada border. Adapted from PSWQA 1993.

contaminant concentrations Collier and Varanasi 1991; (Collier et al. 1994; Stein et al. 1992) (Figure 5). Moreover, both hepatic AHH activity and levels of xenobiotic-DNA adducts in liver were significantly correlated with indicators of exposure, such as biliary FACs and tissue PCBs, measured in the same fish (Stein et al. 1992). A program to measure biochemical indicators of exposure and early responses such as hepatic P450 induction in bottomfish from Canadian waters has just begun. Preliminary results (from samples taken during November 1993) show that English sole from Howe Sound (the site of two pulp mills which in the past used chlorine bleaching) had hepatic EROD activities twice as high as those in English sole from an apparently uncontaminated site (R.F. Addison, unpublished data). Chemical analysis of chlorinated residues in these samples is underway.

Liver Disease

Exposure to contaminants is associated with the development of a variety of pathological conditions in wild fish, including liver lesions that morphologically resemble those induced by experimental exposure of mammals and fish to a variety of toxicants (Frith and Ward 1980; Meyers and Hendricks 1985; Hinton et al. 1992). Bottomfish species from a number of chemically contaminated marine coastal areas in the vicinity of Seattle and Tacoma exhibit liver neoplasms and other lesions involved in the histogenesis of hepatic neoplasia (Malins et al. 1984, 1985; Krahn et al. 1987; Myers et al. 1987, 1992, 1994). In general, the prevalence of liver disease varies with the level of urbanization, with highest prevalences of neoplasms and associated lesions in fish from heavily contaminated sites such as Eagle Harbor and the Duwamish Waterway in Puget Sound (Figure 6). Similarly, in a recent study conducted as part the Puget Sound Ambient Monitoring Program (PSWQA 1992) of neoplastic, preneoplastic, or unique degenerative liver lesions were found in approximately 25 to 40% of English sole sampled from Elliott Bay and Commencement Bay in Puget Sound. At moderately urbanized sites such as Port Townsend, Shilshole Bay, and Port Gardner, low to moderate levels of liver disease (3–8%) were found. Less information is available on the condition of fish in transboundary areas. However, several sites in the vicinity of the US/Canada border were sampled as part of the Puget Sound Ambient Monitoring Program. These included Birch Point, Outer Birch Bay, East Sound off Orcas Island, and a site in the Strait of Georgia. No or very low prevalences of liver lesions (i.e., less than 2%) were detected in these animals (PSWQA 1992).

While neoplasms are the most dramatic of the lesions observed, early degenerative or proliferative conditions such as hydropic vacuolation and nuclear pleomorphism, and megalocytic hepatosis, are much more prevalent and are found in animals from moderately as well as heavily contaminated sites (Figure 6). For example, in a study targeting subadult English sole captured from nine sites in Puget Sound representing a broad gradient of sediment contamination, although neoplasms were rarely detected, higher prevalences of preneoplastic, regenerative, and unique degenerative lesions were detected in sole from contaminated sites (Myers et al. 1992). These non-neoplastic lesions are experimentally inducible in fish by exposure to various toxicants, have consistently been statistically associated with contaminant exposure, and are involved in the process of hepatic neoplasia in adult English sole (Myers et al. 1990). Prevalences of these earlier histopathologic biomarkers were significantly higher at the more contaminated sites, as determined by several statistical approaches, including logistic regression. Moreover, prevalences of most lesion types were significantly correlated with mean biliary FACs levels at the sites, as well as with biochemical measures of response to contaminants such as hepatic AHH activity. Prevalences of certain lesions were also correlated with hepatic PCB and DNA-xenobiotic levels, but less often and at lower significance levels than for AHH. These findings further support the utility of certain liver lesions other than neoplasms as early indicators of biological damage in subadult as well as adult fish exposed to xenobiotics in the marine environment.

Histopathological surveys of fish have also been conducted in the vicinity of Vancouver, British Columbia by the Environmental Protection Service of Environment Canada (Goyette et al. 1988; Goyette and Boyd 1989). These studies examined adult English sole from areas in the outer, inner, central and eastern harbour in the Port Moody Arm of Vancouver Harbour. Neoplastic and preneoplastic lesions were found in up to 75% of sole sampled at sites in the Eastern harbor, near the IOCO refinery in Port Moody Arm, with prevalences declining progressively toward the outer Harbour

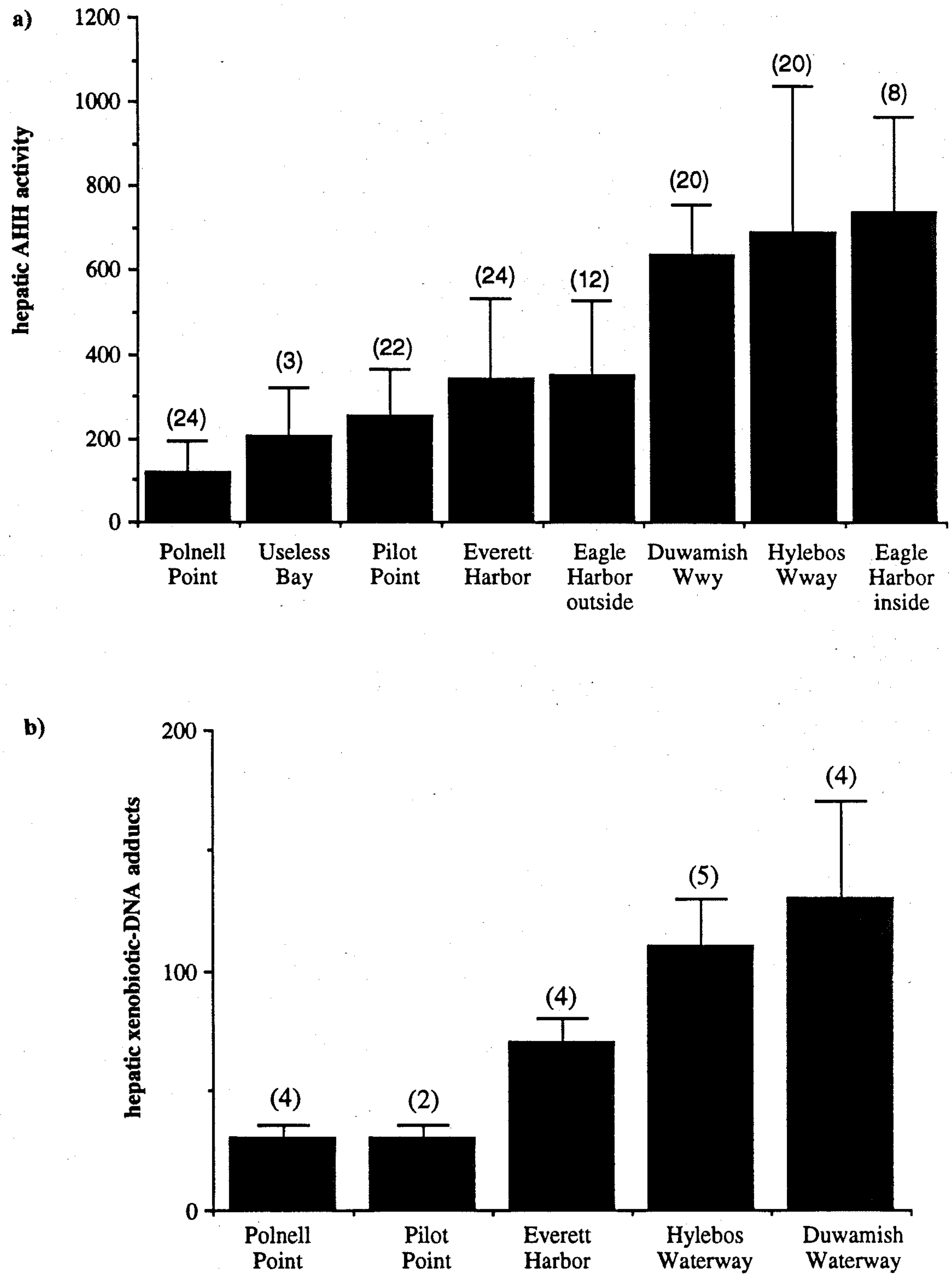

Figure 5. (a) Hepatic AHH activity at eight sites in Puget Sound, and (b) concentrations of xenobiotic-DNA adducts in English sole from five sites in Puget Sound with varying levels of sediment contamination. The number of samples analyzed is indicated in parentheses; each sample consisted of a composite of 6 fish. Data from Stein et al. 1992, Collier et al. 1993.

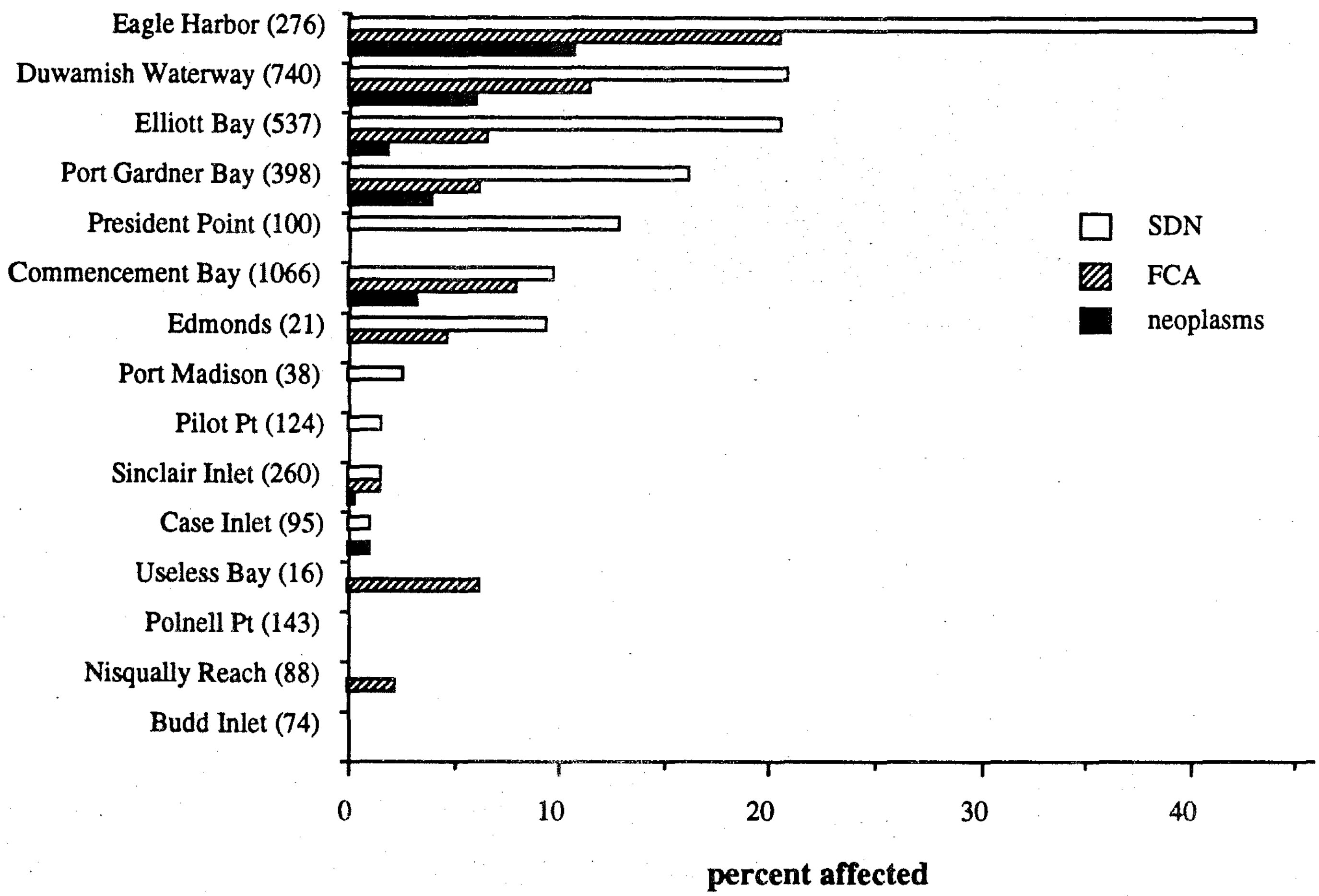

Figure 6. Prevalences of hepatic lesions in English sole from sites in Puget Sound. FCA = foci of cellular alteration; SDN = specific degeneration/necrosis (megalocytic hepatosis and/or nuclear pleomorphism). The number of animals sampled is indicated in parentheses following the site name. EB = Elliott Bay; CB = Commencement Bay. Data compiled from Malins et al. 1984, 1987; Myers et al. 1987; Krahn et al. 1984, Stein et al. 1992.

(Figure 7). No lesions were found in reference fish from Loughborough Inlet, approximately 200 km north of Campbell River. As in Puget Sound, the prevalence of fish in Vancouver Harbour affected by neoplastic and preneoplastic lesions was significantly correlated with sediment PAHs ($r = 0.78$, $p = 0.002$), with the highest PAH levels (up to 23 ppm) detected in sediment near the IOCO refinery. Limited studies on English sole in the vicinity of the Iona Island Wastewater Treatment Plant outside the Fraser River Delta have not detected similar lesions, but sample sizes are as yet too low to make any definitive conclusions about the effect of the outfall on fish health.

English sole and other flatfish have also been sampled near the sewage outfall in Victoria Harbour (Brand 1992) and in the vicinity of two British Columbia pulp mills (Brand and Kusser 1993). Additional sampling and more thorough documentation of contaminant exposure are needed.

The cause-and-effect relationships between chemical contaminants and toxicopathic liver lesions which have been inferred from field surveys in Puget Sound and other areas have been further supported by long-term laboratory exposure studies in which English sole were exposed to model carcinogenic compounds such as benzo-a-pyrene and to extracts sediments from contaminated sites (e.g. Eagle Harbor) in Puget Sound (Schiewe et al. 1991). While these animals could not be held alive in the laboratory long enough to develop frank neoplasms, after approximately 18 months of exposure they exhibited various non-neoplastic degenerative and proliferative lesions and preneoplastic foci of alteration identical to those observed in field-collected fish. Moreover, certain idiopathic hepatic lesions in English sole have been associated with changes in serum chemistry parameters indicative of liver dysfunction (Casillas et al. 1985).

Although liver lesions and other biological effects of contaminant exposure are most common in fish from areas with relatively high levels of sediment contaminants, these effects are initially observed in animals from areas where sediment contaminant concentrations are substantially lower. Researchers from the Environmental Conservation Division are currently using the hockey stick regression technique (Yanagimoto and Yamamoto 1979), a method that has been widely used in toxicological studies with mammals, to identify threshold sediment PAH levels associated with various biological effects in benthic fish and other marine organisms. Preliminary analyses of histopathological, chemical, and biochemical data collected in Puget Sound over the past ten to fifteen years suggest that threshold levels for the early hepatic lesions such as megalocytic hepatosis (Figure 8), and other biological responses such as induced activity of xenobiotic metabolizing enzymes and DNA damage, are in the vicinity of 0.5 to 2 ppm total PAHs in sediment. These sediment PAH concentrations are considerably lower than sediment quality criteria for PAHs (50 ppm) currently recommended for Puget Sound (WDOE 1991; Beller and Barrick 1988). Of over 30 sites surveyed in Puget Sound between 1979 and 1992 (Malins et al. 1984, 1985; Krahn et al. 1987; Varanasi et al. 1989a; Schiewe et al. 1991; Stein et al. 1992) half are at or above that level. While our current threshold estimates require additional validation, they may eventually be useful as an additional tool for evaluating sediment quality.

Reproductive Impairment

In addition to toxicopathic liver disease, studies suggest that fish residing in contaminated areas in Puget Sound may also suffer from various types of reproductive impairment (Table 1). Field studies on ovarian development in English sole from urban and non-urban sites in Puget Sound (Johnson et al. 1988) demonstrated that animals with elevated levels of FACs in bile were less likely to enter vitellogenesis and had lower plasma concentrations of estradiol than female sole with low levels of contaminant exposure. In minimally to moderately contaminated sites within Puget Sound such as Port Susan and Sinclair Inlet, approximately 80–90% of adult females undergo gonadal development, while at the Duwamish Waterway and Eagle Harbor, the percentage declines to 40–60%. These findings suggest that contaminant exposure may disrupt vitellogenesis in female fish. Results of this field study were supported by laboratory experiments showing that pretreatment of gravid female English sole with extracts of contaminated sediment decreased levels of endogenous estradiol (Casillas et al. 1991). A similar response was observed in rock sole and flathead sole treated with Prudhoe Bay crude oil (Johnson et al. 1993). However, the mechanisms through which chemical contaminants alter endocrine function in fish are not fully understood. A recent study suggests that reductions in endogenous

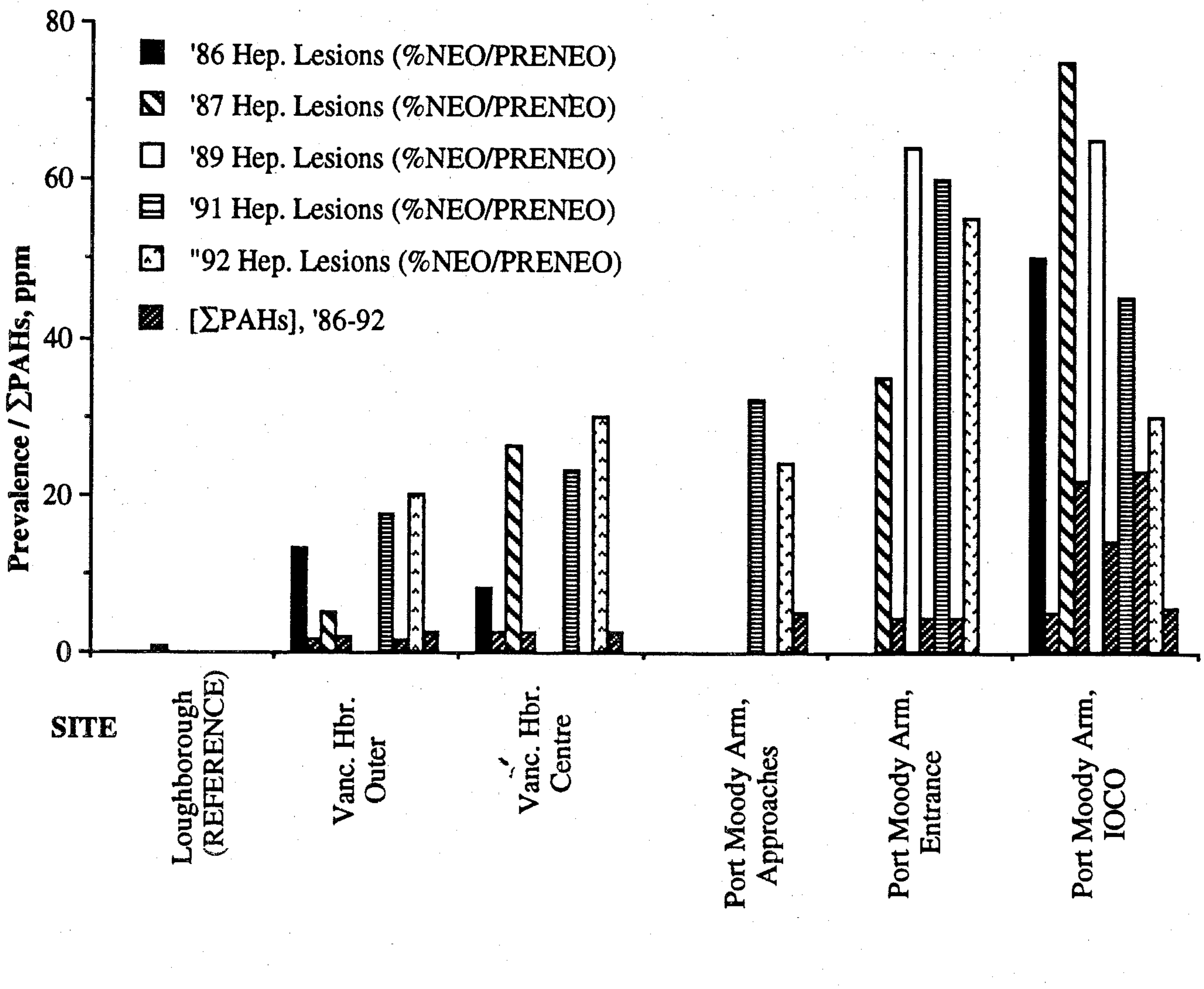

Figure 7. Prevalences of hepatic lesions in English sole, and sediment polycyclic aromatic hydrocarbon (PAH) concentrations at selected sites within Vancouver Harbour. Adapted from Goyette et al. 1989.

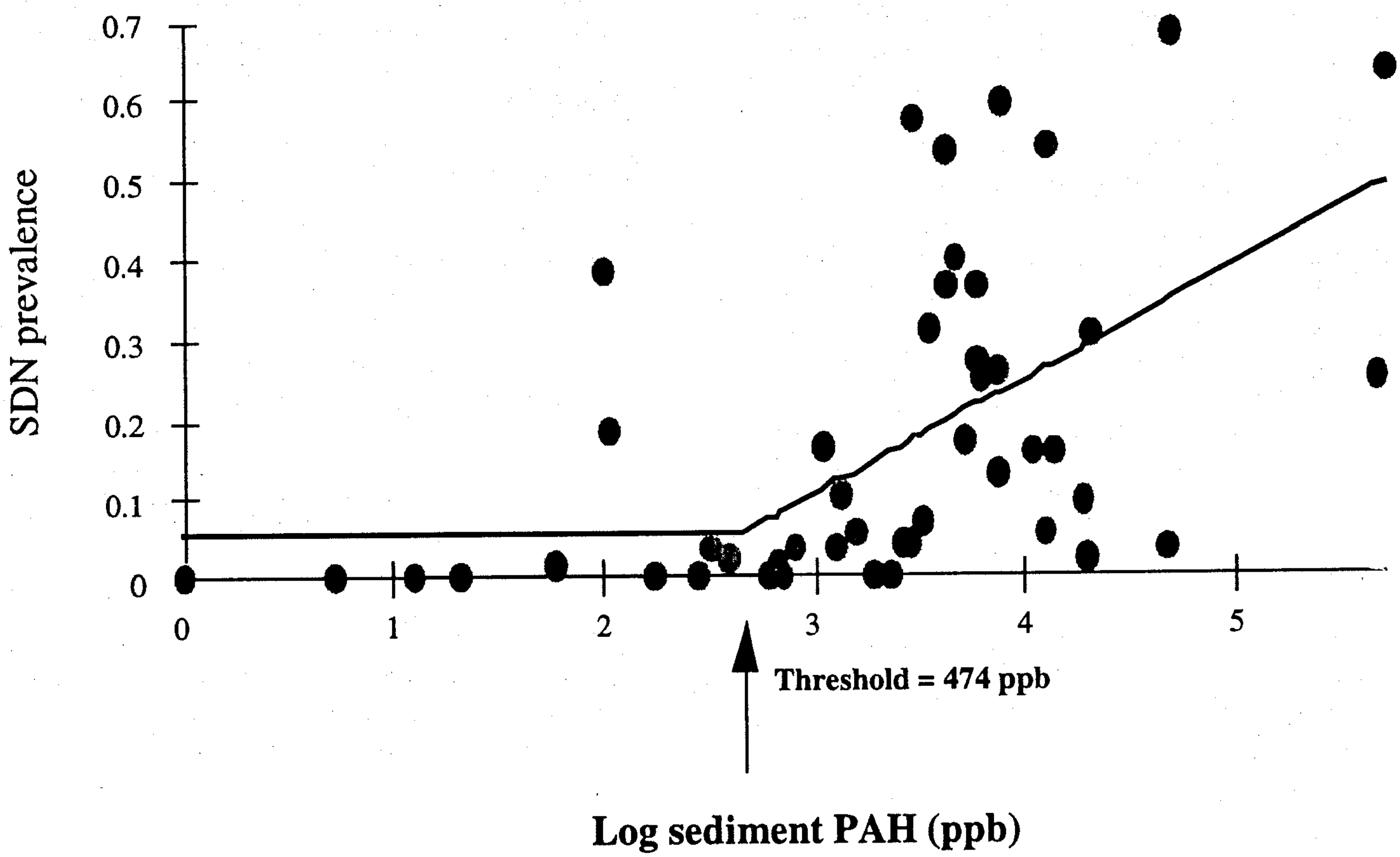

Figure 8. Threshold sediment aromatic hydrocarbon concentration associated with the appearance of specific degeneration/necrosis (SDN) in English sole, as estimated by the Hockey Stick regression method. Data on sediment chemistry and liver pathology are from Malins et al. 1984, 1985; Krahn et al. 1987; Myers et al. 1992; Johnson et al. 1988.

estradiol levels may result from depressed ovarian steroidogenesis, as contaminant-associated reductions in *in vitro* ovarian estradiol production were observed in English sole, rock sole, and flathead sole (Johnson et al. 1993). However, other mechanisms such as altered pituitary function (Thomas 1990) or increased clearance of metabolites of steroids (Stein et al. 1991) may also be involved.

Studies also suggest that English sole from contaminated areas that do successfully enter vitellogenesis may experience inhibited spawning ability and reduced viability of eggs and larvae. When gravid English sole from Port Susan, Sinclair Inlet, the Duwamish Waterway, and Eagle Harbor were brought into the laboratory and artificially induced to spawn, spawning success was significantly lower in fish from Eagle Harbor and the Duwamish Waterway (Casillas et al. 1991). However, when actively spawning sole were collected from breeding areas and egg and larval viability were examined, it was found that contaminant body burdens of spawning sole were relatively low, and no correlation could be found between indicators of exposure and spawning success (Collier et al. 1992). These findings, combined with results of other studies on early phases of the reproductive cycle in English sole, suggest that animals from heavily contaminated sites may not be migrating successfully to spawning areas in Puget Sound. Preliminary field studies with rock sole and flathead sole (Johnson et al. 1993) suggest that they may also experience some alteration in reproductive function as a result of exposure to contaminants, but the degree of impairment appears to be less severe than in English sole.

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 Harbour. Fish residing in areas adjacent to pulp mills may also be at risk, as studies in eastern Canada have shown that bleached kraft mill effluent may disrupt or alter reproductive function in several fish species (Munkittrick et al. 1991). However, there is little likelihood of such problems occurring at non-urban sites which have thus far been sampled in the US/Canada transboundary region, as sediment contaminant levels in these areas are quite low (PSWQA 1992).

Chemical Contaminants and Fish Abundance

The long-term impact that hepatic lesions and other toxicopathic disease conditions have on the survival of English sole and other affected fish is not known. Although they undoubtedly make some contribution to overall mortality, their importance in relation to other sources of mortality is not entirely clear. In a recent study, Johnson and Landahl (1994) estimated mortality rates in English sole from heavily and minimally contaminated areas in Puget Sound, and in sole with and without selected hepatic lesions, including neoplasms. For English sole three years of age and above from urban and non-urban areas of Puget Sound combined, the annual mortality rate was 0.38. This estimate is similar to published mortality rates for English sole from northern Puget Sound and other flatfish species from the North Sea, Grand Banks, and western

TABLE 1

Survival rate and indicators of reproductive success in English sole from four sites in Puget Sound, Washington. Data compiled from Johnson et al. 1988; Casillas et al. 1991; Landahl and Johnson 1993; Johnson and Landahl 1994.

	Port Susan	*Sinclair Inlet*	*Duwamish Waterway*	*Eagle Harbor*
Sediment	least polluted	moderlately polluted	high organics	high PAHs
Survival rate (3+ years)	0.62	0.62	0.62	0.80
% maturing	80	90	64	57
% spawning	90	75	54	35
% fertilization	52	35	44	24
% normal larvae	74	54	59	68
% overall reproductive success	28	13	9	3.2

Canada. Mortality rates in sole from heavily contaminated sites or in sole with toxicopathic liver lesions were not significantly higher than those for English sole from Puget Sound as a whole. These findings suggest that although toxicant-related death due to disease or other impairment may contribute to mortality rates in English sole, its impact, at least in older animals, is overridden by other factors that could deplete English sole populations, such as fishing pressure, predation, or fluctuations in food supply. However, these estimates did not take into account the contribution of natural factors to mortality rates in Puget Sound fish, nor the impact of fishing pressure, which was likely to be higher at the minimally contaminated sites than in the heavily contaminated areas at the time the data upon which this study was based were collected. For a more accurate assessment of the impact of contaminant exposure on English sole mortality rates, intersite variations in natural mortality and fishing mortality must be incorporated into these calculations.

An important question to consider is whether disease and reproductive impairment associated with chemical contaminants have the potential to contribute to declines in fish populations. We have no definitive answer at present. However, in a recent study (Landahl and Johnson 1993) the potential impact of contaminant-related mortality and reproductive impairment on the population growth rate in English sole was examined using techniques of simulation modeling. A preliminary Leslie matrix model was constructed for investigation of contaminant effects using the mortality rates for English sole in Puget Sound estimated from recent historical data (Johnson and Landahl 1994), as described above. Age-specific fecundity was determined from previously collected English sole ovary samples. Existing data on the effects of contaminants on reproduction, including impaired gonadal development, reduced spawning ability, and decreased egg and larval viability, were incorporated into the fecundity component of the model. Preliminary results suggest that declines in the fecundity component of the model, such as those observed in field studies in fish from contaminated sites such as the Duwamish Waterway and Eagle Harbor, may have the potential to decrease the growth rate of the English sole population in Puget Sound, assuming that a significant proportion of recruits come from these industrialized areas (Figure 9). To better evaluate the true magnitude of this effect, more accurate life-history data for larval and juvenile English sole are needed because the model is particularly sensitive to variation in mortality rates of these life stages. Patterns of recruitment and immigration in Puget Sound English sole should also be considered.

Effects of Contaminants on Anadromous Fish

In addition to fish such as English sole, which reside in bottom sediment, recent studies indicate that transient species such as outmigrating juvenile salmon accumulate detectable levels of contaminants as they migrate through urban estuaries. McCain et al. (1990) found that stomach contents and liver of juvenile salmon captured from the Duwamish Waterway showed significantly higher levels of PCBs and PAHs in stomach contents, as well as elevated PCB levels in liver and levels of metabolites of AHs in bile metabolites, than juvenile chinook from the relatively uncontaminated Nisqually Estuary (Figure 10).

More recently, juvenile salmon were collected from hatcheries and the respective estuaries of four river systems of Puget Sound: the Green-Duwamish, Puyallup, Nisqually, and Snohomish. Salmon collected from the Duwamish and Commencement Bay estuaries adjacent to Seattle and Tacoma had elevated hepatic AHH activity as well as elevated levels of DNA adducts in liver (Varanasi et al. 1993). When these fish were held in tanks with flow-through seawater for a period of several months, salmon from the Duwamish Waterway exhibited increased mortality and reduced growth (Figure 11 a, b) in comparison with salmon from the non-urban Nisqually system (Casillas et al. 1993; Varanasi et al. 1993). Juvenile salmon from the urban estuary also showed evidence of immune dysfunction (Figure 12). These animals exhibited altered *in vivo* production of primary antibody and showed no enhanced secondary *in vitro* response of plaque-forming cells when exposed to a standard antigen (Arkoosh et al. 1991; Casillas et al. 1993; Varanasi et al. 1993). Suppression of immune function could weaken the fish's resistance to pathogens and increase vulnerability to a variety of diseases, and could, in part, have accounted for the decreased survival of juvenile salmon from urban estuaries during holding at Mukilteo. These studies suggest that the effects of chemical contaminant exposure should be evaluated as a potential contributing factor affecting future salmon returns.

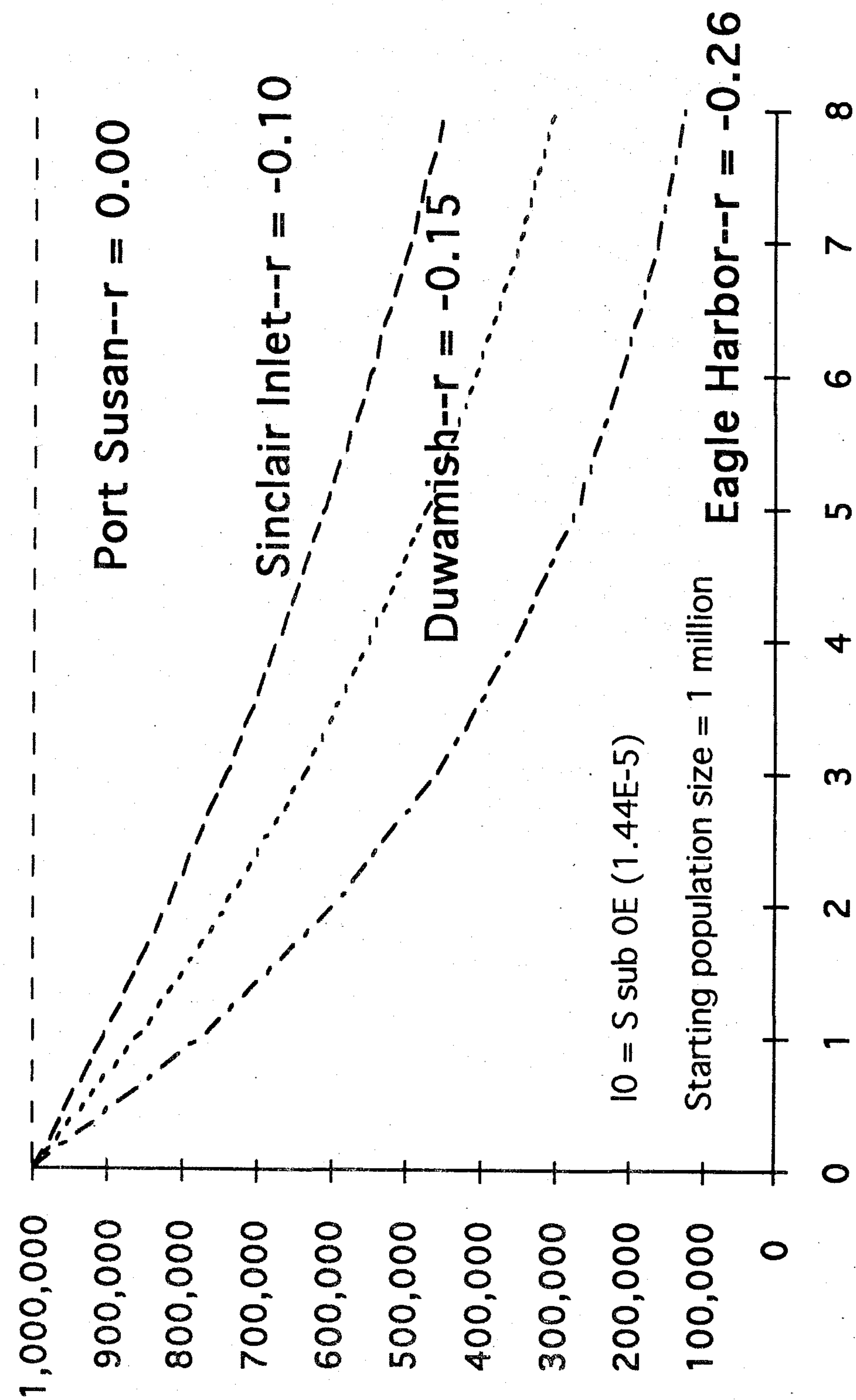

Figure 9. Projected population trajectories over a period of eight years for English sole at four sites in Puget Sound on the basis of *r* computed from a Leslie matrix model incorporating field data on reproductive ouput and survival in sole from the areas. Initial population size is one million fish. Adapted from Landahl and Johnson 1993.

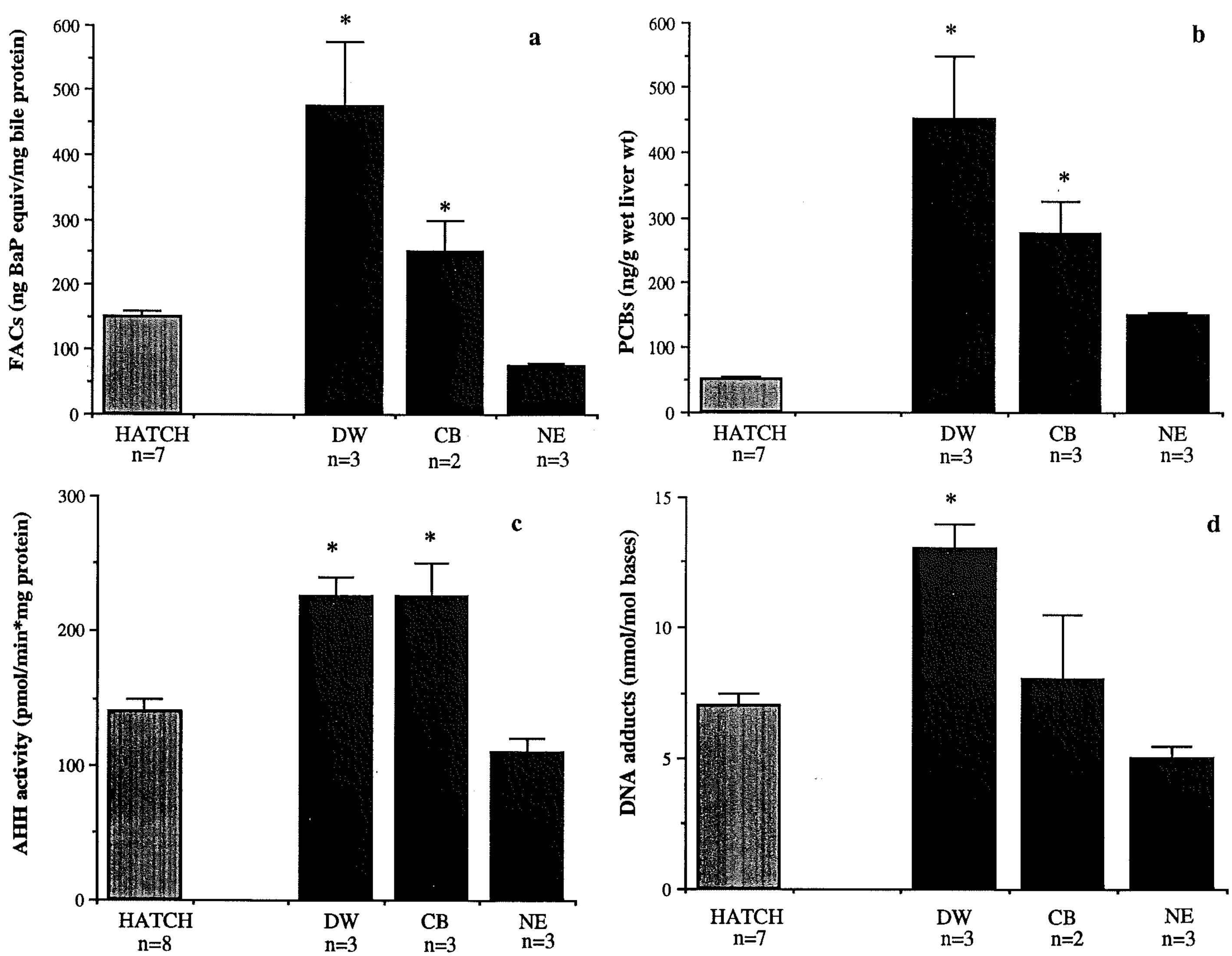

Figure 10. (a) Biliary fluorescent aromatic compounds (FACs) (ng BaP equiv/mg protein), (b) hepatic PCBs (ng/g wet liver wt), (c) hepatic aryl hydrocarbon hydroxylase (AHH) activity (pmol/min*mg protein), and (d) hepatic DNA adducts (nmol/mol bases) in juvenile salmon from estuaries and hatcheries sampled from Puget Sound, Washington. The bars represent the mean ± standard error. The sample size (n) equals the number of tissue composites that were analyzed. DW = Duwamish Waterway, CB = Commencement Bay, NE = Nisqually River Estuary. Adapted from Varanasi et al. 1993.

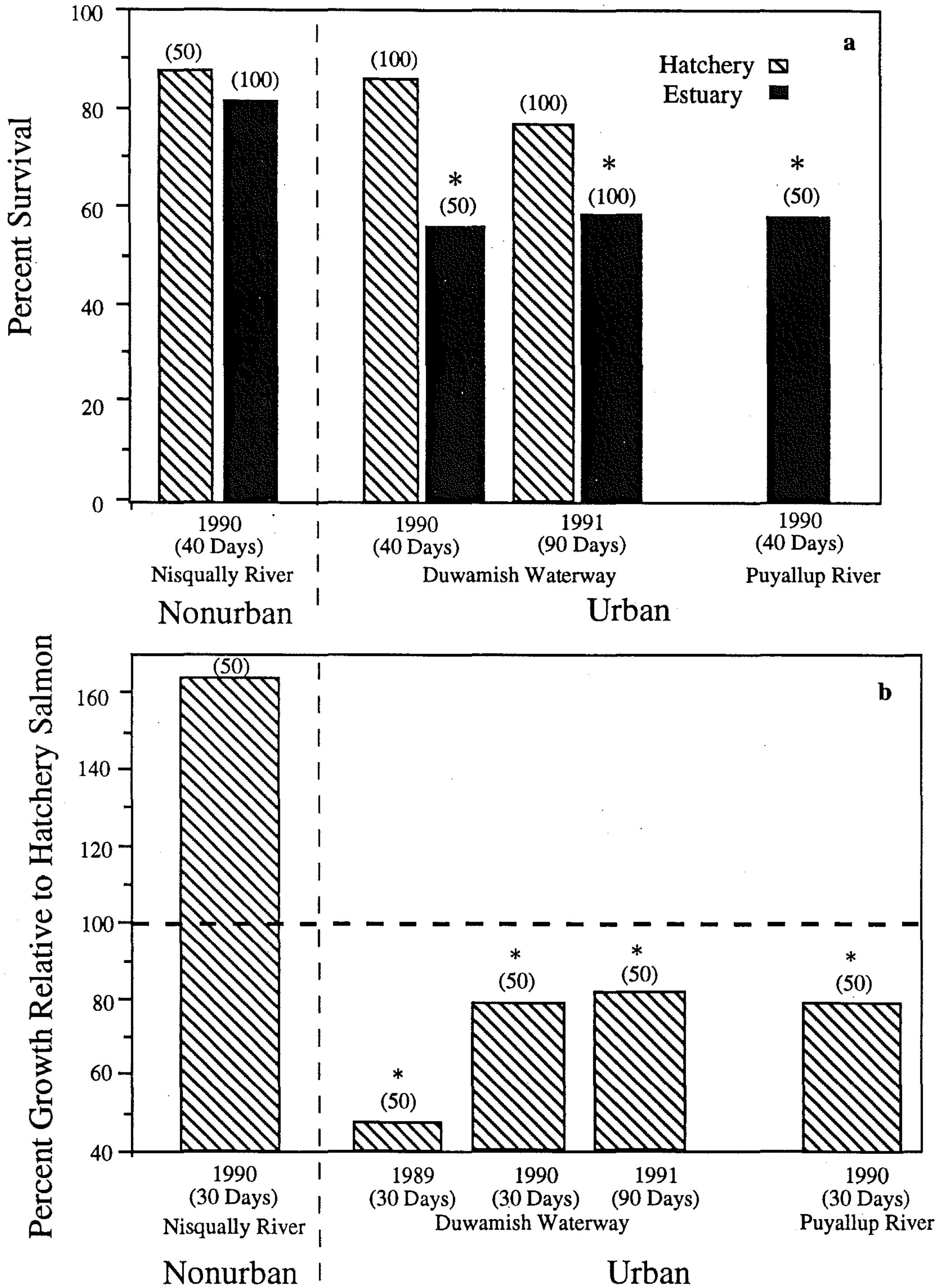

Figure 11. (a) Percent survival over a 30-day period in 1990 and a 90-day period in 1991 of juvenile salmon collected from the Nisqually River and the Duwamish Waterway. (b) Percent growth (length) of juvenile salmon from Nisqually River and the Duwamish Waterway relative to growth of salmon from the respective hatcheries for a 30-day period in 1990 and a 90-day period in 1991. Adapted from Casillas et al. 1993 and Varanasi et al. 1993.

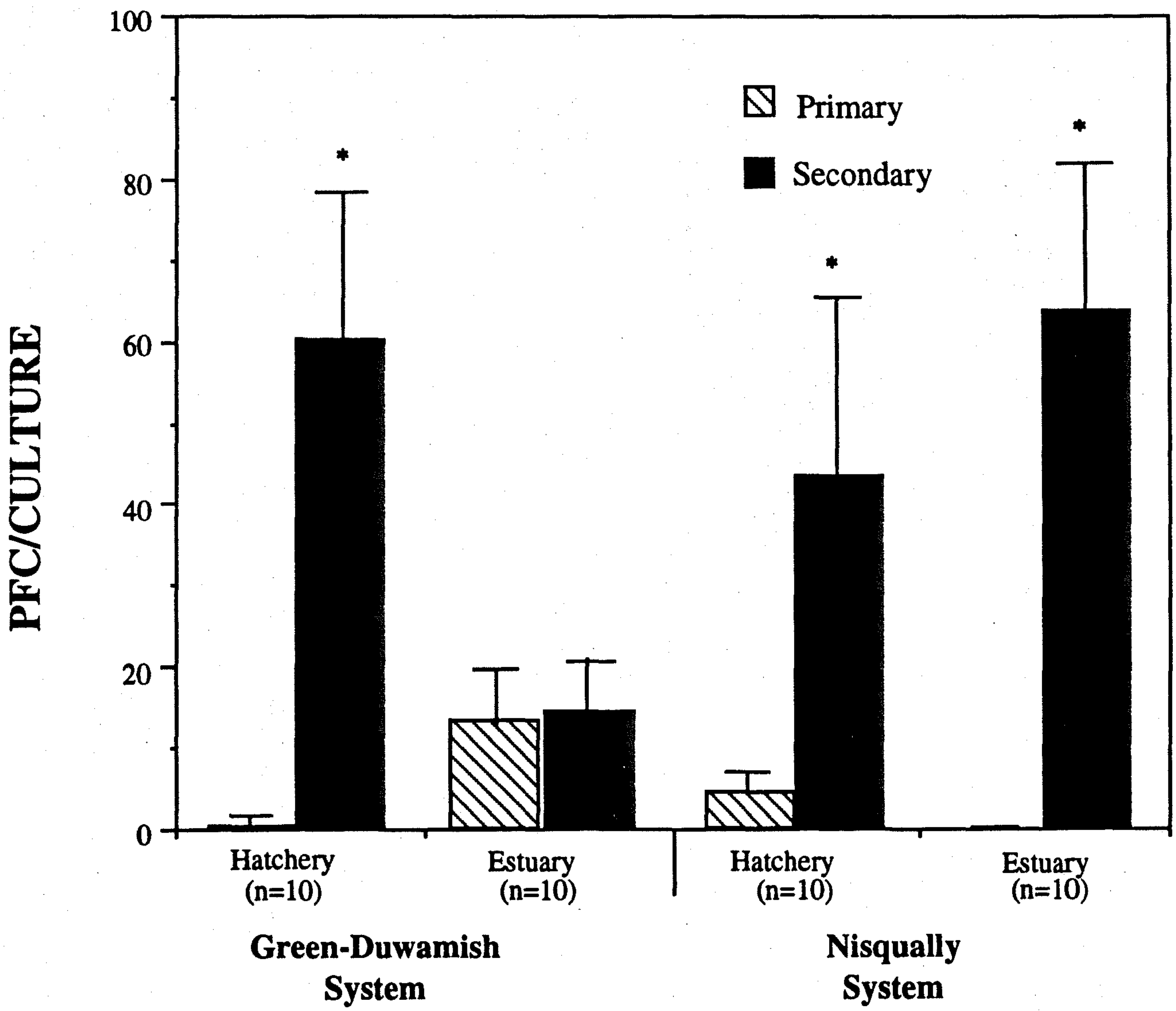

Figure 12. Primary and secondary *in vitro* plaque-forming cell response per culture (PFC/culture) (mean ± SE, n = 10) to TNP-KLH antigen generated in the anterior kidney of juvenile coho salmon from the Green-Duwamish and Nisqually River systems. * indicates that the secondary response (PFC/culture) to the antigen was significantly higher than the primary response. Adapated from Arkoosh et al. 1991 and Varanasi et al. 1993.

Trends in Fish Health

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 State and British Columbia. However, conditions appear to be improving at certain industrialized areas in Puget Sound (Figure 13). Data collected over the past ten years show a decline in biliary FAC levels in English sole from Elliott Bay. This trend is paralleled by a decrease in the prevalence of certain hepatic lesions, such as nuclear pleomorphism and megalocytic hepatosis, in fish collected from these sites. These findings suggest that regulatory measures that have been instituted in Elliott Bay over the past several years, such as changes in sewage effluent treatment, reductions in the number of combined sewer overflow events, restrictions on hazardous waste disposal, and more frequent onsite treatment of industrial point sources, have had a positive impact on the marine environment. However, levels of chemical contaminants and disease in fish from Elliott Bay are still among the highest in the United States (Myers et al. 1994). Moreover, although input of certain types of industrial wastes such as PCBs and DDTs has certainly declined in recent years, these compounds are persistent in the environment and may exert their effects for some time unless sediments containing them are buried by natural depositional processes or removed, capped or otherwise remediated. Sediment remediation programs are now underway in selected areas of Puget Sound (e.g. Eagle Harbor, Commencement Bay, and Elliott Bay), and over the next several years may have a positive impact on fish health. On the other hand, the input of aromatic hydrocarbons into the marine environment from non-point 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 (Figure 13), but it is likely that toxicant levels in such areas will increase at least moderately as a result of increased population density. Under such conditions, animals will probably show signs of exposure, perhaps accompanied by elevated prevalences of early degenerative conditions in the liver. However, the potential impact of long-term, relatively low-level exposure and associated disease conditions on fish populations in unknown.

CONCLUSIONS AND RECOMMENDATIONS

The quality of the marine environment in Puget Sound and the Georgia Basin is a major concern to leaders and the general public in both the State of Washington and British Columbia. As the region's population and discharges into the marine environment continue to increase, these impacts pose a threat to the ecological health of this area. On the basis of research conducted to date, there is considerable evidence that anthropogenic contaminants are impairing the health of fish that reside in areas adjacent to major population centers or at the sites of industrial activity. While the impact is greatest at sites with highest levels of sediment contamination, even moderate levels of sediment contamination (e.g. PAH concentrations in sediment of 1–3 μg/g dry wt) are associated with increased disease prevalence and other biological changes associated with contaminant exposure in bottomfish.

Sampling studies conducted to date indicate that at sites removed from areas of industrialization, disease prevalences and chemical concentrations in fish tissue are relatively low. These finding suggest that chemical contaminants discharged into urban harbors are generally not being transported across international borders to cause harm to bottomfish, although spills of oil or toxic compounds in transboundary regions certainly would have a negative impact on animals in these areas. On the other hand, increased population growth and urbanization in areas around the Strait of Georgia, Puget Sound, and Juan de Fuca Strait that are currently undeveloped can be expected to result in increased exposure and disease prevalence in marine fish unless toxicant inputs, especially non-point source pollutants, are strictly controlled. Fortunately, however, conditions at some of the most heavily contaminated sites in Puget Sound and Vancouver Harbour appear to be improving as a result of improved regulation and treatment of industrial pollutants and sediment remediation efforts.

In terms of potential impacts on fish populations, contaminant-associated alterations in reproductive processes and in survival and viability of larval fish are perhaps of the greatest concern, especially if fish residing in urban areas contribute a significant proportion of recruits to offshore populations. Potential effects of urban contaminants on transient fish species such as salmonids are also of considerable concern. Both of these areas would merit greater attention in future

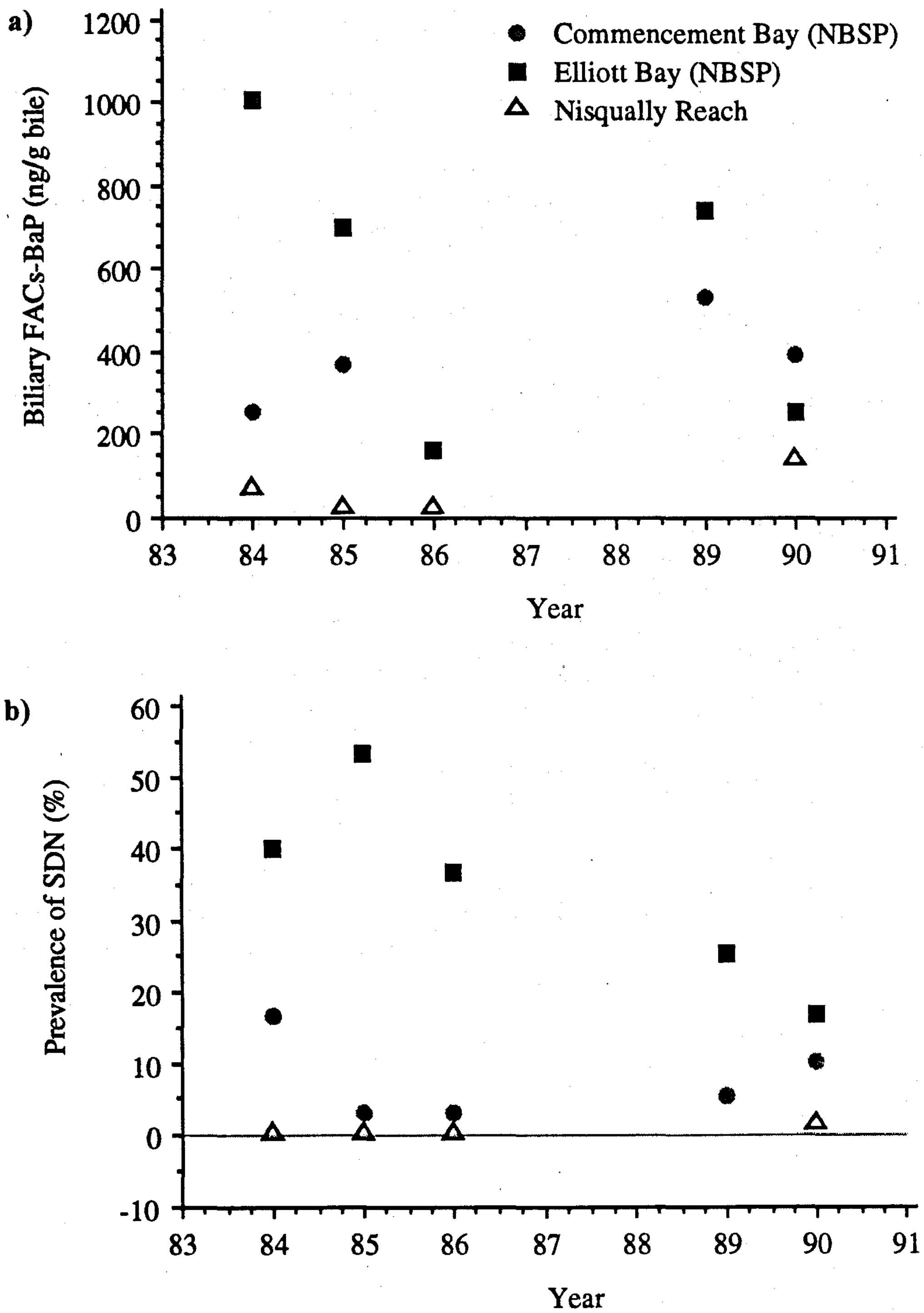

Figure 13. Concentrations of (a) biliary fluorescent aromatic compounds (ng/g bile) and (b) prevalences of specific degeneration/necrosis in English sole collected from Nisqually Reach, Commencement Bay, and Elliott Bay from 1979 through 1991. Data from Malins et al. 1984, 1985; Myers et al. 1994.

monitoring and research programs. There is also a need to link information on toxicant impacts on fish with available data on recruitment and abundance of commercially important marine fish stocks, to determine if effects on fish in urban areas are great enough to impact offshore populations when immigration and density-dependent population regulation have been taken into account.

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DISCUSSION

Andrea Copping *(Panel)*: Based on the liver lesions, do you see being able to predict population impacts?

Mark Myers: Based on the liver lesions, no. I think that it's a little too early to be able to actually come up with predictions of population effects based on adduct levels. We do know that there are apparently no ill effects on populations of fish that are affected with these liver lesions, although it's a little confusing.

Tom Pedersen *(Panel)*: Based on what you have shown with the cause and effect relationship between organic biochemicals and fish, is it a fair deduction that heavy metals are not particularly an issue in the basin?

Mark Myers: We believe that they're not. None of the heavy metals are really hepatotoxic or hepatocarcinogenic, and very few of them are accumulated to any degree. Copper is to a certain extent, lead to a certain extent, but those are not hepatotoxins or hepatocarcinogens. Metals don't make biological sense as the cause of these livers lesions. They may be causing other problems that we're not looking at.

Andrea Copping *(Panel)*: What we can say with these indicators, which are often very dramatic indicators, of the effects of an organic contaminant?

Mark Myers: Based on our information, the liver lesions probably don't have much of an impact on population levels. However, PAHs certainly affect reproductive function.

Lyndal Johnson: I should probably say that the work we've done looking at the effects of liver lesions on English sole mortality is preliminary. From the data we've collected since 1979 we were not really able to see any big increases in mortality, at least of adult fish from the contaminated areas, or fish that had lesions. When we did these studies we didn't have very good information on fishing pressure at the sites, differences in depuration rates, or food supply at the sites. Also, when some of the data were collected, the fisheries in southern Puget Sound hadn't been closed yet, so there could have been some fishing pressure. So if all of these things were factored in, you might actually see some increased mortality because of the lesions, but generally we didn't find it to be a big factor, whereas the reproductive impairment seemed to contribute more. We might also see more contribution to mortality of juvenile fish. We don't really have good data on mortality rates of young-of-the-year fish in the wild; we have information from maybe three years of age and above.

Curtis Ebbesmeyer *(Panel)*: Are there other abnormalities in the fish that might be caused by lower concentrations?

Mark Myers: Lower levels of exposure will cause elevated AHH levels. The same thing would be true of the DNA adduct levels. Lower levels of exposure could cause elevated DNA adduct levels, which have the potential to become molecular lesions, that can lead to cell death, etc. In terms of other liver lesions, for those that can be detected with a light microscope, I think we've reached the limit with those early lesions that I was discussing.

Curtis Ebbesmeyer *(Panel)*: We seem to be following a particular line of scientific inquiry which has been very fruitful, but are there other effects on the population that come from lower concentrations that we will need to look at in the next 20 years?

Mark Myers: Those kinds of effects should be looked for, but we don't have information to support that there would in fact be those sorts of effects. While we've come up with some pretty low effects thresholds for some conditions, it's not stretching the imagination too much to think that there may be other effects that could occur at even lower levels of exposure. Perhaps we don't have the tools yet to detect them, or to even identify them.

Dave Levy *(Hatfield Consultants Ltd., West Vancouver)*: My company works for five of the pulp mills in the Strait of Georgia region. We're responsible for designing some environmental monitoring programs to look for effects of pulp mill effluent disposal on fish populations in the receiving environment. This is a result of new legislation under the Fisheries Act, as part of the environmental effects monitoring program. We need to identify two sentinel fish species for these studies, and we're considering using English sole as one of them. We're being asked to take some very coarse measures, for example liver weight and gonad weight, and my question is: Are these going to be sensitive

enough to detect some of these effects that you have been able to identify?

MARK MYERS: If that is all you're looking at, no, I think it's a waste of time. If you're going to be evaluating possible exposure in these fish you have to incorporate several measures of exposure. My belief is that liver histopathology can be pretty sensitive. Liver weight occasionally can be related to contaminant exposure, but it's far too crude a method to be defensible at a scientific inquiry.

DAVE LEVY *(Hatfield Consultants Ltd., West Vancouver)*: Okay that was my suspicion. There is no biochemistry written into this program as it stands right now. The second question is: What do you know about the population ecology of English sole? Will there be any response from neighboring uncontaminated populations to swamp out the negative effects that you are able to document?

LYNDAL JOHNSON: We really don't know. English sole tend to reside in localized areas, but they do move out from embayments to spawn. So even though they are in fairly small discrete stocks, what makes up a single stock is probably more widespread than, for example, the Duwamish waterway. They have pelagic eggs, so I would think that probably there will be contributions to the urban embayments from sub-populations in other areas, but exactly how large those are is something that we don't know very well. Within our agency we really don't have the resources to do the population studies that need to be done to answer these questions. We really need more cooperation with state agencies or with universities that are doing these kinds of studies to collect the information we need to answer these questions.

Habitat Changes in Georgia Basin: Implications for Resource Management and Restoration

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ABSTRACT

Filling, diking, water quality changes, and watershed modifications are some of the major causes for decreases in fish and wildlife habitat in the Strait of Georgia and Puget Sound. Global environmental change poses a relatively newly recognized threat to these habitats for which research is almost totally lacking in the region. Quantifying the area of habitat loss is difficult because studies have used a variety of classification methods and several time intervals to measure change. There have been large net losses of vegetated habitat (swamps, flood plain forests) in the Fraser River estuary (1890s baseline), but some net gain in marsh habitat. Eleven major deltas in Puget Sound have suffered wetland losses in the order of 76 000 ha (47%) since the mid-1800s. In Puget Sound, between 1912 and 1978 there appears to have been a net increase in kelp habitat, in the order of 53%, probably partially due to increased hard substrata in the shallow subtidal zone. Changes in eelgrass habitat is difficult to assess due to lack of comprehensive historical records. However, losses of 'wetland' habitat have probably included losses of eelgrass.

Introduced species of seaweed such as *Sargassum muticum* and the seagrass *Zostera japonica* have impacted native systems significantly in some areas. Harvesting of seaweed resources appears to have exacerbated the decline of kelp on urban beaches and increased the abundance of *Sargassum.* Changes due to variation in water quality have not been evaluated. In the Strait of Georgia, 540 km^2 of intertidal gravel, sand and mud habitat is currently closed for shellfish harvesting because of bacterial contamination. 730 km^2 of shallow water habitat (<20 m) usable for crab and shrimp fishing was closed (1992) because of dioxin contamination. Of the 31 000 ha of classified commercial shellfish-growing areas in Puget Sound and Juan de Fuca Strait, 9863 ha (32%) were either restricted or prohibited for harvesting due to water quality issues as of 1992. Relations between habitat loss and the growth and survival of aquatic resource species are difficult to establish because of problems in identifying limiting factors and separating climate and harvest effects. Placement of oyster shell on mud and sandflats in Grays Harbor estuary has resulted in increased densities of newly settled Dungeness crab. Placement of gravel on mudflats has similarly shown an increase in bivalve densities in Puget Sound. These two lines of evidence suggest that carrying capacity for these resources is limited by substrata. Comparisons between habitat areas and functions for fish and wildlife species are hampered because of difficulties in habitat classification procedures within and between the two jurisdictions. There is clearly a need to restore aquatic habitats from loss due to human activities in the Strait of Georgia and Puget Sound. However, procedures need to be established that will enable managers to plan restoration on a sound scientific basis. Techniques involving landscape ecology concepts could be useful for developing guidelines.

We see a clear need to establish cross-boundary habitat research in at least these topics: 1. A common habitat classification system; 2. Common methods for habitat assessment studies; 3. Understanding the limiting factors for fisheries resources that are habitat-related; 4. Development of regional restoration technologies and goals targeted at species that migrate and utilize regional habitats; 5. Development of a better understanding of water, sediment, and habitat quality variations; 6. Development of a common and cost-effective regional habitat monitoring program for transboundary species; and 7. Development of a better understanding of the effects of global environmental change on habitats and resources in the region.

INTRODUCTION

Aquatic habitats in the Strait of Georgia and Puget Sound (hereafter referred to as the Georgia Basin) have been inexorably changed since the arrival of European settlers in the early 1800s. There have been major changes in the shorelines in large urban areas such as Seattle, Vancouver, Bellingham, and Victoria. In addition, changes in the watersheds of the rivers of particular estuaries have led to differences in sedimentation rates, freshwater flow, and other features of estuarine circulation.

In this paper we summarize what is known regarding aquatic habitat change in the Georgia Basin and possible impacts on fish and wildlife resources that have resulted from these losses. General summaries of the water quality and habitat changes in the region have been prepared in earlier documents (e.g. Strait of Georgia: Waldichuk 1983, Thomson 1981; Puget Sound: Strickland 1983, Downing 1983). In addition there have been several papers dealing with specific habitats (e.g. benthos, Levings et al. 1983; intertidal wetlands, Hutchinson et al. 1989; Thom and Hallum 1990). However there has not been a summary of data on habitat, and its change over time, that considers the Strait of Georgia and Puget Sound as a single ecological unit.

We also provide suggestions for joint habitat management and research, as well as a perspective on habitat restoration to provide for net gain of habitat in the region. Even though the Georgia Basin supports over five million people, this inland sea is one of the few heavily populated coastal regions in the world that is still producing major catches of fish and other aquatic resources. For example, the Fraser River and its estuary supports the largest run of sockeye salmon of any single river in the world. However there are certain species that are not as abundant as they once were, especially in Puget Sound where habitat loss has been implicated in the demise of numerous salmon stocks (Schmitt et al., this volume). Habitat restoration is one of the techniques that resource managers can use to rehabilitate production, but relationships between habitat and species need to be established before proceeding rationally.

MIGRATORY SPECIES AND HABITAT USE

There is likely a myriad of invertebrates and plants with passively drifting larval stages that move between the Strait of Georgia and Puget Sound, but this movement may be restricted to between the islands along the border and contiguous shorelines. Judging from knowledge of the surface and mid-depth currents between the Strait and the Sound (Thomson, this volume), the movement between the two basins of larvae from stocks of commercially significant species appears limited (Bourne and Chew, this volume). The planktonic organisms important as food for fish and other resource species, as well as reproductive products of vegetation such as kelp, also probably move between the two water bodies, but the scale of this movement is not known.

The migration of juvenile salmonids between rearing habitats on either side of the border has not been documented but is likely in selected areas such as Boundary Bay. Juvenile chinook, chum, pink, coho, and sockeye are present in significant numbers on Roberts Bank and rely on food organisms which in turn are part of the detrital food web originating with eelgrass and algae in the intertidal zone (Levings 1985; Webb 1991). A similar food web dependence was described for Drayton Harbour, Blaine, where extensive use of nearshore habitats by juvenile chum was found by Thom et al. (1989). The migration pattern of chum salmon leaving Drayton Harbour has not been described in detail but it is likely that during their seaward movement these fish move into Boundary Bay,

especially if their movement is being influenced by surface currents. Whether this stock moves to the ocean via the Strait of Georgia or Juan de Fuca Strait is not known. There may be extensive mixing of juvenile salmon from numerous Canadian and American stocks as they move to the northeast Pacific from the estuaries. For example, Miller et al. (1980) documented beach seine catches of juvenile salmon on the Washington side of Juan de Fuca Strait, and some of these fish may have originated from the Fraser River system. Similarly, young salmon caught on shorelines near Discovery Passage (northern Strait of Georgia) (Levings and Kotyk 1983) could have been produced in rivers flowing into Puget Sound.

Larval drift may also carry juvenile fish between habitats in the two jurisdictions, but this movement may be restricted. For example, herring *(Clupea harengus pallasii)* developed from spawn deposited on shoreline algae habitat on Point Roberts, probably drift onto Roberts Bank and feed on epibenthic crustaceans associated with eelgrass (Levings 1983). Spawning and rearing habitats in this instance are clearly totally contiguous, although the long causeways on Roberts Bank may prevent some longshore movement parallel to the shoreline. The herring on Roberts Bank are in turn eaten by juvenile chinook salmon rearing in the same area (MacDonald 1984). Herring spawn in the extensive eelgrass beds on Boundary Bay (Hay et al. 1989), but have not spawned on Roberts Bank for several decades.

DESCRIPTION OF HABITATS

Strait of Georgia

A number of classification systems have been developed for aquatic habitats on the Strait of Georgia, by a variety of groups. There does not appear to be a particular system adopted by all potential users. One of the more comprehensive fish habitat classification systems was developed by Williams (1989) for use by fish habitat managers within DFO. This system uses a hierarchical methodology with four levels, within which are nested eight categories. Geophysical descriptions of shoreline reaches using methods originally developed by Howse and Harper (1984) are the basis of the system. This method recognizes the functional values of habitats and is to be used with a matrix which gives species habitat requirements and an accompanying biophysical description. Several classification schemes have been developed to determine the sensitivity of nearshore habitats in the Strait to oil spills (e.g. DFE 1978; Dickins et al. 1990), and new systems are being developed at present by the Province of British Columbia and other agencies (Don Howse, pers. comm.). Two additional systems have been developed primarily for waterfowl habitat management purposes. These are:

- The Canadian Wetland Classification System (CWCS) (e.g. Ward et al. 1992), which uses a system of five classes of wetland, within which are nested a number of forms.
- The British Columbia estuary habitat mapping and classification system, which uses categories as habitat types and components; the latter are described by specific modifiers (Hunter et al. 1983).

Puget Sound

Classification systems in Puget Sound differ from those used in British Columbia. The five primary classification systems that have been applied in Puget Sound include Cowardin et al. (1979); Bortelson et al. (1980); Downing (1983); Dethier (1990); and Simenstad et al., (1991).

- The Cowardin system was developed to classify wetlands and deepwater habitats for all of the United States, and because of this has shortcomings in its specificity for Puget Sound habitats. The Cowardin System has a mixture of physical substrate and biological communities as the lowest level of classification, and lacks an indication of major driving factors (e.g. wave or current energy) structuring nearshore communities.
- Bortelson et al. divided nearshore habitats into intertidal wetlands and subaerial wetlands for the purpose of mapping historical changes in the area covered by deltaic wetlands in Puget Sound. This simple system was probably the finest resolution that could be applied when using the old Coast and Geodetic Survey maps for baseline data for their study.
- Downing used a system primarily based on geology to discuss general processes affecting the coastline of Puget Sound. He classified beaches in Puget Sound according to substrata types (e.g. rock, gravel, sand, mud/sand, mud). He also summarized a classification

scheme developed by the Washington State Department of Ecology (WDE) which quantifies the amount of coastline according to whether it is depositional, neutral, erosional or modified. Depositional systems include those with marshes, sand and mud flats and eelgrass beds, whereas neutral and erosional habitats comprise gravel, cobble and rock. Modified beaches include those that contain seawalls, piers, logs booms, etc.

- Dethier developed a highly-specific system that includes all of the habitats that occur in Puget Sound down to a depth of 100 m, and classifies these habitats by major physical and chemical (i.e., salinity) factors. Her system provides diagnostic as well as characteristic species for each of these habitats.
- Simenstad et al. used a system consisting of eight habitat 'types' which is a simplified combination of Cowardin, Downing and Dethier systems. The purpose of Simenstad et al. was to develop sampling protocols for each of these habitat types, not to develop a new classification system. This system lacks the specificity of Dethier, but is probably the most commonly applied system in Puget Sound.

Classification System Used in the Present Study

In order to simplify comparisons between the Strait of Georgia and Puget Sound, we have decided to use nine categories to quantify loss and gain of aquatic habitat. Several habitat management schemes (e.g. Fraser River Estuary Management Program [FREMP] 1990) use simpler descriptions of intertidal habitat, usually relying on basic appearance of the landform. For example a net gain/loss balance sheet for fish habitat in the Fraser River estuary was recently established using the following five units: sand, mud, marsh, riparian vegetation, and unvegetated subtidal (Langer 1993). We added the following four units because of their prominence in the Strait and Puget Sound: eelgrass, intertidal algae, kelp beds, rock/gravel (Levings et al. 1983).

WHAT DID WE HAVE IN THE LATE 1800s COMPARED TO THE PRESENT?

Strait of Georgia

Marshes and Riparian

North and Teversham (1984) constructed vegetation maps in the lower Fraser River flood plain (upstream to Hope) using survey notes made by the Royal Engineers in the 1890s. Areas of vegetation types listed by North and Teversham have recently been quantified (Kistritz et al. 1993). A total of 962.3 km^2 was vegetated habitat when the surveys were made. Excluding Sturgeon and Roberts Bank, 8.2 km^2 of marsh were estimated in the study area at the time of the surveys. The most extensive vegetation types were grasslands ('wet meadows'), mixed woodlands, and a variety of flood plain forests types. For the purposes of this paper we have classified all the latter vegetation as riparian. Table 1 shows

TABLE 1

Changes in extent of habitats in the Fraser River estuary and lower river

Habitat	*Past (km^2)*	*Present (km^2)*	*Change (km^2)*	*Change (%)*	*Notes*
Saltmarsh[a]	22	4	–18	–81.8%	
Brackish marsh[a]	8	16	+8	+100%	Related to mudflat accretion
Freshwater marsh[a]	2	6	+4	+200%	Related to mudflat accretion
Riparian: bog, meadow, etc.[b]	645	uncertain	uncertain	>–50%	Current riparian unmapped esp. wetland forest
Flood plain lake (Sumas)[c]	36	0	–36	–100%	

[a] Hutchinson et al. 1989 (upstream to New Westminster).
[b] North and Teversham 1984 (upstream to near Hope).
[c] Siemens 1966.

that 645 km² of the historical vegetation in the lower Fraser (upstream to near Hope) mapped by North and Teversham (1984) was considered fish habitat by Kistritz et al. (1993), on the basis of inferred connections for invertebrate production and detrital supply. Contemporary surveys of wetland vegetation using the CWCS system (Ward et al. 1992) did not assess the present total extent of riparian vegetation. Hutchinson et al. (1989) concluded that because of accretion of mudflats on the foreshore of Sturgeon Bank and Roberts Bank and in Woodward Island area of the South Arm, there had been a 100% increase in brackish marsh and a 200% increase in freshwater marsh in the Fraser estuary in the past century. There have been major losses or isolation of flood plain lakes further upstream, some within areas under tidal influence (e.g. Hatzic Lake). Sumas Lake, about 60 km upstream from the mouth, has been completely drained and converted to farmland, representing a loss of 36 km² (Siemens 1966). Hutchinson et al.'s data (1989) also show that almost 82% of the salt marsh in the estuary has been lost, primarily due to diking. According to Hutchinson et al. (1989), there are presently 26 km² of marsh habitat in the Fraser estuary. This is comparable to Ward et al.'s (1992) figure of about 28 km² for estuarine marsh (upstream to New Westminster). When assessing all marsh types in the Fraser River lowlands (upstream to Hope, including the estuary), Ward et al. (1992) gave about 61 km² as the total marsh area. In the North Arm of the Fraser estuary, recent detailed analyses of changes showed 96% loss of wetlands since the turn of the century (Kistritz et al. 1993). The species composition of brackish marsh communities at the Fraser estuary has also changed in the recent decade because of the invasion of purple loosestrife *(Lythrum salicaria)*, which is considered to outcompete native species such as sedges (*Carex* spp.).

Hutchinson et al. (1989) and Prentice and Boyd (1988) gave data on the past and present extent of marsh habitat at a number of estuaries other than the Fraser (Table 2). Because of differences in baseline data, calculations of percent loss over all the estuaries is not possible; however there has been approximately 60% loss of this type of habitat. The extent of the loss has been most dramatic in the marshes in Burrard Inlet (93% loss). Dike breaching and habitat restoration at the Cowichan and Englishman River estuaries has not yet recovered habitat lost. At the Campbell River estuary, a net gain of 13% was achieved by removal of log storage and creation of brackish marsh habitat (Levings and Macdonald 1991).

Sandflats

Data from Levings et al. (1983) showed that approximately 424 km² of sandflat habitat (Table 3) are currently present in the strait, mostly on Sturgeon

TABLE 2

Changes in extent of marshes and estuaries on the Strait of Georgia (excluding the Fraser River)[a,b]

Location	*Past (km²)*	*Present (km²)*	*Change (km²)*	*Change (%)*	*Notes*
Baynes Sound	1.22	1.17	−0.05	−4.1%	
Courtenay	0.85	0.74	−0.11	−12.9%	
Little Qualicum	0.12	0.11	−0.01	−0.8%	
Campbell River	0.23	0.26	+0.03	+13.0%	Created
Nanaimo	2.80	1.30	−1.50	−53.6%	
Cowichan	1.90	1.01	−0.89	−53.1%	Restored
Burrard Inlet	1.40	0.10	−1.30	−92.9%	1930 base
Squamish	1.65	1.15	−0.50	−30.3%	1950 base
Englishman	0.54	0.47	−0.07	−12.9%	Restored
Chemainus	1.55	1.21	−0.34	−21.9%	
Total	12.26	7.52			

[a] Baseline is 1850 unless noted.
[b] Data from Hutchinson et al. 1989, Figure 8.

Bank and Roberts Bank, and in Boundary Bay. Other extensive sandflats are on the east side of Vancouver Island, north of Nanaimo. Sandflat habitat is being lost from Sturgeon Bank, or at least is not accreting, because training walls are inhibiting dispersal of sand onto the Banks (Luternauer 1980; Levings 1980). About 1 km^2 of sandflat habitat, including some shallow subtidal areas, were lost due to port construction on Roberts Bank (Levings 1985).

Mudflats

There are no published data on the areal extent of this habitat type in the Strait of Georgia from the past. At present there are about 408 km^2 of mudflat in the Strait (Table 3). Most of these mudflats are in the Fraser estuary, where the sediment load enables fairly rapid accretion of mud. Accretion rates for mudflats at the mouths of rivers on the east side of Vancouver Island are much slower (Hutchinson et al. 1989). Although not quantitatively documented, much of the loss of mudflats can be related to dredge and fill activities for harbour construction (e.g. False Creek in Burrard Inlet).

Rock-Gravel Habitats (to –20 m)

Excluding Burrard Inlet, the current area of rock-gravel habitat is 413 km^2, but this habitat accounts for the majority of the perimeter of the shoreline in the Strait (71%; Levings et al. 1983). There are no published data on this habitat type from the past. Intertidal gravel habitats are important for commercial and recreational shellfish harvesting, but their potential for these uses are currently impaired by bacterial contamination. 540 km^2, the majority in Burrard Inlet and Boundary Bay, are currently closed for harvesting (Table 3). Rocky habitats in tidal passages (e.g. Seymour Narrows) support some of the most diverse assemblages of invertebrates in the strait (Levings et al. 1983) and are worthy of protection as natural areas. Log storage can cause severe degradation of these habitats due to sunken debris and poor water quality (McDaniel 1973).

TABLE 3

Extent of habitat types other than marsh and riparian on the Strait of Georgia

Habitat	*Past (km^2)*	*Present (km^2)*	*Notes*
Sandflats[a]	uncertain	424+	Accretion slowed on Sturgeon Bank[b]
Mudflats[a]	uncertain	408+	Accretion depends on sediment load[b]
Rock/gravel[a] (to –20 m)	uncertain	413+ (excludes Burrard Inlet)	540 closed for shellfish (includes Burrard Inlet); 1 on Roberts Bank[c]
Subtidal	uncertain	6487+	730 closed for organochlorine; 12 used as log storage[c]
Intertidal algae	uncertain	0.3 of *Iridaea*[d] +	Unstable re introduced species, climate change[e]
Kelp Beds	125/356 t/km[f] N/S of Saltspring	9 on North shore Juan de Fuca;[g] +	Unstable re urchins, climate
Eelgrass	uncertain	40.2 in Boundary Bay, Roberts Bank[h] +	Unstable re introduced species[i]

[a] Levings et al. 1983.
[b] Luternauer 1980.
[c] Environment Canada (unpublished).
[d] Austin and Adams 1978. Data are km^2 per km of coastline.
[e] Manson 1993.
[f] Cameron 1916.
[g] Sutherland 1989.
[h] Ward et al. 1992.
[i] Baldwin and Lovvorn, in press.
+ indicates additional significant areas of the habitat known to be present but unquantified.

Unvegetated Subtidal (<20 m)

The areal extent of this type of habitat has not been computed, but is likely greater than the surface area of the Strait (6487 km^2). At least 12 km^2 of this deeper habitat has been disrupted by log storage in the strait (Table 3). At present, harvesting and consumption of crab and shrimp is restricted from 730 km^2 of this habitat type because of dioxin contamination (Table 3).

Kelp Beds

Cameron (1916) surveyed kelp beds *(Nereocystis lutkeana)* in the southern Strait of Georgia, including Howe Sound and Burrard Inlet. Kelp beds were mapped and their approximate size estimated from small boat observations in August 1916. Approximately 125 beds were noted, the majority on the southwest side of the strait between Nanaimo and Victoria. South of Saltspring Island, kelp biomass was estimated at 356 tonnes/km compared to 125 tonnes/km north of Saltspring Island. No kelp beds were observed in Howe Sound and only one bed was seen in Burrard Inlet (Coal Harbour). Published contemporary data on kelp beds are not available, except on the north shore of Juan de Fuca Strait, where 9 km^2 were mapped in 1988 (Sutherland 1989). Recent habitat mapping in Burrard Inlet showed that the bed that Cameron (1916) observed is still present at Coal Harbour, and that another more extensive bed (estimated 1 km long) has developed near Brockton Point (DFO, unpubl. data).

Intertidal Algae

There are few quantitative data on the areal extent of this habitat type. However successional changes and community dynamics of algal assemblages have been studied intensively near Gabriola Island and these data are summarized in Levings et al. (1983). Austin and Adams (1978) surveyed red algae *(Iridaea)* between Campbell River and Denman and found approximately 0.3 km^2/km was present in this area (Table 3). Algal communities in the strait have changed in the past decades owing to introduced species (e.g. *Sargassum muticum)* as well as recent climate effects (Manson 1993).

TABLE 4

Changes in extent of habitat coverage in Puget Sound

Habitat	*Past (km^2)*	*Present (km^2)*	*Change (km^2)*	*Change (%)*	*Notes*
Marshes & Riparian	732.0[b]	176.1[b]	−555.9	−75.9%	a
Sandflats	uncertain	90.4	loss		b
Mudflats	uncertain	155.1[b]	loss		b
Rock/gravel	uncertain	93.4	increase?		c
Unvegetated Subtidal	uncertain	17.1	increase?		d
Kelp beds	205.5	313.8	+108.3	+52.7%	e
Intertidal Algae	uncertain	93.4	increase?		f
Eelgrass	uncertain	659	loss?		g

[a] Data from Bortelson et al. (1980) includes subaerial and intertidal wetlands from 11 major deltas. Estimate of tidelands area from Nesbit (1885) for Stilliquamish-Skagit tidelands.

[b] Substantial losses (i.e., 100%) are documented for the urban estuaries of the Puyallup River and Duwamish River (Thom and Hallum 1990). Estimate for present is from Downing (1983, Table 5.1).

[c] Estimate for present is from Downing (1983, Table 5.1).

[d] Estimate from Boule et al. (1983) as "subtidal aquatic bed" which may include seagrass and kelp.

[e] From Thom and Hallum (1990). Estimate is length of shoreline with kelp.

[f] Estimate for present is based on rock/gravel coverage from Downing (1983, Table 5.1). This estimate is high for macroalgae since most algae grow in a narrow range of elevation (see text).

[g] Unquantified declines are indicated in several areas. An increase may have occurred in Padilla Bay (Thom and Hallum 1990). Estimate is length of shoreline with eelgrass.

Eelgrass *(Zostera marina)*

The only quantitative data from the strait show that significant beds of eelgrass are present in Boundary Bay and Roberts Bank, where about 40.2 km^2 has been mapped (Ward et al. 1992). There are significant beds elsewhere in the strait, but data on their areal extent are not available. Eelgrass loss has been primarily related to harbour and port developments in the strait (Levings 1991). Because of the spread of an introduced species *(Zostera japonica)*, eelgrass beds have been changing in species composition in recent decades, especially in the southern straits (e.g. Boundary Bay; Baldwin and Lovvorn 1994).

Puget Sound

Marshes and Riparian

Tidal marshes were of early interest in Puget Sound for use as agricultural lands (Nesbit 1885). By the early 1880s, 267 km^2 of tidal marshes and swamps surveyed in nine counties bordering the Sound contained approximately 320 km of dikes enclosing 4.1 km^2 of marsh. The massive Skagit-Stilliguamish tidelands covered 520 km^2 and extended 20 km landward from the present shoreline. Nesbit noted that tide marshes greatly exceeded tideflats in area, and that non-tidal freshwater marshes were 3 to 4 times as great in areal extent compared with tide marshes at that time. Boule et al. (1983) estimated that Puget Sound presently contained 58% of the state's estuarine wetlands for a total of 54.6 km^2 of vegetated intertidal habitat.

It is clear that substantial losses of marshes and riparian habitat have occurred over the past century in Puget Sound. Estimates based upon eleven major deltas in Puget Sound indicate that there has been at least a 76% loss in tidal marshes and riparian habitat (Table 4). The major losses were within highly urbanized estuaries including the Puyallup and Duwamish River deltas. Substantial diking on the Skagit River delta and other deltas has also resulted in the loss of major portions of the tidal wetlands in the region. Diking has resulted in a shift of wetland type from tidal saltmarsh to freshwater palustrine marsh in the Nisqually River delta (Burg 1984).

Sandflats

Sandflats and mudflats contain unique populations of organisms as well as substantial abundances of microalgae (Dethier 1990). There are no early comprehensive estimates for sandflats in the region. Present estimates, based on the Coastal Zone Atlas (CZA) by the Washington Department of Game, indicate that sandflats occupy 90.4 km^2 of Puget Sound (Downing 1983). There have been substantial declines in sandflats as well as mudflats in urban bays which are located on the deltas of the Puyallup, Duwamish and Snohomish Rivers (Thom and Hallum 1990). Sand and mudflat losses amount to approximately 700 ha and 600 ha in the Puyallup River and Duwamish River deltas, respectively (Boule et al. 1983). Most losses occurred during intense filling and dredging operations prior to the 1950s. Burg (1984) noted that placement of dikes at the Nisqually River delta resulted in erosion of 160 ha of unconsolidated shore. Erosion of intertidal sandflats due to alterations caused by channelization of rivers, construction of dams, shoreline armouring and dredging has not been documented fully in Puget Sound, but could be substantial.

Mudflats

At present, approximately 155 km^2 of Puget Sound is covered by mudflats (Table 4). There have probably been substantial losses in this habitat type which are similar to losses of sandflats. Because mudflats occur in highly depositional environments, back bays and quiet areas in southern Puget Sound and Hood Canal have probably seen the greatest declines. In these areas, which have not had as much dredging and filling activities, losses may be linked more strongly to shoreline armouring (Thom and Shreffler, in prep.).

Rock-Gravel Habitats (to –20 m)

Gravel/cobble shorelines are the major habitat type on beaches in Puget Sound (Downing 1983). It is probable that this habitat type has increased in area due to loss of sources of fine material from bluffs caused by significant shoreline armouring throughout Puget Sound (Canning and Shipman 1993). At present, it is estimated that rock-gravel covers 93.4 km^2 of Puget Sound beaches (Table 3). Most of this habitat occurs along narrow, steeply sloping shoreline away from the major river deltas. Rock and gravel habitats can contain substantial clam and seaweed standing stocks (Armstrong et al. 1976; Thom et al. 1976).

Unvegetated Subtidal (<20 m)

Unvegetated subtidal shallower that 20 m has probably increased substantially in area since the mid-1800s in Puget Sound. Increases have resulted from dredging in major deltas such as the Puyallup River, Duwamish River and Snohomish River. Burg (1984) noted that 160 ha of subtidal unvegetated bottom was developed from erosion of intertidal sandflats on the Nisqually River Delta. Erosion was a result of altered sediment input to the delta due to diking and dam construction.

Kelp Beds

Beds of kelp, *Nereocystis luetkeana*, have been of some interest in the past as a navigational aid, marking the location of shallow rocky bottom areas, and as a source of potash. Early records of kelp were made by the Wilkes expedition which showed beds on maps produced in 1841 (Thom and Hallum 1990). Hydrographic charts as far back as 1852 contained locations for kelp. Maps produced between 1892 and 1924 had symbols distinguishing kelp and eelgrass. Some information is also available from early phycological studies in the region (Scagel 1966). Comprehensive surveys conducted in 1911–12 for the US Department of Agriculture by George Rigg (1915) documented kelp beds throughout Washington State. These maps provide an extremely good picture of the location and size of beds during that time. In 1977, the beds were resurveyed by the Washington State Department of Game for the CZA. Despite differences in methodology between the two surveys, the coverage of the region was comprehensive and was conducted by knowledgeable scientists, and as such, provides the best available picture of changes during the intervening period.

It appears that the distribution of kelp increased between 1912 and 1977 (Table 4). Beds not noted by Rigg existed in 1977 and are still present. The bed at Lincoln Park in west Seattle was studied over the period of 1914–17 by Rigg (1917). He noted that the bed never exceeded 180–215 m in length. Observations between 1974–1993 indicate that the bed is at least 610 m long (Thom and Hallum 1990; Antrim et al. 1993). The increase is most likely due to an increase in rocky subtidal substrate caused by construction of a seawall at Lincoln Park and subsequent removal of the source of fine sediment to the beach (Thom and Hallum 1990). Substantial shoreline armouring has occurred in Puget Sound (Canning and Shipman 1993), which may have resulted in increased kelp throughout the region.

Invading species of seaweed, in particular the brown alga *Sargassum muticum*, may be effectively outcompeting *Nereocystis* for space. Complete replacement of the *Nereocystis* bed at Alki Point by *Sargassum* has been documented and may be exacerbated by heavy harvesting of young *Nereocystis* (Thom and Hallum 1990). The occurrence of *Sargassum* inshore of *Nereocystis* has been noted at many beaches in Puget Sound (Thom, unpubl.).

Nereocystis is an annual plant that grows from a microscopic phase to 20 metres in length over a short period in spring-summer. Such a high rate of growth requires copious nutrients as well as adequate light. Alteration in water quality could potentially affect the development of kelp in Puget Sound, suggesting this species may be an excellent indicator of water quality in the region. However, more research is needed to establish the requirements for optimal growth in this species.

Intertidal Algae

An extremely rich flora consisting of approximately 600 species of macroalgae occur in the Washington-British Columbia region (Mumford 1990). Thom et al., (1976) listed 157 species of seaweed from five beaches in central Puget Sound. Mumford (1990) noted that 20 species of the genus *Porphyra* occur in Puget Sound, several of which may be commercially valuable as food (e.g. nori). Puget Sound also contains substantial natural populations of carrageenin-producing taxa such as *Gigartina* and *Iridaea* (Mumford 1990).

Records of intertidal algae do exist from extensive phycological investigations in the region from the mid-1800s (Scagel 1966). However, no attempt has been made to compile a list of species or to resurvey old collection sites to document changes. Although we believe that the coverage of seaweed in Puget Sound is linked to the distribution of rocky substrata (Table 4), most of the seaweeds grow in a narrow elevation band extending from about +1 m down to −5 m MLLW. Hence, the estimate of 93.4 km^2 is high. Substantial pressures on intertidal algae from human trampling, erosion, shoreline pollution, and overharvesting exist.

Eelgrass *(Zostera marina)*

Eelgrass forms a band along depositional shorelines from about MLLW and −10 m. Although there are no complete early records for eelgrass, pre-1900 hydrographic charts note 'grass' in some areas of Puget Sound. Ronald C. Phillips conducted surveys of eelgrass in 1962–3 at 107 sites in Puget Sound and Hood Canal (unpublished field notes), and showed that eelgrass occurred throughout the region but was less frequently observed in southern Puget Sound (Thom and Hallum 1990). Remote sensing studies have documented the distribution of eelgrass in selected areas including Padilla Bay, Lummi/Bellingham Bays, the Skagit River delta and Port Susan (Webber et al. 1987). The most comprehensive records of eelgrass distribution come from the CZA and observations of Washington Department of Fisheries (WDF) biologists (Daniel Pentilla, pers. comm.), who have conducted extensive surveys of herring spawning sites as well as for surf smelt and sandlance. It is estimated that approximately 659 km of shoreline is presently occupied by eelgrass in the region (Table 4) which represents about 25% of Puget Sound (Thom and Hallum 1990). This estimate is believed to be low because the CZA surveys noted intertidal beds only, and other records from the region are not comprehensive (Thom and Hallum 1990).

Changes in eelgrass habitat are poorly documented. Based upon comparison of recent and old hydrographic maps, Thom and Hallum (1990) showed that eelgrass has decreased in Bellingham Bay and the Snohomish River delta by 30% and 15%, respectively. The decreases are related to dredging and filling activities. In contrast, 1887 maps of Padilla Bay indicate that eelgrass occupied roughly 598 ha. Estimates made in the 1980s indicate that eelgrass occupied on the order of 3,208 ha (Bulthuis 1991). The increase is speculatively attributed to reduction of sedimentation and freshwater input to Padilla Bay, in turn a result of extensive diking and the re-routing of major flows of the Skagit River from Padilla Bay to Skagit Bay (Thom and Hallum 1990). *Zostera japonica* now occupies a substantial portion (i.e. 6%) of formerly unvegetated flats in Padilla Bay (Bulthuis 1991). Loss of unvegetated flats to the invasion by *Z. japonica* is believed to still be occurring in Puget Sound, although this invasion has not been documented. Ronald Phillips has noted declines in eelgrass in Elliott Bay since the 1960s (Thom and Hallum 1990). There are also a number of anecdotal observations made by beach residents through Puget Sound that indicate declines in this habitat type. Erosion of depositional beaches as well as changes in water quality may be reasons for these changes, although this is untested.

WHAT IS THE STATUS OF HABITAT MANAGEMENT IN THE REGION AT PRESENT?

Strait of Georgia

Some of the aquatic habitat management in the Strait is conducted under the DFO Habitat Management policy (DFO 1986), which requires a hierarchy of approaches to fish habitat management and protection. Mitigation, compensation, and restoration are the three key strategies of the policy. In this policy, mitigation means moving a proposed project to another site in order to completely eliminate impacts on sites considered to be sensitive; this strategy is preferred. Compensation ratios for replacement of lost habitat have been 2:1 for marsh, and 1:1 for mud/sandflat and riparian habitats (Levings 1991). The overall goal of the policy is no net loss, and preferably a net gain, in productive capacity of fish habitat. The impact of proposed developments on aquatic habitat is assessed through a system of referrals, wherein all stakeholders (municipal, provincial, federal) have an opportunity to review plans. Impacts on marine and anadromous fish (e.g. salmon) and resident fish (e.g. trout) are reviewed by federal and provincial agencies, respectively. At the Fraser River estuary, a 'one-window' approach to reviews has been provided by the Fraser River Estuary Management Program (FREMP). There are also specific initiatives such as zoning (North Arm of the Fraser River estuary; Williams and Colquhoun 1987) and comprehensive estuary management plans (Squamish estuary; Deans 1992) to deal with fish habitat management. The Province of British Columbia is usually the lead agency in these initiatives because the Province owns most of the foreshore landbase in the Strait. Sandborn (1993) provided a review of the developing provincial goals for land use, including aquatic habitat and wetlands. Aquaculture leases (clams, oysters, salmon farms) in the foreshore are also managed by the Province, as is marine plant harvesting.

Management of wetlands and waterfowl habitat around the Strait of Georgia is of concern to the Canadian Wildlife Service and provincial wildlife agencies. The Federal Policy of Wetland Conservation has been recently published and is described in Lynch-Stewart (1992). The National Wetlands Working Group offered the following definition of a wetland:

> "Wetland is defined as land that has the water table at, near, or above the land's surface or which is saturated for a long enough period to promote wetland or aquatic processes as indicated by hydric soils, hydrophytic vegetation, and various kinds of biological activities that are adapted to the wet environment" (Lynch-Stewart 1992, p.19).

A system for rating the importance of coastal wetlands for waterfowl, wildlife, and fish was proposed by Hunter et al. (1985, cited in Prentice and Boyd 1988) for use by the British Columbia Ministry of Environment. It is not known how frequently this system has been used in wetland management in the Strait of Georgia.

In some areas, important habitat for both fish and wildlife have been purchased by conservation agencies such as the Nature Trust and the Pacific Estuary Conservation Program (e.g. Nanoose-Bonell estuary, Dawe and White (1986); Englishman River estuary, Dawe and MacIntosh (1993); Cowichan River estuary; Duck-Barber-Woodward Island sedge marshes in the Fraser River estuary). This strategy protects habitat in perpetuity.

Semi-quantitative balance sheets for habitat have been constructed for the Fraser River estuary and the Campbell River estuary using vegetative units as surrogates for fish habitat productive capacity. On the Fraser River estuary, Langer (1993) calculated a net gain of 6.1 ha of marsh habitat, achieved through a combination of creation of aquatic habitat from areas previously not flooded or accessible by fish, by enhancement of existing areas (e.g. removal of logs from marshes), and by compensation measures such as marsh transplants and conversion of mud and sand flats to marsh. Net losses of 90.3 ha of subtidal habitat, 9.8 ha of sand/mudflat habitat, and 100 m of riparian habitat were calculated. At the Campbell River estuary, rehabilitation achieved a net gain of 3.2 ha of marsh, 22.8 ha of sand/mudflat, and 7.8 ha of unvegetated subtidal habitat. The gains were achieved by cleanup of areas previously used for log sorting, by creation of marsh on intertidal islands, and by dredging of terrestrial habitat to subtidal elevations (Levings and Macdonald 1991).

Puget Sound

State agencies have long recognized the importance of Puget Sound habitats. Management of habitats in Puget Sound is primarily under the purview of the Washington Department of Ecology (WDE) and Natural Resources (WDNR). These agencies rely on input from WDF and Washington Department of Wildlife (WDW), as appropriate, to the type and location of development that may harm habitats. For example, impacts to tidal freshwater marshes with potential importance to waterfowl would generally be addressed with substantial input from WDW, while projects which may alter eelgrass meadows and kelp beds generally receive substantial review by WDF. WDE coordinates the input from the state agencies and either issues a permit or takes other actions relevant to the project. WDNR provides direct oversight to aquatic lands owned by the State. They review and rule on applications for development, disposal of dredged material, leasing of lands for aquaculture or geoduck harvesting, and other activities. WDNR has developed a management program for seaweed resources and cordgrass *(Spartina alterniflora)* (Mumford 1990). Seaweed management involves limits for harvesting for personal use. Cordgrass has invaded Puget Sound as well as coastal estuaries, where it is cause for concern among oyster growers and resource managers. WDNR has embarked on a program to control cordgrass through cutting as well as herbicide treatments. So far, control by cutting has been attempted in Puget Sound. WDF specifically has jurisdiction over projects that may impact beaches. They issue hydraulic permits for projects that either do not impact beaches, or that provide sufficient mitigative measures for expected project impacts. WDE has developed a management scheme which identifies various habitat types and places a quantitative value on those habitat types that can be used for designating appropriate mitigation. For example, very highly valuable wetlands may require six-to-one mitigation. This means that for every acre of wetland lost, six acres must be constructed and be proven functional through a monitoring program. WDE is also responsible for assessing damage and claims for impacts of chemical

spill (e.g. oil) on habitats. For example, they have developed a formula which allows the calculation of monetary claims based on the volume and type of oil spilled, habitat and resources impacted.

The Puget Sound Water Quality Authority (now within WDE), develops policies and plans specific to Puget Sound. These plans include issues directly involving Puget Sound habitats. The Authority has developed and coordinates a monitoring program which include habitats and water quality. Monitoring of the distribution of nearshore Puget Sound habitats has been carried out for the Authority by WDNR for the past five years. This program includes aerial imagery of one-third of the shoreline of Puget Sound each year, so that the entire Sound is covered every 3 years.

Federal agencies including the US Environmental Protection Agency (EPA), National Oceanic and Atmospheric Administration (NOAA) and the US Fish and Wildlife Service (USFWS) provide input, guidance and funds for many of the state programs. In particular, the US Army Corps of Engineers is responsible for regulating placement of fill on wetlands and in water of the United States. The Puget Sound Water Quality Authority was an outgrowth of EPA's Puget Sound Estuary Program conducted during the late 1980s. The USFWS office in Olympia has a habitat restoration program that is focused on restoring habitats in Puget Sound.

Overall, there is excellent coordination and commitment among the various agencies that effect the management of Puget Sound's habitats. Bottlenecks most often arise in situations where data are insufficient to allow decisions to be made on a project. In addition, although management and regulations are fairly well established, loss of habitats continue (K. Kunz, Seattle District US Corps of Engineers, pers. comm.). In general, these losses are due both to poor follow-up on mitigation efforts and to physical alterations in habitats as described above.

RESTORATION AND RELATED INITIATIVES

Strait of Georgia

Habitat restoration initiatives in the Strait of Georgia have been mostly focused on marsh habitat and this technique has resulted in net gains in several estuaries where habitat has been quantified. For example, marsh habitat has been restored by breaching of dikes at the Englishman and Cowichan River estuaries (Dawe and McIntosh 1993). At the Squamish River estuary, previously isolated marsh habitat has been reconnected by excavation of ditches (Ryall and Levings 1987). In the Campbell River estuary, 3.3 ha of marsh habitat were successfully created by transplanting sedges into a section of the estuary rehabilitated from log storage effects (Levings and Macdonald 1991). Transplants have also been conducted for pickleweed *(Salicornia virginica)* at the Fraser River estuary (Pomeroy et al. 1981) and in Baynes Sound (Russell 1992). Transplant experiments at the Fraser were unsuccessful but the plants moved at Baynes Sound apparently are surviving.

Eelgrass was transplanted at Gibsons Harbour in Howe Sound to compensate for losses due to marina construction. However, there has been no long-term monitoring of the site, so results of this work is not known. Eelgrass transplants in the Strait have generally been unsuccessful (Levings 1991). Natural expansion of eelgrass on southern Roberts Bank was attributed to a causeway deflecting turbid and brackish water from the Fraser River (Harrison 1987).

Kelp beds have been created as compensation for loss of other types of habitat in a few instances. For example, hard substrates (e.g. concrete debris, etc.) were placed on the sea bed near the Roberts Bank coal port to compensate for loss of the productive capacity of intertidal and shallow water habitat. Kelp beds colonized the concrete debris (DFO, unpubl.), but data are not available on the final results of this initiative.

Puget Sound

Although a number of projects have been conducted as mitigation for development, few projects have been carried out with the sole purpose of restoring damaged or lost habitats. Opportunity for true restoration may come through efforts associated with the cleanup of Superfund sites in Puget Sound and other initiatives. Substantial portions of Commencement Bay and Elliott Bay have been designated for cleanup and restoration, with much of the money for these actions coming from the principal responsible parties (PRP's). Restoration plans have been developed with the involvement of agencies for PRP's for both embayments, and implementation of these plans awaits com-

pletion of the entire planning process. In general, restoration involves removal or burial of contaminated sediments and soils and construction of several habitat types. It is anticipated that restoration activities in each bay could begin within two years.

Several small tidal habitat projects are now underway, as part of the Coastal America Program initiated during the Bush Administration. These projects include the creation of tidal channels and marshes in the Duwamish River and elsewhere in Puget Sound. Efforts spearheaded by the WDE, EPA and USFWS have focused on restoration of tidal marshes in the Snohomish River delta. These efforts, which encompass in one instance (Spencer Island) over 140 ha, are the largest tidal marsh restoration projects undertaken to date in Washington State. The above group of agencies is actively seeking opportunities for restoration of Puget Sound habitats. In addition, tribal communities such as the Skokomish Indian Tribe, are pursuing restoration in estuarine systems within their lands.

Mitigation projects have involved construction of tidal marshes, embayments and eelgrass meadows and kelp beds in Puget Sound. The 4 ha Gog-Li-Hi-Te tidal marsh on the Puyallup River has proven to successfully serve targeted resources such as juvenile salmon and shorebirds since construction in 1986 (Thom et al. 1991). An 8 ha marine embayment was constructed on the seaward side of Jetty Island in Everett for juvenile salmonid habitat, and has proven successful in increasing salmonid prey responses (PENTEC 1993). Eelgrass transplantation has not been well studied for mitigation in Puget Sound, and there remains considerable controversy over the probability of success of eelgrass transplantation efforts (Thom 1990). Presently, projects at West Point, La Conner and Lincoln Park represent small but important efforts in understanding how eelgrass transplantation will work. Kelp beds have been the target for several artificial reef projects in Puget Sound, designed as mitigation for construction of the Elliott Bay marina. The general understanding is that kelp beds can be established relatively easily.

Recent interest in developing ecologically sound criteria for selecting sites for restoration prompted the WDNR to fund work in this area. A report detailing ecological goals and criteria for site selection and habitat design was developed from this effort (Shreffler and Thom 1993). The report will serve as guidance for restoration planning in areas under the jurisdiction of the WDNR.

METHODS FOR LINKING TO RESOURCE SPECIES

Most species that are considered economic or aesthetic resources in the Strait of Georgia and Puget Sound depend upon nearshore habitats for part or all of their life history. Because of the complex life histories and the open nature of the ecosystems of the Strait and the Sound, it is very difficult to provide quantitative estimates of the carrying capacity of various habitat types for resource species. However, in all the habitat management schemes we reviewed, a positive relationship between amount of habitat and stock production was assumed. Table 5 provides a summary of some of the mechanisms or management procedures involved for the various species. There are a number of species groups that depend heavily on nearshore habitats (e.g. English sole, shorebirds, waterfowl) which we have not elaborated on, but they must be considered in habitat management and restoration efforts for the region.

HERRING

The use of algae, eelgrass, and kelp as spawning substrate for herring eggs has been well described, but the factors that determine whether a particular area or vegetation community will be used are not known. A number of general intertidal locations in the Strait of Georgia and Puget Sound have been used regularly over the past few decades (Hay et al. 1989; Daniel Pentilla, pers. comm.). Biologists working in the Strait of Georgia have used measurements of the areal extent of herring spawn in both the intertidal and shallow subtidal routinely for assessments in the past few years. The biomass of spawning herring populations are back-calculated from egg deposition data using the product of area (m^2) of spawn, egg density/m^2, and a factor of 200 eggs/g female weight. By adding the catch made in a particular area to the calculated biomass, an estimate of the total herring stock present in a particular spawning area can be estimated (Schweigert and Haegele 1988). For forecasting purposes, the anticipated spawning population in year $t + 1$ is estimated from the spawning escapement in year t, times an

estimate of the average survival rate for one year, plus an estimate of the stock production during that time period (Haist et al. 1986).

Rockfish

Rockfish are adapted to use high relief habitat, which in shallow water often in turn supports algae, including kelp. Haldorson and Richards (1987) gave data on the density of young of the year copper rockfish *(Sebastes caurinus)* from *Agarum*, *Nereocystis*, and *Zostera* sp. from near Nanaimo. The density of the rockfish ranged from 1.6 to 145.8 fish/100 m in *Nereocystis* (August to October), with density in the other habitats of intermediate value.

Juvenile salmon

All species of juvenile salmon are found in nearshore habitats in the Strait of Georgia and Puget Sound at either the fry or smolt, or both, life stages. In estuaries, chum and chinook salmon fry are considered estuarine-dependent because of reliance on the detrital food web characteristic of these habitats (e.g. Sibert et al. 1977; Simenstad and Wissmar 1985) and the survival benefits accrued by residency (Levings et al. 1989). The other species of salmon (pink, coho, sockeye) appear to have shorter residency times in estuaries, but use marine foreshores as smolts or postsmolts during their seaward migration. For example, juveniles of the latter three species were found in association with kelp beds at Discovery Passage, a migration route out of the Strait of Georgia for young salmon (Levings and Kotyk 1983).

Dungeness crab

The megalopa stages of Dungeness crab drift onto intertidal or nearshore habitats and settle out in vegetation, especially eelgrass. It has been found that oyster shell placed on mudflats harbours greater densities of juvenile crabs than do barren mudflats. These data provide evidence that unstructured habitat is limiting the carrying capacity for survivorship at this critical stage in crab life history (Dumbauld et al. 1993)

TABLE 5

Selected references showing how habitat data can be used to determine effects on stocks and populations

Species/Community	*Data*
Herring (Haist et al. 1986)	Habitat area to estimate spawner biomass, using egg density and eggs/g female; forecast at t + 1 possible
Rockfish (Haldorson and Richards 1987)	Number of juveniles per 100 m of algae, kelp, and eelgrass
Juvenile salmon (McAllister and Brown, in press; Levings et al. 1983; Simenstad et al. 1991)	Carrying capacity limitation for wild chinook fry identified in an estuary; detrital food web well defined
Dungeness Crab (Dumbauld et al. 1993)	Substrate limitation; shoreline with eelgrass or shell/gravel showed enhanced capacity for settled crab larvae
Manila clams (Thompson and Cooke 1991)	Substrate limitation; shoreline with shell/gravel showed enhanced capacity for clam juveniles
Geoducks (Harbo et al. 1992; Noakes and Campbell 1992)	Substrate limitation; wood debris affected growth
Waterfowl and shorebirds (Mahaffy et al. this volume)	Direct reliance on vegetation (Brant, Snow Geese) or detrital-feeding invertebrates (e.g. shorebirds)

Hardshell clams

The post-veliger stages of hardshell clam drift onto intertidal or nearshore habitat and settle onto sand or gravel habitat. It has been found that placement of gravel on mudflats results in extremely high densities of clams. Reduction in predation on small clams on the gravel substrate can be achieved through the use of netting (Thompson and Cooke 1991).

Geoducks

This species of bivalve is adapted to both sand and mud habitats and is most abundant at depths <20 m in both the Strait of Georgia and Puget Sound (e.g. Harbo et al. 1992). Substrate conditions can limit the production of this species, as shown by the reduced growth of the species owing to log debris (Noakes and Campbell 1992).

SUMMARY AND CONCLUSIONS

Habitats have undergone substantial changes in the Georgia basin over the past hundred years. These changes are linked to alterations in biological resources including important salmon species, shellfish and a variety of birds, but many connections are not well understood. Although the region contains substantial amounts of unaltered habitat, major declines have occurred in river deltas where fish and birds spend considerable time feeding and rearing. While there has been considerable evaluation of the levels of toxic components in marine and estuarine sediments in the region, habitat loss has received substantially less attention as a source of impact to our biological resources.

We discovered several common goals based upon our review of habitat loss and restoration in the region. These goals require coordination and research efforts to satisfy. They are directed at better management of the existing habitats and resources, and on more effective restoration of these habitats. The recommendations are as follows:

1. Develop a common habitat classification. This scheme would help in the communication of results of research and monitoring efforts.
2. Develop common protocols for habitat assessment studies. Again, common methods for sampling would allow direct data comparison.
3. Develop a better understanding of habitat characteristics that may be key limiting factors to biological resources. There is a critical need to develop and refine quantitative measures of resource dependence on habitats. Models that link habitat variability with resource variability are especially needed.
4. Develop common restoration goals that can be used to plan restoration efforts that focus on resources that utilize both sides of the boundary.
5. Develop the technology of habitat restoration especially in the context of the landscape. Restoration efforts must rely on solid information on what works and will provide benefits to target resources.
6. Develop a better understanding of water, sediment and habitat quality variations. There is virtually no data at present regarding the effects of water and sediment quality on habitats for the region.
7. Develop a better understanding of the effects of global environmental change on habitats and the resources that utilize these habitats. There is a growing body of evidence indicating that changes in climate will significantly affect the region. We need to know what this will do to habitat distribution and function.
8. Implement a common monitoring plan that encompasses the entire region and allows assessment of changes in the habitats throughout the region.

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DISCUSSION

Tom Pedersen *(Panel)*: Of those nine types of habitat that you listed near the beginning, which one is the most vulnerable in your opinion, with particular respect to biodiversity.

Colin Levings: Eelgrass would be my bet at this point, based on its rather sensitive nature, importance to resource species, difficulty in restoration, and shortage.

Ron Thom: I agree with Colin. If you take a beach seine through an eelgrass bed you can pull up hundreds of species of fish and invertebrates. It's just amazing how productive and important it is. As I understand, shoreline developments affecting eelgrass are actually the Number One environmental issue facing the Seattle District Corps of Engineers and the Port Authorities.

Tom Pedersen *(Panel)*: My understanding is that there has been a lot of eelgrass colonization between the Tsawwassen ferry terminal and the Super Port. So are such things super ports in fact beneficial, in that they foster the growth of eelgrass beds, or are they detrimental?

Colin Levings: Well I think the Roberts Bank situation is a special case. In most cases the eelgrass beds are lost due to port development. But in that particular case, the Fraser River plume seemed to be affecting the eelgrass beds that were there before the port went in. Also some of that recolonization was *Zostera japonica*, so there was a species shift involved.

Richard Beamish *(Panel)*: Colin what do you think the impact has been where you've seen significant losses of habitat?

Colin Levings: I think the bird populations have probably suffered first of all. I'm not a bird biologist, but they are species that are tied very directly to the vegetation. As for fish species, some of the riparian habitat in some of the small streams may have been important for coho, for example.

Richard Beamish *(Panel)*: I have been hearing more and more people living around the Strait of Georgia report changes in the nearshore community — loss of, say, sea urchins, loss of plant life growing on rocks. I'm wondering whether or not that is something that you have heard, and something that you can associate with habitat loss.

Colin Levings: There's no doubt that the nearshore area is going to be the first reflection of these changes. If people are seeing gross changes, then there probably are changes. Because urchins are pretty ephemeral, I wouldn't want to rely on them totally as an indicator of man-induced change, but they probably are indicative of climatic changes. We have really good baseline data on algae from Gabriola Island from Ron Foreman's work in the early 70s. Since the most recent El Niño there has been very significant changes in algal species composition right around Gabriola Island.

Ron Thom: In some small urbanized embayments we've looked at, you can get very high nutrient concentrations in the water, in the streams and around the beaches. We've seen some blooms of *Ulva* on eelgrass which have basically wiped out the eelgrass, and then the *Ulva* gets so dense that it breaks off in the summertime, piles up on the beach and causes a tremendous odor problem.

John Armstrong *(Environmental Protection Agency)*: You mentioned restoration quite a few times in your recommendations, but I didn't hear you mention preservation at all. Restoration is costly and doesn't always work, but if you think we need restoration in some places, I assume you think we've exceeded acceptable losses in certain habitats. I'm wondering how important is preservation?

Colin Levings: A number of estuaries that we mentioned in the paper have been bought by conservation agencies, and you just can't mess around in them anymore. That obviously is the ultimate preservation. There are about half a dozen of them in the Strait of Georgia and there are some fairly large areas in the Fraser Estuary where the conservation agencies own property.

Bill Austin *(Khoyatan Marine Lab, Cowichan Bay)*: I think it is a public perception that there are unique flora and fauna here. A lot of us have mentioned unique flora and fauna in the Strait of Georgia in the past, but I haven't heard it at this symposium, I think maybe because some of us are loathe to speak of unique species. There are lots of species which have been described only

from the Strait of Georgia, or only from Puget Sound. I think we also need to look at those habitats which we perceive as rare or unusual, for example in the Strait of Georgia. My bias is sponge habitat which is only found elsewhere in shallow water in the Antarctic. There are other species which come in with that intermediate water in the Strait of Georgia, which otherwise occur only in deep water. There are very interesting things about the Strait of Georgia and Puget Sound, which if not unique, are very unusual and we need also to keep those things in mind.

Cheryl Niemi *(Washington Department of Ecology)*: It looked from the data that there were several wetland areas that were dependent on existing or restored habitat. What I am wondering is — for none, some, or all of those — do monitoring programs exist that look at whether those restoration projects are fulfilling the goals of the initial restoration, and if those monitoring programs exist, how well are they working? Are we actually getting what we thought we would get?

Colin Levings: Restoration should be monitored a long time to show whether it is effective. I was involved personally in what I think is the longest restoration evaluation program — at the Campbell River estuary. We evaluated it in detail for five years, and we concluded that it's probably between five and eight years before the plants, the bugs and the fish were doing things almost up to the same production rate as natural habitats. We didn't evaluate all the functions, which is a criticism of the study, but we did evaluate a number of them, such as the tidal production and food production and so on. People are still going there once a year and doing gross sort of inspections.

Cheryl Niemi *(Washington Department of Ecology)*: We worked a lot with salt marsh in the San Francisco Bay area, and it sometimes did take 10 or 15 years to set up the salt marsh communities. It seemed like you needed the vegetation before you got the critters. Are you seeing that type of thing?

Colin Levings: No, we actually saw invertebrates moving in within several hours of creation of the habitat and then as the plants developed the invertebrates colonized the plants. Colonization is dependent on individual life histories.

Ron Thom: You can make a marsh in a day, literally, by planting plants there, but to get it functioning to where the below-ground biomass is developed to the level of a natural marsh may take in the order of 80 years.

Michael Coon *(Ministry of Agriculture, Fish & Food)*: I led the province's seaweed program for about 12 years, and I have a comment for the Panel. You have to keep in mind that seaweed is a very diverse group of organisms. There are something like 650 taxa in British Columbia, many commonly shared in Georgia Strait and Puget Sound. They are highly variable in time and space. There has been very little work to give some sense of the normal range of variability of population structure. Even species and biomass change quite profoundly within a year and between years. Trying to get a handle on what changes might be caused by human activities, without knowing something about the normal scope of variability, is a fool's game, a really difficult thing to do. Some work has been done in California for instance. Fifty years after some initial very quantitative work was done on well-marked shoreline strips, somebody went back and found that just the impact of people going on the shoreline, in this case a rocky shoreline — a very popular place for residents and tourists to go down to — has reduced the species diversity by about 25%. This is something I guess we can look forward to in a negative kind of way, unless we have some form of public education that creates public awareness about these kind of things.

Laurie MacBride *(Save Georgia Strait Alliance)*: Somebody said during this question period that there have been incidents of *Ulva* blooms that wiped out eelgrass. That's a situation I've seen at a beach near Crofton where I remember going as a child. Even into my 20s there was eelgrass and lots of life on the beach. Returning there a few years ago, all I could see was the *Ulva* piled up on the beach. It looked horrible, it wasn't inviting at all. I'm wondering what causes *Ulva* blooms, and if there is any link between them and contaminants or nutrients. Is the bloom coming first to cause the change, or is some kind of pollution causing the bloom?

Ron Thom: The cause looks like nutrients in situations like embayments where nutrients get very low in the summertime. With a lot of light there, and a little bit of nutrients coming in from a stream, the *Ulva* grows really fast. You can get blades a meter by a meter very quickly and that will really do a lot of harm to the eelgrass.

Marine Pollution and Human Health: Current Status and Future Prospects

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ABSTRACT

The effects of land-based disposal practices and other human activities on marine environments may be predicted using knowledge of releases and transport/distribution processes, or observed through marine environmental quality surveys. Interpretation of such assessments regarding potential human health consequences of marine pollution requires knowledge of (or assumptions regarding) routes by which exposures occur on a population and subpopulation basis; toxic agents present and doses delivered via each route of exposure; and health effects associated with each dose for each kind of population exposed. Geography, season and human behavioral patterns (including the species of seafood consumed and method of preparation) are all known to significantly affect delivered dose. Uncertainty in many or all of these factors can mask distinctions between 'clean' and 'polluted' marine environments. Alternatively, direct investigation of human health outcomes related to marine pollution requires some knowledge of exposures and the presence of statistically detectable disease. This requirement limits the feasibility of detecting health effects from environmental contamination to instances of high contamination levels, or when large population studies are conducted. Given current mechanisms for attributing illness, human health monitoring is not a sensitive indicator of environmental degradation resulting from transboundary processes.

Based on the experience of the Puget Sound Ambient Monitoring program and of local and state health officials, we will consider whether there is a presently-discernible pattern of human illness, or a likelihood of significant disease in the Puget Sound area attributable to transboundary effects. Issues regarding distinguishing significant from insignificant health risks will be identified. We will also discuss potential improvements to the assessment process, and the prospects for significant future health impacts, based on improved assessment and on changes in environmental quality.

INTRODUCTION

The Panel has posed several questions related to the overall assessment of marine environmental quality, impacts and trends of transboundary effects of discharge practices and other activities. We have been asked to comment on the questions from a human health perspective, and have restated the relevant questions in two groups. The first four questions will be addressed in this paper:

1. For the populations using the Strait of Georgia, Juan de Fuca Strait, or Puget Sound, what evidence is

there of human health effects (i.e., disease) attributable to transboundary marine pollution or other anthropogenic influences?

2. Is human health a sensitive indicator of transboundary environmental effects?
3. What trends are expected for the future, assuming continued population growth, and current levels of pollution control?
4. What kinds of monitoring would be most useful in improving recognition of human health effects?

The last two questions must be deferred to the future or to environmental scientists studying transport, fate, and ecological effects:

5. What time trends are discernible over the past 5–10 years, based on observations of human health effects?
6. Among the discharge practices and other activities leading to transboundary effects, which specifically have the greatest potential to result in harm to human health?

At the outset, it must be acknowledged that these are broad-reaching and in many cases unanswerable questions. In the course of this discussion, we hope to convey a sense of the task represented by these questions, rather than to provide definitive answers. The implications of this analysis are important to the formation of policy regarding environmental management, as well as to development of specific strategies for monitoring or other surveillance. In this paper, we shall focus on chemical toxicants discharged to marine environments.

To begin with, here is a summary of our best judgments on these points:

- There is no discernible pattern of human illness attributable to transboundary effects, or to overall marine environmental (chemical) pollution from local and remote sources.
- Given current mechanisms for attributing illness, human health monitoring will not be a sensitive indicator of environmental degradation resulting from transboundary processes.
- Marine environmental monitoring results to date do not suggest a general human health problem arising from seafood contamination (probably the most important route of chronic exposure to marine contaminants).
- Certainty regarding the lack of health risk(s) is lowest in the following instances: agents not currently monitored, such as dioxins in Puget Sound; agents lacking toxicological criteria; specific population groups that have higher-than-average fish consumption rates and/or consume organ tissues, and/or harvest seafood in industrial embayments with greater contamination levels.
- Experience in other locales suggests that discharges to marine systems can result in disease or in conditions that represent a significant threat to public health (such as contamination of Minimata Bay in Japan, leading to toxic quantities of mercury in seafood). However, to the extent that 'trans-boundary' means 'remote', such dramatic levels of environmental impact as have accompanied past disease episodes are not currently probable.
- While it might be supposed that continued population growth, accompanied by no significant increases in pollution control or other remedial measures, will lead to increased public exposure and therefore increased health risk, other factors will probably play roles as great or greater in determining the need for increased management of transboundary effects. These factors include:
  - new and/or better data to discern effects, and predict impacts to environment or health;
  - changes in public and regulatory attitudes regarding acceptable risks;
  - competing needs to safeguard or improve public health (allocation of resources);
  - other reasons for protecting marine environmental quality.

DEFINING PUBLIC HEALTH RISKS FROM ENVIRONMENTAL CONTAMINATION

Health-Based Approach

Figure 1 is probably familiar to many readers; it is adapted from an article on biological markers by Dr. Frederica Perera (1982). This conceptual framework illustrates the theoretical linkages between release to the

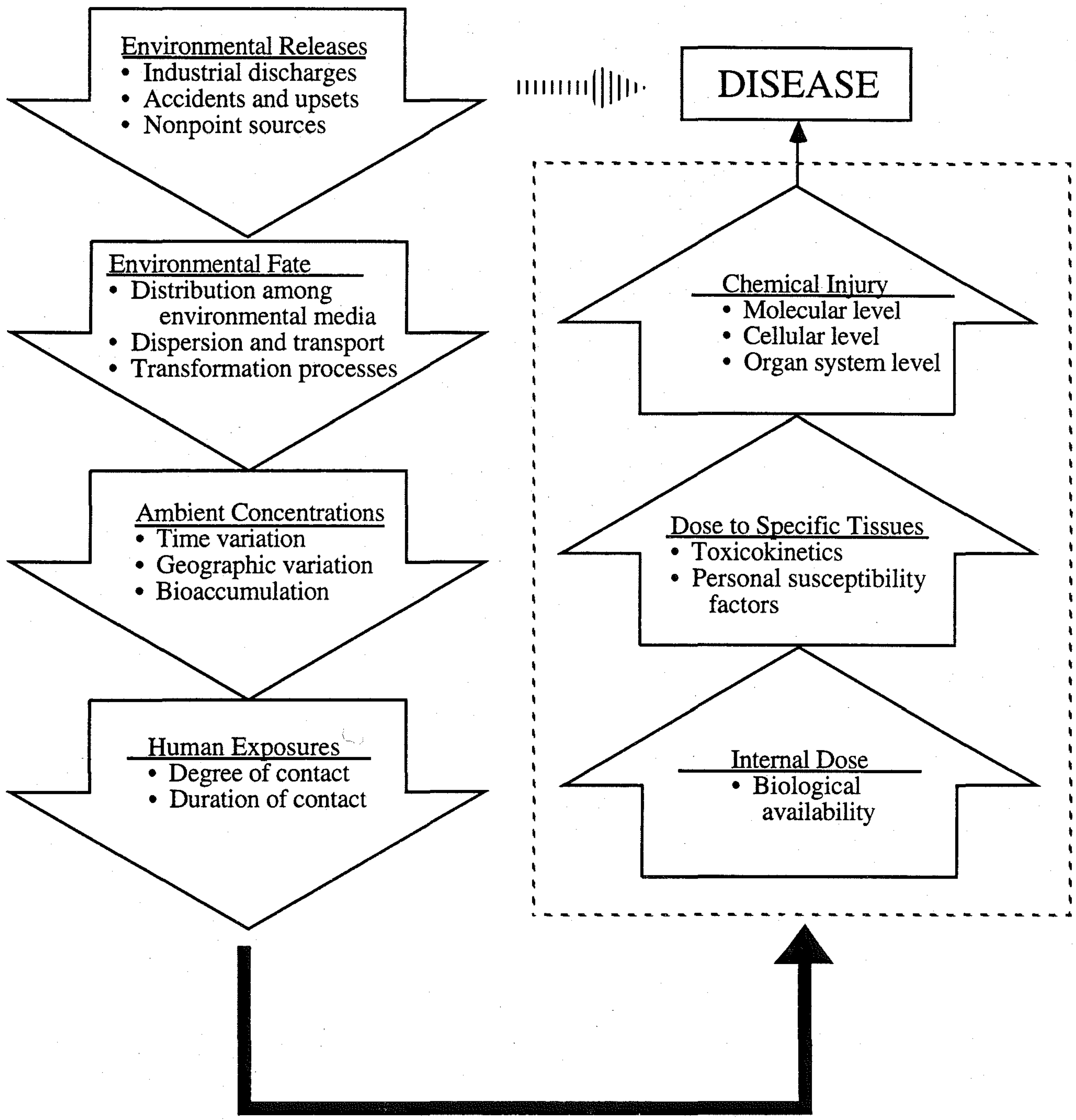

Figure 1. Schematic of pollutant release, transport, environmental exposure, and resulting disease. (Adapted from Perera 1982).

environment of toxic chemicals and the ultimate manifestation of human disease. It provides a qualitative human health rationale for control of process chemistry and emissions, disposal practices, and environmental protection. As a single example, US regulatory decisions curtailing the use of lead as a catalyst in gasoline clearly aimed to reduce environmental levels of lead, thereby reducing environmental exposures to the general population, and upon implementation were followed by demonstrated reductions in human body burdens of lead. Analysis of the contribution of a specific source of lead to the multiple sources leading to public exposures was the basis for determining the probable efficacy of the lead-reduction strategy, and also played a role in determining new permissible lead use.

From this scheme, a logical connection may be inferred between environmental changes or degradation such as loss of species diversity in benthic communities, and the prospect of human exposures leading to disease. Despite the contrary example of lead in gasoline, this model is often **not** very useful as a basis for evaluating severity of public health impacts, or even whether such impacts are occurring. Establishing quantitative relationships among the amount of a toxic agent observed as source emissions, its level in environmental compartments, ultimately its dose to human receptors, (and then predicting subsequent physiological events) requires detailed information that is usually lacking. Such relationships are significantly affected by environmental conditions, human behavior, and biological variability. Predictions of disease or health effects based on environmental release, fate and transport models, are therefore highly uncertain, perhaps more so in the context of marine environments than (for example) in the case of health effects resulting from local discharges to air.

Alternatively, public health agencies must act on a demonstrated or likely significant health risk. Therefore, it is more appropriate to view the sequence of steps in Figure 1 backwards, and to consider the ultimate endpoint (observed disease) first, and then to back away from this result one step at a time in looking for indicators of adverse impacts. Marine environment-related disease might be detected as the result of epidemiological studies (usually based on a specific disease hypothesis), or through reports from physicians or clinics. For the latter, the ability to recognize an increase in disease and to attribute it to marine environmental exposure will depend on the 'signal-to-noise' (that is, elevation-to-background incidence) character of the outbreak. Unless the particular disease is unusual and consequential, recognition would depend on a dramatic increase in incidence.

In the absence of an observable outbreak of disease, public health effects may be assessed given knowledge of **doses** of toxic agents or pathogens, and information relating dose to illness. Barring spills or events carrying a risk of acute intoxication, assessment of environmental health risks is far more uncertain than is the measurement of environmental contamination. Doses to humans of marine contaminants are not directly measurable, but can be estimated using knowledge of environmental contaminant concentrations and by making assumptions regarding exposures to the marine environment.

Interpretation of environmental monitoring data in terms of public health significance requires:

1. Consideration of possible or likely routes by which individuals may be exposed to marine environmental media (such as surface water, sediments, biota). According to several previous analyses (Tetra Tech 1988; Humphrey 1987; Lipton and Gillet 1991), consumption of contaminated fish or shellfish will be the major route, although exposure via direct contact with water or sediment, or inhalation of marine aerosols are also theoretically possible.

   In the rest of this paper, we will make the general assumption that ingestion via seafood is the most important route of chronic exposure, and that other routes of exposure will not be significant contributors to health risk. This assumption is justified by the low chronic contact rate for other routes and by the bioaccumulation potential in edible tissue for many of the contaminants of key concern (Di Toro et al. 1991; Murdock 1992; Lake et al. 1990).

2. Reliable (statistically-based) descriptions of toxicant loadings in the relevant marine environmental compartments. Despite the relative intensity of monitoring in Puget Sound, the large number of variables that can/do significantly alter environmental concentrations in many cases leads to order-of-magnitude uncertainties. For example, spatial distributions of chemical contaminants are frequently highly

patchy and variable, particularly in areas of deposition. Physical transport phenomena and compartmental inhomogeneity also cause levels in the water column or surface microlayer to vary. Tissue concentrations of toxic chemicals may vary with species and tissue sampled, age of specimen, or according to the natural cycle of that species. The consequence of these considerations is that environmental concentrations are estimated as statistical distributions that can vary according to the assumptions made about these and other environmental variables.

Collection strategies for Puget Sound monitoring of marine tissues are based on significance to human consumers of fish and shellfish (PSAMP 1991; 1992). Collection sites do not necessarily represent the 'highest impact' (i.e., most contaminated) locations, but are intended to represent those species, tissues and locations with the greatest potential for public consumption of pollutants.

Evaluation of tissue concentrations of contaminants is frequently confounded by low levels and high detection limits, and by historical and widespread environmental contamination that makes recognition of either time-trends or source-contributions difficult. One useful document that compiles fish tissue contaminant levels for the US is the two-volume report *National Study of Chemical Residues in Fish* (US EPA 1992a). This document provides a cross-section of contaminant levels in fillet tissues, and a screening-level cancer risk calculation for 362 coastal and freshwater locations in the United States. Most sites were represented by a single species/fillet sample.

3. Contact rates or quantities of tissue(s) consumed. Good data describing population fish consumption rates have historically been lacking. In formulating such descriptions, one would need to consider the particular species being consumed, the part of the fish/shellfish, method of preparation, the quantity eaten, and the source of the fish/shellfish (Landolt et al. 1985; 1987). Definition of populations of concern and variations in consumption patterns might easily produce orders-of-magnitude differences in dose estimate. For example, a hypothetical 'average' individual might eat salmon and cod muscle fillets obtained from commercial sources, prepare the fish by baking, barbecuing, or frying, and might consume 6.5 grams per day on average — the US population average level supported by EPA (1992a). A hypothetical 'most exposed' individual might eat mainly bottomfish and shellfish (including species not considered edible by other ethnic groups) obtained by shoreside fishing and collecting in a relatively polluted urban location. The fish might be cooked into a stew or sauce, with all tissues being consumed. This individual might rely on fish exclusively for meat, consuming up to hundreds of grams per day. Given the diversity of consumption practices, available data indicate that large differences in exposures might be experienced by individuals contacting the same marine environment simply because one is consuming black cod filet and the other's diet includes crab hepatopancreas. For the purposes of approximating a probable worst-case-exposure, we will assume chronic consumption of 140 grams of fish per day or 18 grams of shellfish per day, the 90th percentile value determined by EPA for recreational fishermen and shellfish consumers. However, for specific groups that may consume higher fish quantities or more polluted organ tissues, higher chemical intakes would result. Data to address these special situations is largely lacking at present.

Several recent efforts to better define fish consumption rates in order to arrive at dose estimates and health risk estimates are worth noting. In an effort to collect information on how different states issue bans or advisories on shellfish and finfish consumption, the US Environmental Protection Agency (EPA) sponsored a 1990 international symposium entitled Creel and Angler Surveys in Fisheries Management, aimed at better methods for collecting information on anglers. The proceedings were published in 1991 (Guthrie et al. 1991). The EPA has organized peer review of 18 studies of consumption surveys, has issued recommendations for how these are to be conducted (US EPA 1992b) along with information regarding costs and options, and has produced a guidance manual for assessing risks associated with consumption of chemically contaminated seafood (EPA 1989). Finally, EPA has formed a Fish Consumption Risk Management Special Interest Group within its Nonpoint Source Information Exchange Bulletin Board System (US EPA 1992c), that permits dial-in access to an electronic

database that indexes fish consumption bans and advisories, consumption surveys, and related reports or announcements. These efforts may lead to more consistent procedures and criteria for defining public health risk from consumption of contaminated fish, but at present they are still developing. As populations that have particularly high consumption rates and/or potentially higher exposures due to consumption practices are identified, targeted studies of consumption and seafood toxicant levels will probably be required to reliably estimate health risks. Among the current local efforts is an EPA-sponsored study of fish consumption rates of the Tulalip and Squaxin tribes.

4. Dose-response information. In the absence of concentrations high enough to invoke acute toxicity (such an absence would probably be true for environmental exposures, and from transboundary sources particularly), chronic, low-level exposure outcomes would be considered. Carcinogens, cumulative neurotoxic agents and teratogens would be of particular concern. Generation and application of dose-response estimates for environmental levels of carcinogens is one of the more controversial aspects of the EPA risk assessment approach. While a complete discussion of sources and magnitude of uncertainties arising from dose-response estimation is not feasible within this paper, a short list of example issues would include the fact that cancer-potency factors are most commonly generated from (genetically homogenous and uniformly in good health) animals given high relative doses for short intervals, and are then in risk assessment calculations applied to (genetically and conditionally diverse) humans receiving very low doses over long-term exposures. Because of these factors, many experts argue that risk assessment calculations systematically overestimate actual risks (US EPA in agency preface to Tetra Tech 1988).

As a result of this evaluation process, an estimate of population health risks arising from marine pollution might be undertaken. The findings of such an evaluation would apply to remote or transboundary sources only if that source's contribution to overall contamination were known. This is unlikely to be the case, unless (a) the transboundary source is nearby and/or dominant, or (b) the transboundary source is the unique source for a given pollutant. While there may be specific instances that fit these criteria (Tijuana River sewage discharges come to mind), it is not obvious that this would be true in Puget Sound or the Strait of Georgia. Other papers presented at this symposium will, hopefully, illuminate this question, but our expectation is that clear definition of relative impacts or quantitative contributions of pollutant chemicals from transboundary sources versus other sources will in most cases be highly uncertain at best.

Environmental Contamination Data: 'Greater' Puget Sound

In Puget Sound and contiguous waters, environmental monitoring has been ongoing since the mid-1970s, initially by NOAA and academic researchers (Malins et al. 1980; 1982; Pavlou and Hom 1979) and currently by a consortium of Washington State agencies coordinated by the Puget Sound Water Quality Authority (PSAMP 1991; 1992). Similar programs and reports have been conducted in Canada by Environment Canada (Environment Canada 1984, 1987, 1989, 1993). These programs have documented the occurrence of anthropogenic chemicals in sediments, water column, and marine biota. In specific locations (typically industrial/urban embayments) ecological changes indicative of toxicity to multiple marine species have been noted.

Two programs within PSAMP (Puget Sound Ambient Monitoring Program) specifically monitor edible tissue contaminant levels. The Washington Department of Fisheries surveys finfish on an annual basis, and the Washington Department of Health monitors clam tissue. The summary of target compounds addressed by these surveys is shown in Table 1, and Figure 2 depicts the shellfish sampling locations as of 1992/93. It is worth noting that the compounds routinely monitored in Puget Sound fish and shellfish tissues do not include several groups of chemicals known to have sources in Puget Sound or in industries common to the Pacific Northwest. Chlorinated dibenzo-p-dioxins and dibenzofurans found in pulp and paper effluents; alkyltin compounds used in antifouling paints and coatings, and chlorinated aromatic compounds produced in bleaching operations are a few examples. While some data have been collected describing marine levels of these agents, there are few or no data to address human exposures via marine contamination.

It is virtually certain that the chemical concentrations detected by PSAMP monitoring far exceed in magnitude the incremental contributions from remote sources including transboundary sources. Setting aside for the moment the question of attribution of contamination to remote transboundary sources versus local sources, what health implications can we project from ambient marine environmental quality data from Puget Sound, regardless of pollutant source?

HUMAN HEALTH IMPLICATIONS OF PUGET SOUND MONITORING DATA

Table 2 summarizes the levels of pollutants detected in edible tissue in Puget Sound fish and shellfish. Liver samples assayed for English sole are excluded from this summary, but are typically several times higher in PCBs and chlorinated pesticides such as p,p′-DDE than related muscle tissue. While our ability to establish a causal relationship between pollutant loadings and human illness is elementary at best because of limitations in the required information as discussed above, the US EPA risk assessment methodology is a useful initial approach for assessing upper-bound human health risks associated with chemical exposures.

THE EPA RISK ASSESSMENT APPROACH

The overall process of estimation of health risk from environmental monitoring data has been formalized by EPA in its quantitative risk assessment methodology. EPA defines risk assessment as a scientifically based procedure to estimate the probability of adverse health effects associated with exposure to a specific toxic agent (EPA 1989). Risk assessment, however, is only one aspect of risk analysis, which also includes risk management. Risk assessment results cannot be conveyed as a single value, due to the need for qualifiers, explanations and caveats arising from assumptions made and uncertainties in the data used. Risk assessment focuses on scientific issues within the constraints of the prescribed methodology, while risk management allows for the consideration and incorporation of additional technical, socioeconomic and public health information (Figure 3). The product of the risk analysis may then be used by local authorities, for example as the basis for issuing public health advisories related to local fisheries.

EPA risk assessment methods have been well-documented (US EPA 1993, 1987b, 1986a-f; National Research Council 1983). Specific guidance documents regarding the use of risk assessment for determination of potential human health risk associated with the consumption of fish and shellfish have been prepared (US EPA 1989, 1993). Assessment of the risks associated with the consumption of contaminated seafood consists of three elements within which the necessary scientific information is grouped:

1. Hazard identification: the review of available chemical-specific data to address the question, "Does this chemical pose a threat to human health?"

TABLE 1

Compounds monitored in fish and shellfish PSAMP tissue samples.
(9 data sets, 105 compounds)

#	*Contaminant class*	*Example*	*Tissue detection limits (ppb wet weight)* Minimum	*Median*
17	Polynuclear aromatic hydrocarbons	pyrene	3	6
15	Phenol and substituted phenols	pentachlorophenol	4	30
6	Phthalate esters	dibutyl phthalate	4	10
4	Other oxygenated compounds	benzoic acid	3	24
9	Chlorinated hydrocarbons	hexachlorobenzene	3	19
5	Halo-ethers	bis(2-chloroethyl) ether	4	27
15	N-containing compounds	dimethylnitrosamine	3	20
20	Organo-chlorine pesticides	dieldrin	0.1	0.5
8	PCBs, toxaphene	Aroclor 1260	1	8
4–6	Metals	mercury	4	30

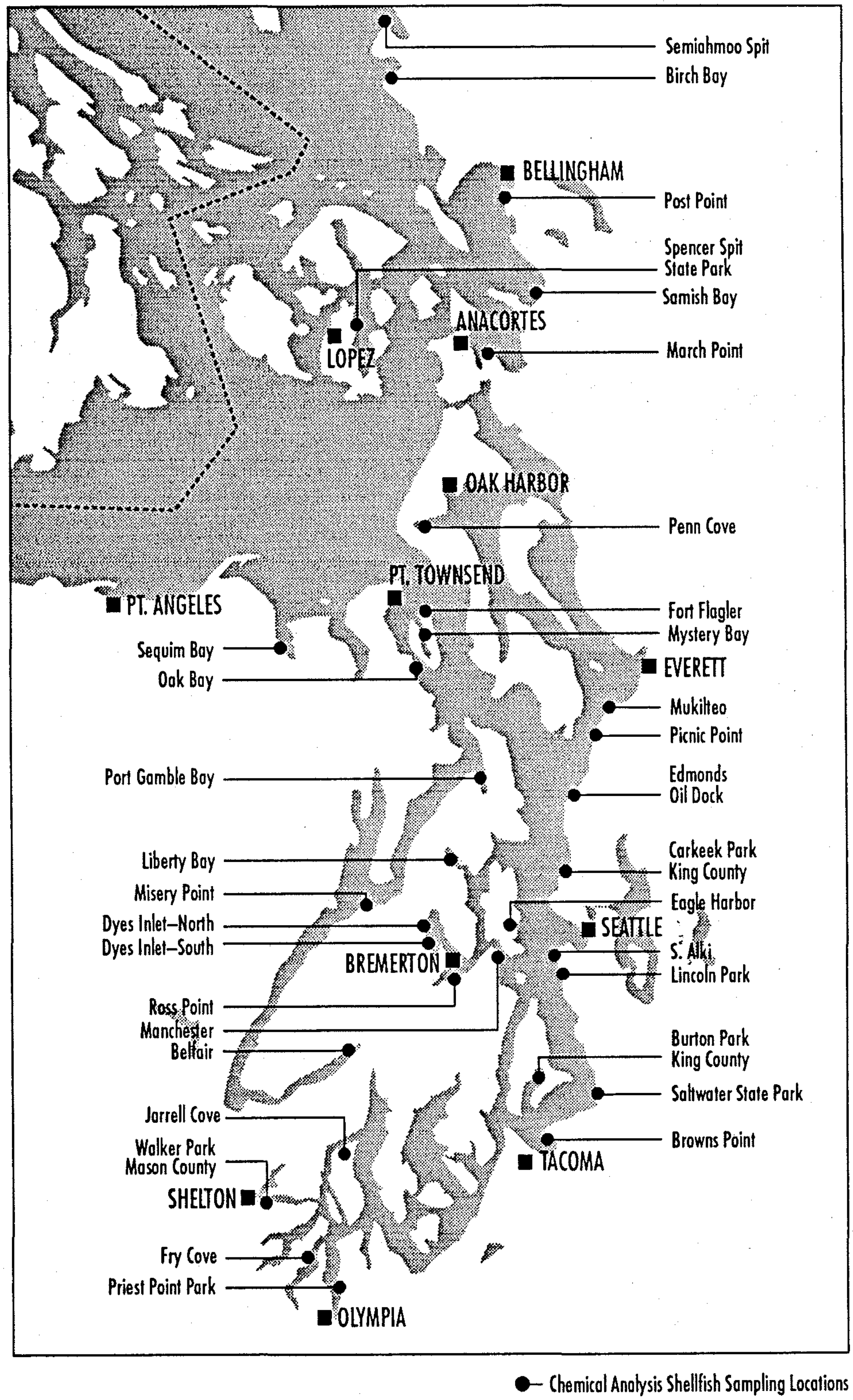

Figure 2. 1990–1993 Puget Sound Ambient Monitoring Program (PSAMP) shellfish sample locations for chemical analysis.

Table 2 Levels of pollutants detected in Puget Sound fish and shellfish PSAMP tissue surveys

Species	Clams	Sole	Cod	Rockfish	Salmon	all	highest
Collection years	1991/93	1991/92	1992/93	1991/92	1992	species	level
Total samples	148	107	28	61	75	419	found
Compound	--------------number of positive samples-----------					detection rate	wet ppb
benzoic acid	143	38				0.432	8800
Aroclor 1260		59	2	25	55	0.337	65
di-iso-octyl phthalate	48	37	3	22	18	0.305	5350
Aroclor 1254		47			75	0.291	120
p,p'-DDE		24		11	75	0.263	45
p,p'-DDD		6			74	0.191	6
benzyl alcohol	11	50				0.146	68
alpha-BHC					60	0.143	4
dibutylphthalate	48	12				0.143	1522
dieldrin				3	55	0.138	3
p,p'-DDT	1				35	0.086	8
butyl,benzyl phthalate	22	1				0.055	220
2-methylphenol	21					0.050	150
lindane					12	0.029	1
diethyl phthalate	8					0.019	8
fluoranthene	6					0.014	54
phenanthrene	3					0.007	3
Aroclor 1248		3				0.007	22
phenol		2				0.005	29
pyrene	1					0.002	22
isophorone		1				0.002	21
Endosulfan 1	1					0.002	0.7
endosulfan II	1					0.002	0.8
arsenic	148	107	28	61	75	1.000	14000
copper	148	107	28	61	75	1.000	1100
mercury	145	107	28	61	75	0.993	510
lead	148	13	1		2	0.391	1200
cadmium	148					1.000	390
zinc	148					1.000	19000

Figure 3. Elements of risk assessment and risk management. (From National Academy of Sciences 1993).

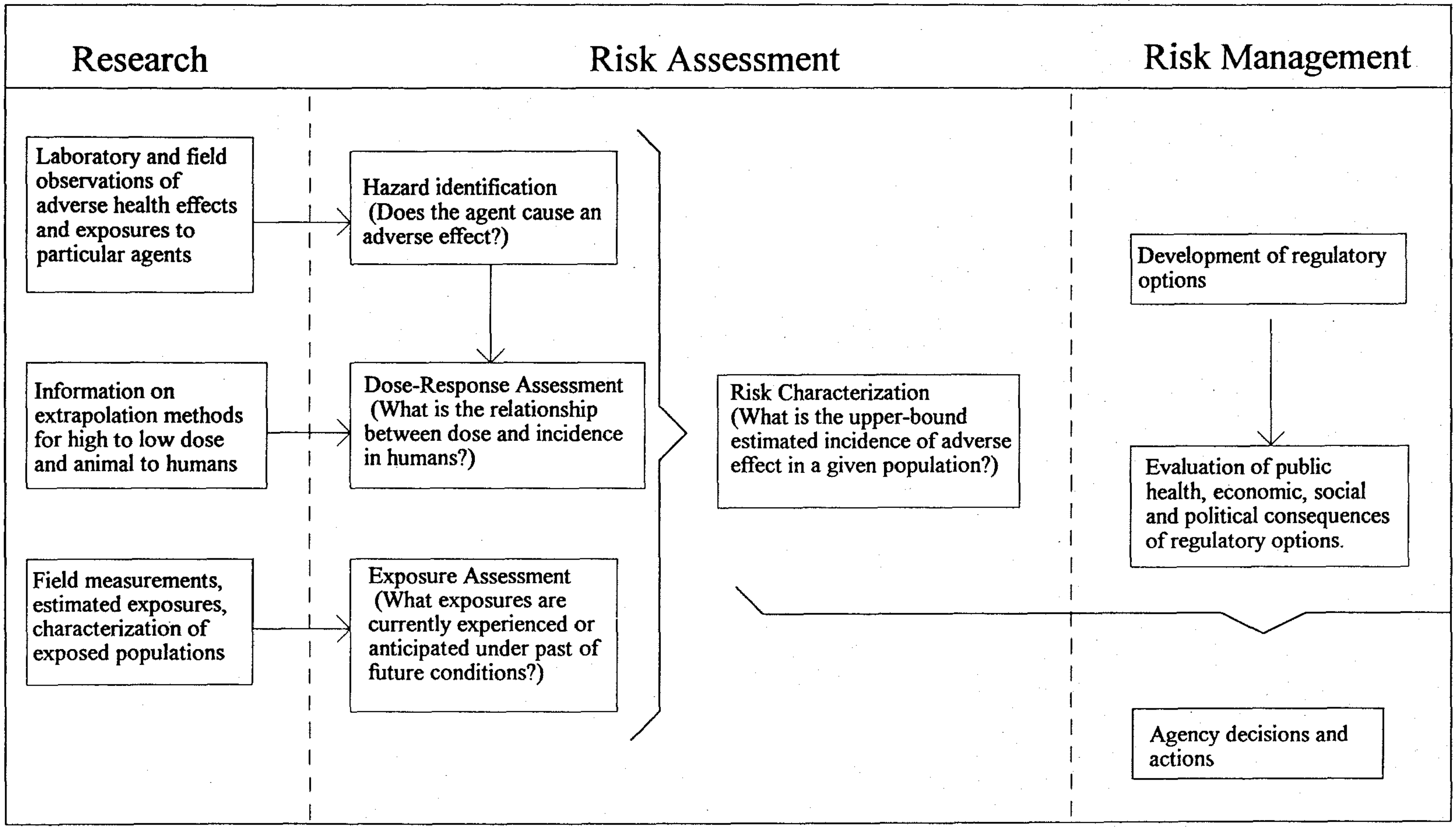

Figure 3. Elements of Risk Assessment and Risk Management

(From: National Academy of Sciences [NAS], 1983

2. Dose-response assessment: determination of the quantitative relationship between a chemical dose or exposure and an observed response. Results from dose-response assessments, stated in terms of slope factor (SF) for suspected carcinogens and reference dose (RFD) for non-carcinogens, along with the respective assessment background documentation and caveats, are available from the Integrated Risk Information System (IRIS) (US EPA 1987a).

3. Assessment of human exposure: involves the quantitative characterization of the magnitude, frequency and duration of human exposure, as well as identification of the population of concern, environmental pathways and exposure routes. Pertaining specifically to the aquatic environment, exposure assessment primarily involves the consumption of fish or shellfish. Initial characterization requires determination of the level of chemical contamination on a species- and site-specific basis. Contaminant concentration data is then combined with population exposure data to determine a chronic daily intake (CDI) for the population of concern.

Figure 4 illustrates the computational form of this approach.

Before human health impacts could be assessed, additional information beyond risk-calculation results would need to be considered, including: chemical form and species (of metals); the mean or median tissue chemical concentration as opposed to the maximum reported concentration; the significance of seafood consumption as an exposure source relative to other sources; regulatory limits established by other agencies; and the health benefits associated with seafood consumption aside from the potential health hazards associated with contamination.

Differing Views of Health-Based Acceptability Criteria

Application of population-based risk estimates to specific exposure situations is made more complex by coexisting contaminant or exposure criteria that differ in both approach and in tolerance level. Criteria values may (do) vary by orders of magnitude, even in some instances when based on the same scientific data (Reinert et al. 1991). These criteria differences may result from differing interpretation of the scientific data, differing assumptions regarding intake or other exposure indices, or even differences in agency policy or legal mandate(s) regarding the tests to be applied and the factors to be balanced in prescribing a tolerance level. Examples are:

- The US EPA fish tissue concentration screening values, which are health-based chemical concentration tolerance levels for fish (fillet) tissue, calculated assuming 6.5 g/day intake by a 70 kg individual);
- The US Food and Drug Administration (FDA 1987) 'action levels' governing tolerance levels in commercially grown/harvested and exported foods, which balance protection of public health with economic interests;
- A threshold calculated specifically from carcinogenicity risk, using EPA assumptions for chronic daily intake (Equation [1], Figure 4) and carcinogenic potency, with the tolerance level defined as equivalent to 1×10^{-5} lifetime incremental cancer risk.

The differences in these criteria are illustrated in Table 3 for three chemicals: inorganic mercury, DDT, and PCBs.

TABLE 3

Comparison of health-based recommended maximum consumable fish tissue concentrations for Mercury, DDT, and PCBs

Chemical	*Units*	*EPA (US EPA 1993)*	*FDA (US FDA 1987)*	*Risk Calculation*[a]
Mercury	mg/kg	0.6	1.0	0.2
4,4'-DDT	μg/kg	300	5000	10
PCBs	μg/kg	10	2000	0.6

[a] Equivalent to 10^{-5} incremental lifetime cancer risk, calculated from Equations (1) and (2), Figure 4.

The following equation is used to estimate chronic daily intake (CDI) from the consumption of chemically contaminated fish:

$$CDIijk = TCijk * ABi * IRj * ED * UCF1 / BW * AT * UCF2 \quad (1)$$

Where:

CDIijk	=	Chronic daily intake of chemical "i" from consumption of species "j" from location "k" (mg/kg/day)
TC_{ijk}	=	Tissue concentration of chemical "i" in species "j" from location "k" (mg/kg)
ABi	=	Absorption efficiency of chemical "i" (unitless)
IR_j	=	Ingestion rate of species "j" for population of concern (g/day)
ED	=	Exposure duration (70 years) (US EPA 1991)
UCF1	=	Unit Conversion factor 1 (0.001 mg/µg) for organic concentrations expressed as µg/kg
UCF_2	=	Unit conversion factor 2 (1000 g/kg)
BW	=	Body weight (70 kg) (US EPA 1991)
AT	=	Exposure averaging time (70 years) (US EPA 1991)

Conclusions for carcinogens are expressed in terms of risk (i.e. the upper-bound probability of additional cancers) where 10^{-3} to 10^{-6} risks are generally considered tolerable. Risk is quantified using the following general equation:

$$\text{Cancer Risk}_{ijk} = CDI_i * SFi \quad (2)$$

Where:

Cancer Risk	=	The potential carcinogenic risk associated with exposure to chemical "i" in species "j" from location "k" (unitless)
CDI_{ijk}	=	See above description (mg/kg/day)
SF_i	=	Slope factor for chemical "i" $(mg/kg/day)^{-1}$

The potential for hazard from exposure to non-carcinogens is assessed by comparing the calculated CDI to the chemical specific RFD. Exceedence of the RFD indicates that a potential human health hazard may exist. The CDI and RFD can be compared by the following equation:

$$CDI_i / RFD_i \quad (3)$$

Where:

CDI_{ijk}	=	See above description (mg/kg/day)
RFD_i	=	Reference dose for chemical "i" (mg/kg/day)

Figure 4. US Environmental Protection Agency risk calculations.

Table 4: Calculation of Chronic Daily Intakes For Maximum Reported Chemical Concentrations In Fish and Shellfish (PSAMP, 1990–93)

						Exposure Assumptions					
Chemical	Species	Location	Year	Units (Wet Wt.)	Max. Tissue Conc.	Body Wt.(kg)	Absorb. Coef.	IR (a) (g/day)	ED (years)	AT (years)	CDI (mg/kg/day)
Lead	Cod	AO	1993	mg/kg	0.08	70	1	140	70	70	1.60E–04
Arsenic	E. Sole	Sinclair Inlet	1992	mg/kg	14	70	1	140	70	70	2.80E–02
Benzoic Acid	E. Sole	Comm. Bay	1991	ug/kg	384	70	1	140	70	70	7.68E–04
Benzyl–OH	E. Sole	PG	1991	ug/kg	68	70	1	140	70	70	1.36E–04
Butylbenzyl phthalate	E. Sole	Liberty Bay	1992	ug/kg	220	70	1	140	70	70	4.40E–04
Dibenzyl phthalate	E. Sole	Bellingham	1992	ug/kg	90	70	1	140	70	70	1.80E–04
Isophorone	E. Sole	Shilshole Bay	1991	ug/kg	21	70	1	140	70	70	4.20E–05
Phenol	E. Sole	Mac Arthur Bk.	1991	ug/kg	29	70	1	140	70	70	5.80E–05
Arsenic	NL Clam	Manchester SP.	1993	mg/kg	3.2	70	1	18	70	70	8.23E–04
Cadmium	NL Clam	Semiahmoo	1993	mg/kg	0.39	70	1	18	70	70	1.00E–04
Copper	NL Clam	Eagle H.	1993	mg/kg	3.2	70	1	18	70	70	8.23E–04
Lead	NL Clam	Eagle H.	1992	mg/kg	1.2	70	1	18	70	70	3.09E–04
Mercury	NL Clam	Eagle H.	1993	mg/kg	0.08	70	1	18	70	70	2.06E–05
Zinc	NL Clam	Ross Pt.	1993	mg/kg	19	70	1	18	70	70	4.89E–03
Benzoic Acid	NL Clam	Eagle H.	1992	ug/kg	8800	70	1	18	70	70	2.26E–03
Benzyl–OH	NL Clam	Jarrell Cv.	1992	ug/kg	2900	70	1	18	70	70	7.46E–04
Bis(2–ethylhexyl	NL Clam	Edmonds OD.	1992	ug/kg	2411	70	1	18	70	70	6.20E–04
Butyl benzyl phthalat	NL Clam	Walker Pk.	1992	ug/kg	130	70	1	18	70	70	3.34E–05
Diethylphthalate	NL Clam	Priest Pt.	1991	ug/kg	8.4	70	1	18	70	70	2.16E–06
Di–n–butyl phth	NL Clam	Liberty Bay	1992	ug/kg	1492	70	1	18	70	70	3.84E–04
Fluoranthene	NL Clam	Eagle H.	1992	ug/kg	54	70	1	18	70	70	1.39E–05
Phenanthrene	NL Clam	March Pt.	1990	ug/kg	20	70	1	18	70	70	5.14E–06
Pyrene	NL Clam	Eagle H.	1992	ug/kg	22	70	1	18	70	70	5.66E–06
Endosulfan I	NL Clam	Post Pt.	1991	ug/kg p	0.82	70	1	18	70	70	2.11E–07
Endosulfan II	NL Clam	Carkeek Pk.	1991	ug/kg p	0.14	70	1	18	70	70	3.60E–08
p,p'–DDE	NL Clam	Lincoln Pk.	1990	ug/kg p	3	70	1	18	70	70	7.71E–07
p,p'–DDT	NL Clam	Spencer Spt.	1991	ug/kg p	0.74	70	1	18	70	70	1.90E–07
Copper	Rockfish	Double Bluff	1991	mg/kg	1.1	70	1	140	70	70	2.20E–03
Mercury	Rockfish	San Juan	1992	mg/kg	0.51	70	1	140	70	70	1.02E–03
p,p'–DDE	Rockfish	Blakely Rock	1992	ug/kg	5.7	70	1	140	70	70	1.14E–05
Aroclor 54/60	Salmon	Budd Inlet	1992	ug/kg	177	70	1	140	70	70	3.54E–04
Bis(2–ethylhexyl	Salmon	Duwamish	1992	ug/kg	5350	70	1	140	70	70	1.07E–02
a–BHC	Salmon	Apple Cove Pt.	1992	ug/kg p	3.8	70	1	140	70	70	7.60E–06
Dieldrin	Salmon	Apple Cove Pt.	1992	ug/kg p	2.7	70	1	140	70	70	5.40E–06
Lindane	Salmon	Apple Cove Pt.	1992	ug/kg p	2.7	70	1	140	70	70	5.40E–06
T–DDT ^	Salmon	Budd Inlet	1992	ug/kg p	58.8	70	1	140	70	70	1.18E–04

^ – T–DDT = Sum of p,p'–DDD, p,p'–DDE and p,p'–DDT Concentrations

(a) – Ingestion Rate (IR) of 140 g/day represents 90th percentile of recreation fishermen (i.e., subsistence fishermen) (U.S. EPA, 1990). Shellfish IR of 18 g/day represents the 90th percentile for shellfish consumers (U.S. FDA, 1993).

Table 5: Calculation of Upper–Bound Risk and Hazard From Maximum Reported Chemical Concentrations In Fish and Shellfish (PSAMP, 1990–93)

			Carcinogenic Risk (Upper Bound)		Non–carcinogenic		
Chemical	Species	CDI (mg/kg/day)	SF (mg/kg/d)	Risk	RFD (mg/kg/day)		Potential Hazard
Benzoic Acid	E. Sole	7.68E–04	N/A	––	4.00E+00	1	No
Benzyl–OH	E. Sole	1.36E–04	N/A	––	3.00E–02	1	No
Butylbenzyl phthalateE. Sole		4.40E–04	N/A	––	2.00E–01	1	No
Dibenzyl phthalate	E. Sole	1.80E–04	N/A	––	1.00E–01	1	No
Phenol	E. Sole	5.80E–05	N/A	––	6.00E–01	1	No
Cadmium	NL Clam	1.00E–04	N/A	––	1.00E–03	1	No
Copper	NL Clam	8.23E–04	N/A	––	4.00E–02	3	No
Mercury	NL Clam	2.06E–05	N/A	––	3.00E–04	1	No
Zinc	NL Clam	4.89E–03	N/A	––	3.00E–01	1	No
Benzoic Acid	NL Clam	2.26E–03	N/A	––	4.00E+00	1	No
Benzyl–OH	NL Clam	7.46E–04	N/A	––	3.00E–02	1	No
Butyl benzyl phthalatNL Clam		3.34E–05	N/A	––	2.00E–01	1	No
Diethylphthalate	NL Clam	2.16E–06	N/A	––	8.00E–01	1	No
Di–n–butyl phth	NL Clam	3.84E–04	N/A	––	1.00E–01	1	No
Fluoranthene	NL Clam	1.39E–05	N/A	––	4.00E–02	1	No
Phenanthrene	NL Clam	5.14E–06	N/A	––	3.00E–02	2	No
Pyrene	NL Clam	5.66E–06	N/A	––	3.00E–02	1	No
Endosulfan I	NL Clam	2.11E–07	N/A	––	5.00E–05	1	No
Endosulfan II	NL Clam	3.60E–08	N/A	––	5.00E–05	1	No
Copper	Rockfish	2.20E–03	N/A	––	4.00E–02	3	No
Arsenic	E. Sole	2.80E–02	N/A	––	3.00E–04	1	Yes
Arsenic	NL Clam	8.23E–04	N/A	––	3.00E–04	1	Yes
Mercury	Rockfish	1.02E–03	N/A	––	3.00E–04	1	Yes
Lead	NL Clam	3.09E–04	N/A	––	N/A		––
Lead	Cod	1.60E–04	N/A	––	N/A		––
p,p'–DDT	NL Clam	1.90E–07	3.40E–01 a	6.47E–08	5.00E–04	1	No
Isophorone	E. Sole	4.20E–05	4.10E–03 a	1.72E–07	2.00E–01	1	No
4,4–DDE	NL Clam	7.71E–07	3.40E–01 a	2.62E–07	5.00E–04	1	No
p,p'–DDE	Rockfish	1.14E–05	3.40E–01 a	3.88E–06	5.00E–04	1	No
Lindane	Salmon	5.40E–06	1.30E+00 b	7.02E–06	3.00E–04	1	No
Bis(2–ethylhexyl	NL Clam	6.20E–04	1.40E–02 a	8.68E–06	2.00E–02	1	No
T–DDT ^	Salmon	1.18E–04	3.40E–01 a	4.00E–05	5.00E–04	1	No
a–BHC	Salmon	7.60E–06	6.30E+00 a	4.79E–05	N/A		––
Dieldrin	Salmon	5.40E–06	1.60E+01 a	8.64E–05	5.00E–05	1	No
Bis(2–ethylhexyl	Salmon	1.07E–02	1.40E–02 a	1.50E–04	2.00E–02	1	No
Aroclor 54/60	Salmon	3.54E–04	7.70E+00 a	2.73E–03	N/A		––

N/A – RFD or CPF Value Not Available

a – SFs From EPA IRIS Database

b – SFs From Hst Tables

1 – RFD from EPA IRIS Database

2 – RFD from EPA IRIS Database, (Dec. 90)

3 – RFD Value for Copper Calculated From Drinking Water Standard of 1.3 mg/l (1.3 mg/l x 2 l/day / 70 kg = 0.037 = 4.0E–2

The disparity in these values, ranging beyond three orders of magnitude (for example, 3.3×10^3 difference between FDA and calculated cancer risk for PCBs), illustrates the fact that, even with perfect and applicable knowledge of contamination level and daily intake, very different views of health significance (and acceptable impact) are possible. For evaluation of Puget Sound data, we will emphasize the EPA (1993) tissue guideline values.

Risk Assessment Applied to Puget Sound Data

We have used the above-described risk assessment method to evaluate the potential for human health effects from the consumption of contaminated fish and shellfish using 1990–1993 Puget Sound monitoring data as summarized in Table 2. As a first-level screening approach, we considered the highest tissue composite value detected for each contaminant, irrespective of fish species. Maximum PSAMP fish and shellfish tissue concentrations were used along with exposure parameters generally representing the 90th or 95th percentile. CDI values were calculated according to Equation (1), Table 4. Calculated CDIs were used in Equations (2) and (3) to calculate upper-bound human health risks for suspected carcinogens and potential health hazard due to non-carcinogens (Table 5).

The results of this screening risk assessment indicate that of the 29 chemicals detected (Table 2) out of the 105 targeted in the analysis, only four (arsenic, mercury, PCBs, and bis(2-ethyl, hexyl) phthalate) were identified as posing a potentially non-negligible health risk, assuming high consumption rates and maximum detected tissue contaminant levels.

Of the few compounds determined to be of possible significant hazard in the screening analysis, PCBs pose the largest potential risk. The tissue levels of arsenic and phthalate esters are strongly confounded, the first by the dominance of naturally-occurring non-toxic organic forms of arsenic found in fish tissue, and the second by the high prevalence of laboratory and field phthalate contamination, rendering measurements suspect.

Table 6 presents median tissue levels for PCBs, DDE (the dominant DDT-related compound), and mercury. These values (which are more reflective of tissue contamination levels that might be encountered chronically), are 1–2 orders of magnitude lower than maximum values considered in Tables 2 and 4. In no case do any of these fish species/collection year median values exceed the FDA standard, and in only one case is an EPA fish tissue guideline exceeded (PCBs in 1992 salmon: 35 vs 10 ppb). The estimated 70-year cancer risk associated with high consumption of 35 ppb PCBs in salmon tissue would be about 5×10^{-4}. These predicted risks will not be detectable in population studies. For example, assume that in the Puget Sound area, there are 100,000 individuals who actually consume 140 grams of salmon per day on a lifelong basis. The cancer incidence attributed by these calculations to PCBs would be 50 cases. The baseline cancer incidence in 100,000 individuals (averaging over all types and the US population) would be 25,000. The normal variation in cancer incidence would certainly swamp the 0.2% increase predicted.

TABLE 6

Median values for key PSAMP contaminants in fish and seafood tissues, Puget Sound

Data Set	*N*	*Total (PCB) aroclor median ppb*	*p,p′-DDE median ppb*	*Mercury median ppm*
1991 sole	53	4.7	<1	0.06
1991 rockfish	34	<2	<0.3	0.15
1992 cod	14	<2	<0.3	0.10
1992 sole	54	9.3	<1	0.05
1992 rockfish	27	5.3	<0.5	0.18
1992 clams	57	<8	<0.2	<0.03
1992 salmon	75	35	12	0.06
1993 cod	14	<8	<1	0.10
1993 clams	58	<2	<0.7	0.01

Earlier studies of Puget Sound seafood contamination (prior to the establishment of current routine monitoring programs) were evaluated in a risk assessment completed for EPA in 1988 (Tetra Tech 1988). Using somewhat lower intake assumptions and generally higher tissue-level data than the present analysis, that study estimated a 'worst-case' risk from PCBs of 2×10^{-3} and described a calculated risk of 2×10^{-4} as 'moderate'. The lower risks calculated for PCBs between the 1988 effort and this report are generally true for all contaminants considered, and reflect declining tissue contamination levels rather than differing approaches. The agency interpretation of the risks calculated in 1988 was that no new regulatory or advisory response was warranted.

This comparison supports the view that current ambient Puget Sound levels, as reflected in these PSAMP fish and shellfish tissue samples do not pose a significant additional risk of disease.

IDENTIFYING THE TRANSBOUNDARY CONTRIBUTION TO ENVIRONMENTAL EXPOSURES/HEALTH RISKS

The analysis described above avoids the need to worry about the exact or even approximate contribution of transboundary pollution to total environmental contamination, by concluding that the combined effect of transboundary sources and other sources does not pose a significant risk to human health, as assessed by present monitoring. While this may be reassuring, there is the possibility that some significant pollutant that is **not** being monitored might be present. There is also the possibility that a currently unrecognized health effect might be occurring, and that health-based population surveillance might eventually disclose a significant human health hazard in the marine environment. Assuming such a scenario, what are the prospects for determining the relative importance of transboundary contributions as one component of the complex of sources and modifying factors relating discharges to fish tissue levels and thereby to human exposures? Other authors in this symposium will doubtless address this question as well, but we offer the following comments:

- For reasons already referred to, for example the non-unique character of the pollutants, their multiple and diffuse sources, and uncertainties in modeling quantitative impacts to receptor environments, the attribution of chemical contaminants (and resulting exposures) to transboundary versus other sources will not be readily achieved in most cases.
- Where unique toxicants are identified, it may be possible to assess transboundary effects. Initiatives such as chemical inventory reporting requirements, annual release estimates, and other 'community right to know' provisions of the US Superfund Amendment and Reauthorization Act, might be signs that such information would become available.
- Although transport and ecological magnification processes can create local environmental concentration elevations away from a point source of pollution, in general one would expect a gradient of environmental concentrations and effects varying with distance from the source. It would be very striking to have unhealthful impacts in a distant location without having even more pronounced effects close to the source. Thus, local discharge management and appropriate monitoring could be a reliable sentinel of transboundary effects.

CONCLUSIONS

While public health concerns underlie many environmental management decisions, quantitative identification of health impacts is highly uncertain, given the current state of knowledge. In addition to changes in environmental quality (from population growth, increased industry, changing disposal practices, and accumulation of contaminant pools), the evaluation of public health consequences of environmental exposures is coloured by the development of new investigative tools, better reporting and information management, new toxicological information, and changing perceptions regarding risk acceptability. At the present time there are inadequate data regarding human exposures to conclude that transboundary contamination is a significant public health problem. The human health risks projected from current levels of marine environmental contamination from all sources are negligible for most chemicals and are not at threatening levels for any. While the specific contributions of transboundary sources are not defined, the health risks resulting from transboundary environmental contaminants are believed to be negligible, as they are 'lost in the noise' of the risk estimation process. It is highly

unlikely that transboundary contamination will become significant to health until overall contamination and the relative contribution of transboundary sources increases considerably.

Based on severity of impacts alone, the apparent need for source control will usually be more influenced by local impacts than by remote, transboundary impacts. This would lead to the expectation that protection of public health close to the source(s) of discharge would dictate appropriate control measures earlier than would be required in order to protect public health at a remote (transboundary) location. Different opinions regarding the public health rationale for source control measures between those assessing local impacts and those considering transboundary impacts could arise from: (a) different approaches to impact characterization leading to different views of impact severity, and (b) differences in standards of acceptability. As governmental bodies and their scientific advisors consider information needs in response to public concern over the possibility of transboundary effects, identification and resolution of differences regarding human health risk estimation need to receive equal priority with additional environmental monitoring.

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DISCUSSION

Chris Garrett *(Panel)*: I guess I'm a bit confused about how humans compare with fish, because I think you're probably assuming here that there is no threshold in terms of the dose-effects relationship. Whereas for PAHs, which I know are different from PCBs, we heard this morning that sole appear to have a threshold at about 500 parts per billion. Are there grounds for saying that there's no threshold in humans for PCBs?

David Kalman: There's a rationale and you can accept it or not. The rationale is that if there is a threshold, and we assume there is no threshold, we over-estimate the risk and therefore that's a conservative approach. There is a great deal of debate about every single one of the cancer risk factors, the slope factors for the different chemicals, and there's a lot of debate about the no-threshold concept. This approach allows you to move forward without insisting on a detailed model. The effect of assuming no threshold is to bias the results to the high side in terms of risk.

Chris Garrett *(Panel)*: I realize that, but then if you do assume no threshold, you can go ahead and not stop at the individual risk, but work out some collective risk. You know the expected number of total casualties from seafood consumption, which can then be factored into economic considerations. Have you done that?

David Kalman: That's true. No.

Andrea Copping *(Panel)*: What about viruses and other exotic things? I know cholera transport in bilge water, and ballast water was of concern.

David Kalman: I can't tell you how glad I am you asked that question. There's not a great deal of information about viability of bacteria, or the prospect for transport over significant distances in a marine environment and then infecting humans. We know, looking at the other side of the picture, that there are lots of locations in Puget Sound with bacterially driven closures, and in most cases those are explained, but in many cases there is uncertainty as to source. Even distinguishing animal sources of coliform from human sources, or going beyond that and saying whether it is the leaking septic tank here or the discharge from some facility there is a major problem. Approaches coming out of molecular biology are applicable to this problem; using genetic typing of coliform and other bacteria to establish a relationship between disease and source. Another new technique is the application of ribosomal RNA typing to molecular epidemiology of outbreaks or detections on beaches. This could allow recognition of a remote influence, and it could be used as a tool to determine the radius of viability and detectability for these organisms.

Lincoln Loehr *(Heller, Ehrman, White & McAuliffe, Seattle)*: Could clarify for us — do the fish consumption rates that go into the computation pertain to total fish consumed or only fish that are contaminated?

David Kalman: The consumption rates are simply based on dietary intake of fish. They assume, among other things, that it is muscle tissue being eaten, and don't take into account consumption of other organ tissues, for example. They do assume that all of the fish consumed are contaminated to the specified level.

Lincoln Loehr *(Heller, Ehrman, White & McAuliffe, Seattle)*: So if people were eating a 140 grams a day, but 40 grams came from an area that was contaminated, and 100 from another area that was not, what would be the correct way to evaluate that risk? Forty grams a day?

David Kalman: That's right.

Brett Betts *(Washington Department of Ecology)*: The Department of Ecology are meeting with public stakeholders on January 26th to discuss optional values for about 50 contaminants for protection of human health. We are planning on using distributional analysis, or non-correlation analysis to look at uncertainty of your assumptions in risk analysis. We have put together a Puget Sound fish tissue database and are aware of organizations, both in Puget Sound and on the Columbia River, that are looking at alternate levels for ingestion and fish tissue concentrations. I just wanted to let everybody know that we'll have numbers pretty soon that will be publicly available.

Cheryl Niemi *(Washington Department of Ecology)*: The Water Quality Program at the Department of Ecology is going into public hearings on rural development at the end of February. We'll be looking at adoption of 91 different chemical criteria for marine and freshwaters for protection of human health through

ingestion of water, or for ingestion of fish tissue. Given the PSAMP program is analyzing mostly fillet tissues, not organs, with the different consumption surveys that are being done, and looking at what different groups eat, are we going to have enough data to actually get a real good handle on different risks for ethnic groups? Will we have enough fish tissue data for skin, for liver, for hepatopancreas, for those types of things, for chemicals with the PSAMP program?

David Kalman: I doubt that we will have the diversity of tissues or even whole organism measurements. This is a difficult problem and in some ways it's easier to define a population of concern and just deal with them, than to try to work out all the variables and appropriate numbers to go with each combination. For example, one scenario that might be a worst-case population exposure would be a southeast Asian immigrant family that fishes in very contaminated waters, uses shore-side fishing techniques that give them the bottom dwelling fish including fish species that we don't normally consider to be edible, and all of this goes in a pot and gets cooked into a sauce so that 100% of the animal is consumed. This is their entire protein source, so they are consuming very high quantities of it. You can compound all of these factors and wind up with a rising expectation of exposure, and a smaller and smaller population size. I doubt very much that we'll ever get to the point where we will be able to confirm any of these projections with measurements of population health because of that.

Laurie MacBride *(Save Georgia Strait Alliance)*: I was at a meeting a few weeks ago where a scientist from Oregon talked about a study in England on environmental estrogens. He said the scientists looked at linking fish populations in English rivers to polymers, including detergents coming out of the treatment plants, and that there was evidence to suggest not only were there impacts on the fish — male fish were becoming feminized — but possibly a link with increase in human breast cancer, and a decrease in human sperm count. Can you comment on that?

David Kalman: Among that list of 105 chemicals are some that are known as reproductive hazards both for men and for women. In a way, a similar question is if you catch a flatfish and it's got a big liver tumor, is the muscle tissue safe to eat? The answer is maybe, and in many cases, yes, because the contaminant is not maintained in the muscle tissue. If that fish is having that particular adverse health effect because of PAHs, for example, those are metabolized away, they're not detectable in the muscle tissue, which is good news for consumption, but bad news for monitoring programs. Whether or not there are some of these hidden problems that could in fact be a significant health threat to people eating muscle tissue, it's hard to say absolutely not, but there's not much sign of it so far.

Laurie MacBride *(Save Georgia Strait Alliance)*: Well apparently the European community is taking it fairly seriously, because they have ordered these detergents out of homes within five years, and out of industry within five years. My second question has to do with farmed salmon. Farmed salmon, as I'm sure you're aware, are raised most often on antibiotics. A University of Washington zoologist told a Washington State hearing in 1988, that eating farmed fish raised on antibiotics could transfer antibiotic-resistant bacteria to humans, and he warned that the diseases caused by that organism could not be medically treated. We have more and more reports of over-use of antibiotics and other chemicals in fish farms, including antibiotics such as erythromycin which is not legally supposed to be used because it is used on humans, and we have increasing reports of triple-resistant strains of bacteria. Could you comment on the whole issue of antibiotics and human consumption of farmed salmon?

David Kalman: I don't really want to comment specifically on antibiotics, I don't know much about that aspect of it, but I think there is an issue of looking at aquaculture separately from environmental quality. To give you another example, I'm aware that not too many years ago there was great concern with pen-reared salmon where the nets had been treated with TBT as an antifouling agent. In some ways the aquaculture story is more subject to management than the whole natural environment is.

Ben Kangasniemi *(Ministry of Environment, Lands & Parks)*: As someone who drags his family and friends out sailing quite often, I was a little distressed that you dismissed recreational contact as a serious health concern. I wonder if this is based on assumptions that recreational contact is primarily swimming and beach activities, and I wonder if health officials are giving consideration to water-based activities like windsurfing and dinghy sailing which expose people to substantial

amounts of water contact, and in my case inhalation and sometimes ingestion of water. People's habits are changing on the water due to more recreational emphasis. Is the health community recognizing that?

David Kalman: Well like everybody else we tend to study what's easy to study, and to redefine our questions to facilitate that. We've already had some comments about the relative levels seen in water column versus sediment or in biota. If you wanted to make some assumptions about the quantity of marine water that you were getting, either by ingestion or inhalation on a chronic basis, I think we would be looking at relatively low numbers and those two facts taken together — low water column concentrations and low quantities of water ingested — would tend to reduce the concern for chronic end points. That doesn't mean that in a specific instance, where you are windsurfing through a plume of something, that you could not contact a quantity that would cause illness. In the most recent issue of the American Public Health Association Journal there was an article describing symptoms related to bacterial contamination in surfing beaches, so there are scenarios where you can have health effects related to casual contact of water. In terms of a chronic chemical toxicity issue, I think that would be pretty surprising.

Open Discussion

Curtis Ebbesmeyer

Moderator

Andrea Copping *(Panel Chair)*: Over the last couple of days I have been thinking — and I wonder how many in the audience would agree — that not just the transboundary area, but the whole shared Washington-British Columbia marine waters, are really very clean and there is little reason for concern. Today I think we got in a little closer to shore with Mark Myers' talk, and talks about the marine bird and mammal habitat, but it has certainly been my experience in Puget Sound that the majority of problems — and I think they are very real problems — are near shore, in localized areas as Dave Kalman mentioned, and that we can't take some of the signals from the open basin, or even the average signals, as being where we need to concentrate our efforts.

Bruce McCain *(Panel)*: For the sake of discussion, it seems to me that if we are talking about doubling population in the next ten years or so, it is inevitable that certain types of contaminants will continue to increase in production and release into the environment, for example the PAHs that have been talked about especially in relation to fish and effects in fish. As we have heard, the contaminants that associate with particulates tend to stay in the Puget Sound Basin or in the Strait of Georgia Basin. Are we concerned that as we generate more and more of these contaminated particulates that we're going to reach a level in these basins that could exceed the threshold and start causing problems? How do we go about making sure that we're properly monitoring these systems, so that when that happens we still have a chance to do some sort of management action?

Curtis Ebbesmeyer *(Moderator)*: One issue that I've noticed is that each of the speakers is highly qualified to talk about their individual subject and we hear about a little overlap into other topics. I'm concerned about things that fall in the cracks, and sort of multiply the insults. For example we have oil spills, contamination, and we've learned about the fish in Puget Sound — well it was a high note speech, but I felt depressed. We have sediment degradation, and we've heard about habitat loss and we've heard some people talk about birds that might have been affected by El Niño, and then a bit later by an oil spill, so there's sort of a cross-disciplinary effect. I'm afraid the disciplines tend to get embroiled in their own discipline and don't talk to each other much. So I'm worried about the cumulative effect of the management aspect, together with the large natural cycles — like El Niño — and spills and other things. It's the cumulative effect that I think may fall in the cracks. We haven't had a paper on that, and frankly I don't know of anybody who is looking at it. My worry is that over the next twenty years we keep going after the next grant, but we forget about the sum total that may become fairly large and surprise us all.

Dave Kalman *(University of Washington)*: I agree with that. One area where I think this business about boundaries and focusing on a particular part of the problem is of particular concern is in the design and, hopefully, updating of monitoring programs.

I have heard the whole business of environmental protection, especially on the chemical side, compared with a guy looking for his wallet at night on a street under a street lamp, when he lost it in the alley, because he can't see what he's doing in the alley. I think we do have a tendency to go for what is easy to observe, and thereby create some blind spots which can easily be lost.

To give you an example: yesterday, when I was listening to the discussion of physical transport, it came to mind that I don't believe that monitoring programs that look at human health as a main point really take much input from where we expect the highly impacted, or relatively highly impacted, shoreline areas to be, based on transport models. We mostly tend to go with population centres, or where people harvest or get their seafood. However, if a location is only half as much used but has ten times the contamination, then on a population basis, perhaps that location needs to be considered. Integrating between what the physical oceanographers have to say and what the people designing monitoring programs from a health point of view are planning, I think, is an example of that kind of thing. It would be

useful to review monitoring programs by making an explicit list of the blind spots — chemicals not considered, locations not considered, new contaminants that they may not have knowledge about — and to try to obtain input from the other disciplines that are describing presence and fate of contaminants in this system.

Martin Keeley *(Friends of Boundary Bay)*: I would like to endorse what you've said. As a non-scientist I am frequently reminded of one of the first anecdotes that I ever heard: that scientists know more and more about less and less, until they know everything about nothing. I'm sure that you've all heard that.

I will give you two or three specifics about potential transboundary problems that I, and the organizations that I work with, are working on right now which, if they go ahead, are going to cause you lots of work and us more problems. One is the expansion of the container port at Roberts Bank on the Canadian side. The Canadian Pacific industrial terminus will be moving to Tilbury Island on the south arm of the Fraser River and trans-shipping things like hazardous goods from there. Not a lot that we can do in Canada to prevent that from happening. FREMP is a wonderful inter-agency group and they have done a lot of things, but they still seem incapable of dealing with Crown corporations who operate with a will of their own, and almost completely without any kind of controls. B.C. Ferries is another case in point.

On the U.S. side, we're working in Cherry Point with a guy from Edmonton who wishes to build a bulk commodity superport between a refinery and an aluminum plant. Right next to that, just filed, we have somebody that wants to build another bulk commodity superport. So it goes on and on, and we as environmentalists and you as scientists go on having to monitor and deal with this on a constant basis, because nobody seems capable of saying, 'No'. You need to come up with some recommendations. We rely on your science, and what we've heard in the last two days, to say we've got a problem.

You know, it doesn't really matter that the sediments are getting buried, what's getting buried is fairly horrific and it keeps on getting buried. Sooner or later there's a tsunami and an earthquake and it all comes up.

Curtis Ebbesmeyer *(Moderator)*: We are meeting in several weeks to review our drafts, and I think we are perhaps a quarter-step ahead of you on at least that minute aspect. Thank you for your comments.

Bill Austin *(Khoyatan Marine Lab, Cowichan Bay)*: I hear us saying 'pollutants' which tends to exclude a lot of other perturbations that may be happening out there, and we should open it up to any kind of perturbation, and then look at whether it is anthropogenic or not, which is another problem.

I'll give you one example that I don't think has been mentioned — and I have no idea how important it is — and that's the bow waves and wakes of ferries. There was a proposal to put a ferry terminal at Crofton, which would have meant going through Active Pass, through thirty or forty kilometers of shoreline that is semi-protected or protected. How would that have affected the erosion? How would it have affected the fauna and flora? I don't know, but it's another kind of perturbation.

The other comment I wanted to make was that I feel the greatest impact on the biota has come from our manipulation of species or species populations, either by reducing populations tremendously through our fisheries, or by adding species, potentially through ballast water, or — more likely — intentional introductions. What's the effect of oyster populations on the rest of the biota? What's the effect of the introduction of Manila clams and subsequently digging them up? I think we shouldn't forget those sorts of questions, because they can have quite an impact if we look at the biota generally or look at those communities generally.

Joe Truscott *(Ministry of Agriculture, Fish & Food)*: For about the last year and a half, I have been involved in coordinating an inter-agency exercise to look at coastal issues, and the need for strategic policy or strategy in coastal management. We held a workshop with public involvement, and it became evident that there is a lot of support for coastal management. I think there is a need to step back from some of the specific problems for a while and realize that we have got a management problem, and a management process problem.

In B.C. there have been a few specific integrated management programs, Fraser Estuary for example, and in a few other estuarine areas, but we've really lacked an integrated program and inter-agency program that is coordinated to deal in a holistic way with coastal problems. So we are looking at lack of institutional integration, and I think that this also applies in a transbound-

ary sense, as well as a lack of integration between watershed planning and what's happening on the coast.

Over the last few months, I've been involved in an exercise with the Commission on Resources and the Environment to develop strategic policy for a number of resource areas. One of the areas — and the area I am involved in — is the coastal area. We can look forward later on this month to the report making some draft policy statements, some of which will be in the area of coastal management. I think that might be something the Panel might look at, in terms of recommendations to Cabinet, to get something concrete happening in integrated coastal management in the province, and between the State of Washington and British Columbia. This involves not just the province of British Columbia, but the government of Canada as well. Thanks.

Dave Somers *(Senior Biologist, The Tulalip Tribes)*: I heard a number of speakers, in fact maybe all the speakers, call for the need for more collaborative research and monitoring, and the Minister this morning called for dissolving the border. Having dealt with forestry and non-point issues for a number of years now, I have found that the jurisdictional boundaries that we put up between agencies and nations are causing great problems in management and research and monitoring. I hope people that have the authority to do so will consider continuing your Panel in some form to assist in the generation of collaborative research and monitoring programs, and also maybe look at some management issues across the border in the future.

Lincoln Loehr *(Heller, Ehrman, White & McAuliffe, Seattle)*: The National Research Council last April released a three-year-long study on wastewater management in coastal urban areas, and it emphasized that for the toxicants the best way to manage them is with source controls instead of end treatment.

Several presentations yesterday dealt with BOD and TSS reductions, and my thought is that those types of numbers are not necessarily environmentally of any significance. Obviously some of those reductions in some places were, but with loadings it also matters where the loadings are going. A lot of stormwater discharge that urban areas have to deal with are on-shore, and they have bacteria and metals and oils and greases in areas where people have much greater exposure. They walk there, they may harvest shellfish from there. That's a lot different than a loading coming out of a diffuser, following some degree of treatment (or no treatment as the case may be). Septic tanks along shore will have a substantial impact on sea lettuce growth right along the shoreline, and that is different than nutrient inputs coming from an outfall far offshore. To give an example, consider the nutrient loading and BOD loading from Victoria, and picture the same loading going to the southern end of Budd Inlet, where Olympia, the state capital is. And we do have water quality problems in the southern end of Budd Inlet associated with our secondary-treated effluent due to the nutrient loading and a very poor location. Location matters on the loadings.

I would also urge you to keep in mind that there are issues of public cost, I'm talking dollars. Both countries have had problems with deficit spending and probably have comparable per capita national debts. I hear people saying, 'Gee it would be nice if we had more money for more monitoring'. I certainly agree with you and I support that, and recognize that our respective governments will be looking very closely at what they can afford to ante up, because there are people who would like to keep costs low. So be very cautious about pushing for cures for problems that are more hypothetical just to err on the side of caution, because the trade-off is that you'll not be able to respond to real problems because you will have committed resources in another direction.

I would urge that you watch out on pushing universal mandates throughout an area. We've had a mandate-approach to secondary treatment of sewage from our federal government and within Washington State, and I would instead encourage that you address site-specific issues and allow for more flexibility to deal with them. And insist that science plays a pivotal role in management decisions. Science, in the secondary treatment requirements in Washington, was excluded by state law from being a consideration, and I have an article that I will pass on to the Panel that outlines that history. I would not recommend treatment for treatment's sake, I would urge that philosophy be rejected. Thank you.

John Armstrong *(Environmental Protection Agency)*: Two comments, one is on loadings also. I hope the Panel will give some recommendations as to how seriously we should take doing a better job of calculating loadings. The first paper talked about loadings,

talked more about a database than actual loadings data. I wonder if the data are there, whether we have a database or not, and I wonder if we need those data. Years ago I thought not, now I'm not sure. It's of course difficult to get non-point loadings. There are models and assumptions one can make, but loadings from CSO, storm drains, industry, etc. A lot of me says if you're going to manage an area and you're going to dump stuff in the water, you ought to know what you are dumping. Maybe especially on an embayment basis, but I'd like some advice on should we go farther into loadings work.

Secondly, habitat. As a late convert to habitat importance, I'm starting to ask, When is enough, enough? How much can we lose? Certainly habitat loss in Puget Sound proper has slowed dramatically as its importance has become better known, but it still goes on. I wonder if we shouldn't identify key types of habitats, if not key habitats of all types in different locations, and just decide. Maybe we should recommend that governments decide enough is enough and this death of a thousand cuts has to stop.

So I would like some advice from this Panel to the state and the province on what we do about habitat loss. When we lose a fishery, there's a chance it'll come back; when you lose habitat, many times you're just not going to get it back. Thank you.

Rowland Atkins *(Hay & Company Consultants, Vancouver)*: I am responding to your comment, Dr. Ebbesmeyer, about what has fallen into the cracks. It seems to me that the major problems we need to deal with in this environment are located near-shore. Dr. Leving's comments were that the biology occurs mainly in the near-shore, certainly in areas of water less than twenty meters deep, and yesterday we heard Rob Macdonald talk about sediments. But it seems to me that the majority of sediment transport, which happens to be a major pathway for contaminant transport anywhere in any sort of waterbody, occurs in the near-shore. We don't really seem to have addressed that, and that seems to me to have fallen into the cracks between talks, particularly since that near-shore environment is the critical interface between the land, which is the source of the majority of pollutants, and the deeper water, which is the sink. Interaction in general occurs right in the near-shore and that seems to have been left behind.

Curtis Ebbesmeyer *(Moderator)*: I guess my biggest worry for the next twenty years is that the generation that is just being born will say, 'Why didn't you see that coming?' Analysis of serious accidents points to lots of different causes. I feel like we are a bunch of bus drivers and we are not looking at the traffic signals. We don't have much in the way of communication between the various buses and we may have some big crack-ups soon if we don't listen to each other.

Ralph Brinkhurst *(Aquatic Resources Center)*: Following up on Andrea Copping's comment about some of us saying that most of this place is relatively clean — that obviously raises the hackles of local environmentalists that see all kinds of problems. Well I want to share with you why I say this is, relatively, a clean paradise.

I am one of those privileged biologists that has travelled all around the world. I have stood on the beaches of estuaries in Peru where reeking mounds of human garbage lined the rivers, and the river is running pure sewage to the point where there were huge typhoid outbreaks not very long ago. And you don't even dare to try and sample. I have taken samples all day in a bay in China and not come up with a living benthic organism. I have worked on beaches where people are bathing and running around and having a great time at a famous resort in China, and the whole thing is running raw sewage, and the only thing you can find is billions of tubificid oligochaetes, all of the same species you find all over the world. So it didn't teach us very much about oligochaete worm distributions from such a place.

I have stood on the famous fjord in Hong Kong where they are losing kilometers a year to total anoxia. Many years ago a lot of colleagues stood around in the Baltic, which is a closed basin with appalling problems of disposing of the stuff that has accumulated in there, and it's getting worse and worse. Very early in my career I tried to find again some marine oligochaetes, the only ones known in those days, off the Bay of Naples. The substratum close to the shore of the Bay of Naples consists of broken china plates, bottles, bicycle wheels, saddles, and other memorabilia, to a depth of feet. You can't find a natural piece of marine benthic substratum to sample at all. I used to teach on the banks of the River Mersey, which used to be referred to as the rectum of England. You could watch from the ferry, you could see the fecal solids and very obvious signals of raw

sewage and associated materials slopping up and down that estuary. A lot of that of course has been cleaned up since.

So some of us do say that this is a very privileged area. Yes there are problems, but don't let's get too hysterical about it. Basically this is a very clean and wonderful and privileged place to be, but obviously we've got to keep fighting to keep it the way it is.

Curtis Ebbesmeyer *(Moderator)*: Thank you. One of our questions has to do with what's going to happen twenty years from now, so we're trying to be particularly sensitive to some of these trends.

Tom Pedersen *(Panel)*: Your point is very well taken that there is no need here to be hysterical, but at the same time I don't think that we want to be complacent, and obviously we want to find the middle ground between those.

Ken Warheit *(Washington Department of Wildlife)*: I would like to add my voice to the effort of trying to have a coordinated effort among all the disciplines, and coming up with some comprehensive understanding about what is going on in the shared waterway environment.

Part of my responsibility is to do resource damage assessment following oil spills. Now it's pretty easy to see how many birds have been oiled from a spill — it's on the news every night following a spill — but that's only a portion of the injury that occurs. What we need to know, obviously, is what's there prior to a spill, but even more important, to know how that would be affected in a situation that we did not have a spill. There are natural fluctuations, El Niños, and all the things we have spoken about over the last two days. So at least for my responsibility, we need to be able to coordinate all the problems that exist in the marine environment and come up with some statement about how injury from an oil spill, *per se*, how that affected the population given the fact that there are natural fluctuations, given the fact that there are contaminants in the environment. I'm asking for guidance from the Panel to help with that particular issue.

Curtis Ebbesmeyer *(Moderator)*: We in turn are asking for guidance from you.

Jeff Marliave *(Vancouver Aquarium)*: I wanted to make two quick comments. One is that over the last two years we have had an annual doubling of the number of the Harbour Seal pups that come to us either orphaned or kidnapped. There has been a remarkable increase in the proportion infected with *Pseudomonas*, to the extent that for the first time in almost a decade we lost most of them this year. They've been in a markedly lower condition and this year for the first time Vancouver's Harbour Master has reported coming upon drifts of several dead pups. We're suspicious that we may be rapidly approaching a plateau.

In line with our concern over our rehabilitation program which the public more or less demands of us, today a mailing is going out for a symposium in early March co-hosted by the Aquarium, UBC, and the Department of Fisheries and Oceans. The topic is the scientific aspect of reintroduction of marine mammals that have been rehabilitated or captive-bred. Feel free to invite yourselves if you are an ecologist interested in designing studies of impacts of reintroduction.

Chris Prescott *(Puget Sound Water Quality Authority)*: I wanted to give you my quick and probably ill-informed nomination for what should be the highest priority transboundary issue — and it's decidedly different from what I view as the highest priority for Puget Sound which I look at — and that is biological population abundance. We have seen that the contaminants by and large probably stay pretty close to their source, but I think that with populations that's a different situation. We know that they do cross the border. We have seen in fish and in birds some populations that do appear to be affected. My concern is that the monitoring programs are not there to address them. We know for instance in Bellingham Bay that English Sole have been affected, because we have to do two, three, and four times as many trolls as we did a few years ago just to get the number we need for the tissue analysis. So we see from some very indirect indices that this is a serious concern. I think there need to be recommendations that we have more monitoring of biological populations.

Ben Kangasniemi *(Ministry of Environment, Lands & Parks)*: Most of the symposium so far has dwelt on identifying and hopefully moving towards solutions on how we can minimize inevitable human impact in this area where the population is going to be growing dramatically. But I think that we have to face the fact that in the long run we are going to lose a lot of these

resources. We are going to lose some of the biodiversity. We need to fight against that and improve how we manage these resources. But there is a whole dimension here that we must keep in mind. There are still several areas on the B.C. coast, the Alaska coast, and I hope further south of us, that are in a fairly pristine condition, and they are becoming more and more valuable in that state as these areas decline in size. I think we have to take the opportunity to put priority on preservation of marine areas so that they do not become subject to intense development which we have difficulty in controlling within the political structure that we have to live within. I think we have to be reminded of the terrestrial folks who are moving towards a 12% preservation of the land mass for biodiversity. We have to look at the level of preservation that we have in the marine environment, and I think figures indicate that we have less than 1% preservation in the natural state. I think that is really an unfortunate situation, and we really need to improve on that.

Dave Peeler *(Washington Department of Ecology)*: Yesterday especially and again this morning, I heard a lot of references to El Niño effects, and yet I don't think we saw any kind of characterization of the physical effects of El Niño on the environment here — that is temperature, salinity changes, that sort of thing. I don't know, as a zoologist, why that is, whether there wasn't data available or it was the idea of the onshore scientists don't talk to the offshore scientists, that was mentioned yesterday, or just what. It seems that since that was mentioned as a possible problem in several of the talks, that would be something worth looking at.

There has been some discussion about looking at acute effects, including death of organisms, whether it is human health or wildlife. But when we take a hard look at some of the effects, we're finding that at very low levels there is contamination where we wouldn't expect it, and there is some effect to the immune systems and others. This is news to us, we didn't expect this, we wouldn't have known about it five years ago. It's hard for me to believe that doesn't have a long-term effect on that particular population. So when we see populations of animals declining at very quick rates, we know that some is due to over-fishing and physical changes to the environment (dams and habitat changes and the like) but there are also other kinds of changes. So we shouldn't abandon the conservative approach, because basically we don't know what we don't know.

I would add one more thing as an illustration. We're doing a short-term bioassay at our new headquarters building in Olympia, where we have high copper levels in the water supply in the building itself. The first we found out about that was not because humans were affected, but because the fish in people's aquariums on their desks died.

Curtis Ebbesmeyer *(Moderator)*: I'd like to comment on a few aspects of that. The Panel has talked unknowns at great length. The presentations that you have seen are just a sampling of what's in the papers. I know that Rick Thomson's paper on Physical Oceanography runs some fifty pages. You can believe that El Niños and other long-term cycles will be in the Panel's report. We have about two feet of paper to read.

Dave Peeler *(Washington Department of Ecology)*: We used to say we didn't find contaminants because our level of detection was quite high compared to where they are today, now we know that they are there, and we can actually find effects because our technology has increased so dramatically. That's another issue, it's not just, 'Have we ever looked for it?' but it's also, 'Was the technique we used really going to allow us to see what we wanted to find — or didn't want to find?'

Concluding Remarks

Andrea E. Copping

Chair, B.C./Washington Marine Science Panel

As Mary Riveland and Tom Gunton told you yesterday, the Marine Science Panel was asked to examine the present state of scientific knowledge of the shared marine waters of British Columbia and Washington. We were also tasked with documenting the expected changes in this marine system and reporting these findings to the Environmental Cooperation Council. To help us with our task, the Council and their staff devised six questions that we, the panel, will attempt to answer.

In planning for our work and for this symposium, we felt that we could best tap into the combined knowledge of the scientific community by requesting papers that followed disciplinary lines, rather than by asking for direct answers to our six questions. We have been privileged to hear 13 very interesting and provocative papers over the past two days. And we have had the opportunity to question the presenters and some of their co-authors. The discussion period this afternoon has given me food for thought, as I'm sure it has my fellow panel-members.

What are some of the significant issues that have been brought to our attention over the past two days?

- As we expected, there are few barriers to the transfer of dissolved materials across the international border. I think it is of interest how much we actually know about some of the transfer mechanisms, and how much direct evidence we have of this transfer. However, we heard that most of the contaminants associated with particles do not travel between Puget Sound, Juan de Fuca Strait and the Strait of Georgia.
- Similarly, no one is surprised that fish, birds, marine mammals and some invertebrates travel across the border at will, although we have heard evidence that many species of fish and shellfish maintain separate stocks in Puget Sound, Juan de Fuca Strait and the Strait of Georgia.
- The poor state of health of many of the marine and anadromous fish stocks may have been an eye-opener to many of us. Many marine mammal, bird and shellfish stocks are also under considerable stress, while others are thriving and, in some cases, reproducing at a level that the environment cannot support.
- Many of us at this symposium are somewhat familiar with the evidence that toxics and other contaminants have affected our resource populations, but the amalgamation of the information that we heard here really makes an impact. Obviously, there are areas within the shared waters where contamination is widespread and detrimental to organisms, while other areas are without noticeable effects.
- The human health implications of marine contamination in the shared waters is a much more open question. The issues raised here pose many additional questions.
- The implications of habitat loss are perhaps the most far-reaching and probably irreversible impacts that we have heard about during this symposium. Fish populations, shellfish, marine mammals and birds are all dependent on a healthy environment, and they are affected by the rapid human encroachment into the estuarine and coastal areas of British Columbia and Washington. The acreages of loss of vegetated near-shore habitat are staggering and are already seriously impairing fish and wildlife rearing and survival in urban areas.
- The absolute necessity of making the public aware of the state of our shared waters and resources was mentioned several times, as was the necessity of involving the public in making decisions about what level of environmental degradation is acceptable, through education and public involvement programs.

What is the panel going to do with this information, and how will we meld some very diverse and sometimes contradictory information into a coherent report?

I can attempt to answer that question in two different ways: First the approach and framework that the panel

will use to arrange and analyse this information, and secondly to talk a bit about the process we will follow to get to our report.

The panel will approach the large amount of written material that we are gathering by considering the shared waters of British Columbia and Washington as an enclosed ecosystem which has important inputs of water, sediment and biota from the Pacific Ocean and from the adjacent land. Within this ecosystem, we will look for the linkages and relationships that allow the resource populations and waters in one location to be affected by anthropogenic activities and natural actions in another location. We will take as our framework the need for a sustainable marine ecosystem in which humans and their activities can coexist with biological populations, clean water and healthy sediments, and in which we need to guard against irreversible impacts like habitat loss.

Much of this meeting and the subsequent deliberations of the panel will be focused on the existing and potential degradation of the marine environment and the impacts on marine populations. We will always keep in mind the affect that human development and waste disposal may have on the nearshore marine environment, and we will be on the lookout for these trends. The land surrounding the Strait of Georgia and Puget Sound are among the fastest growing population areas on the continent. As most aquatic pollution is the result of anthropogenic inputs, it is ultimately caused by the growing human population in the region, and by decisions made about land use in the watersheds. We will consider evidence of marine water and resource degradation, and loss of high-quality habitat in light of what is going on in those watersheds.

The symposium is the first major step in our process. As you know there will be proceedings published from this symposium, along with transcripts of some of the question and answer periods. We will examine the papers and discussion sessions in detail. Also, next week the panel will spend a day in Vancouver and another day in Seattle, meeting with individuals and groups who have given us additional written material, and who have information that might not have been covered in the symposium. We will take into account material submitted to us in the next few weeks, and will add it to the growing store of knowledge that we are accumulating.

The panel intends to work on the six questions over the next few months and meld them into a coherent report and recommendation to the Environmental Cooperation Council. We will report to the Council at the end of May, and our report will be available shortly thereafter.

Our commitment to you — the speakers, co-authors and symposium participants — is to take the knowledge that we are accumulating and to write a short, pithy report. We will see that this report is brought to the attention of senior agency staff and decision-makers on both sides of the border. Our report will be driven by scientific knowledge and analysis of the state of the shared British Columbia/Washington State marine waters, without regard for political affiliation or influence.

As the symposium draws to a close, we have a number of people to thank for making this event possible. Staff at the British Columbia Ministry of the Environment, the Washington Department of Ecology, and the Puget Sound Water Quality Authority have been instrumental in making all this happen. Our symposium manager, Wendelin Fraser, and her staff have taken care of all the logistics. And we have to thank the Environmental Cooperation Council for their support and confidence as we take on this challenging task. But most of all, I would like to express the heartfelt thanks of the panel to the speakers and their co-authors who put a great deal of time and effort into pulling together the scientific information we need to get on with our task. Finally we would like to thank all of you who took the time and effort to participate in this way. We hope that we can continue to interact with many of you in this process.

At this point I want to leave you with the idea that is driving the panel in our work — the take-home message. So often public policy proceeds with a misrepresentation of the science. We hope to be able to leave a record of the current scientific knowledge of the shared British Columbia/Washington waters, from which sound public policy decisions can be made.

Thank you for your time and attention in working with us at this symposium.

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Ed Casillas is Assistant Manager of the Physiological Toxicology Program in the Environmental Conservation Division of the National Marine Fisheries Services, NOAA. He and his colleagues are developing new bioassays to study the chronic effects of sediment-associated contaminants on the survival, growth and reproduction of various marine invertebrate and vertebrate species. This research includes both mortality and sublethal tests, of which the latter are particularly useful for monitoring areas with low to moderate levels of pollution. In addition, Dr. Casillas and his colleagues are working on biomarker development in the blue mussel, and linking these effects to growth and reproduction in molluscs, and optimizing conditions for the development, holding and testing the sensitivity of larval flatfish to environmental contaminants. Their research also includes assessment of the effects of contaminant exposure on immune function in marine fish species, using state-of-the-art immunotechniques. Dr. Casillas earned his BA in Environmental Biology from University of California (Santa Barbara), and his MS (1974) and PhD (1978) in Fisheries Biology at University of Washington. Prior to joining the ECD in 1980, Dr. Casillas was a research associate in the Department of Laboratory Medicine at the University of Washington.

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Ken Chew received his BA from Chico State College in California and his MS and PhD from the University of Washington, then joining the staff of the School of Fisheries, University of Washington. At present he is Professor in the Division of Aquaculture. He is also Center Director for the Western Regional Aquaculture Consortium which represents one of five aquaculture centers designated by the U.S. Department of Agriculture. The center in Seattle administers research, development and demonstration projects related to aquaculture for the twelve western states. Dr. Chew's qualifications cover a wide spectrum with respect to global aquaculture, shellfish aquaculture, paralytic shellfish poisoning and problems related to baseline ecological studies involving benthic intertidal and subtidal invertebrate communities. Throughout his professional career he has maintained a close working relationship with the molluscan shellfish industry in Washington. Dr. Chew has traveled as science advisor to numerous foreign countries, serving as a consultant to molluscan aquaculture projects in developing countries.

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Paul Harrison received his PhD from the University of Washington in Biological Oceanography. Dr. Harrison's area of expertise is phytoplankton physiology and ecology. His laboratory research has focused mainly on the uptake and utilization of various nutrients (nitrogen, phosphorus, silicon, iron and selenium) by marine phytoplankton. Dr. Harrison has been studying nutrient and phytoplankton dynamics in the Strait of Georgia for the last ten years. The main focus of this work has been on how the Fraser River discharge and the Fraser River plume affect biological productivity in the southern portion of the Strait. He is currently working in the Departments of Botany and Oceanography at the University of British Columbia.

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Rita Horner is an oceanographer in the School of Oceanography at the University of Washington in Seattle, where she earned her PhD in Botany. Her interests lie in the ecology, morphology, and taxonomy of marine phytoplankton and the dynamics of phytoplankton blooms. Dr. Horner has worked with a number of toxin-producing and harmful species in Pacific Northwest waters.

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Lyndal Johnson leads the Reproductive Toxicology Program of the Environmental Conservation Division, and oversees the Division's research on the effects of chemical contamination on reproductive success and other aspects of endocrine function in benthic fish. She is also active in the development of the Division's new Ecological Modeling Program and has been involved in several recent studies whose objective is to link contaminant-related declines in survival and reproductive

potential to changes in fish abundance. Her other areas of expertise include histopathology, biological monitoring, and statistical analysis. Ms. Johnson earned her BS in Biology from Western Washington State University and did additional post-graduate study in ecology and systematics at the University of Washington. She is currently pursuing a doctoral degree in Fisheries at the University of Washington, specializing in fish endocrinology.

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David Kalman is a chemist by training, and is currently associate professor of Environmental Health, University of Washington. His major research interests are in the area of chemical issues related to human exposures and health, with emphasis on exposure assessment and environmental monitoring. He was co-investigator with Dr. Marsha Landolt in a NOAA-sponsored project entitled *Potential for Human Exposure to Puget Sound Contaminants* (1984–86), which surveyed tissue chemistry as well as fish consumption data, to generate a model for pollutant exposures via dietary intake in Puget Sound fish. Dr. Kalman has been actively involved with the Puget Sound Ambient Monitoring Program since 1987. Other major current research activities include NIEHS-funded projects on human dosimetry for volatile organic solvent exposures, and an exposure and effects assessment of arsenic exposures in rural Chile; and several topical areas in industrial hygiene and occupational exposure assessment.

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Blair King received his BSc (Hon) in Chemistry and Biology from Queen's University (Kingston, Ontario) in 1989. He joined the University of Victoria organic indicators working group in 1991 as a research assistant to explore environmental data management concepts, principally through the development of the Continental and Oceanographic Data Information System (CODIS). More recently, Blair has been involved in developing an information base on chemical contaminant data for the Fraser River and Strait of Georgia. Blair is currently a graduate student at the University of Victoria studying to obtain his MSc in Environmental Studies.

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Robie Macdonald is a chemical oceanographer with the Institute of Ocean Sciences in Sidney. His work has been divided between the Canadian western Arctic and the Pacific coastal fjords. In the Arctic he has been working on problems related to oil exploration and development in the southern Beaufort Sea. There

he has used a variety of oceanographic measurements to determine the sources, quantities, transport pathways and fates of natural compounds on the Beaufort shelf to set in context the likely impact of chronic and acute discharges from the oil industry. More recently, work in the Arctic has focused on the emerging issues of long-range transport of organochlorine compounds and radionuclides. For the Pacific coast, his recent efforts have been to derive contaminant records from age-dated sediment cores. In particular, his interests lie in applying chemical and statistical techniques to identify contaminants by source, and to determine the quantities and residence times for these contaminants entering the coastal waters.

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TOM QUINN is an associate professor in fisheries, University of Washington (1990–present). Formerly, he was an assistant professor, University of Washington (1986–90), and research associate in oceanography, Univirsity of British Columbia (1984–85). He is a member of the American Fisheries Society, American Society of Ichthyologists and Herpetologists, Animal Behavior Society, and American Institute of Fishery Research Biologists. Dr. Quinn's main areas of expertise are the migration, homing and spawning behavior of Pacific salmon. He received his BA in biology from Swarthmore College (1976), MS (1978), and PhD in fisheries, University of Washington (1981).

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MANSOUR SAMADPOUR BS (1981) and MS (1987) in Microbiology, and PhD (1990) in Food Science & Technology and Molecular Biology, University of Washington. Dr. Samadpour is acting Assistant professor in the Department of Environmental Health. His recent research has focused on tracing sources of colifrom contamination of shellfish beds; differentiating between fecal coliform of animal and human origin;

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MAX TAYLOR was educated in Scotland, Australia and South Africa. He earned his BSc (Hons.), and PhD from the University of Cape Town. Dr. Taylor has been a faculty member at the University of British Columbia since 1964, Full Professor (1975) with a joint appointment in the Departments of Oceanography and Botany. Dr. Taylor is the former President (now Honorary Member) of the International Society for Evolutionary Protistology; Canada-France Exchange Fellow, Killam Senior Fellow (UBC); Christensen Fellow (Oxford University). He has conducted field studies for UNESCO, IDRC and CIDA. He is currently a member of the steering committee for the IOC-UNESCO International Program on Harmful Algal Blooms and a member of Scientific Committee of Oceanographic Research Working Group 97 (Physiological Ecology of Harmful Algal Blooms). Dr. Taylor current research interests include harmful algal bloom ecology, especially 'red tides' and fish-killing blooms in BC and SE Asia. Dr. Taylor has also worked on ciguatera fish poisoning in the eastern Caribbean, Hawaii and the western Pacific.

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RON THOM joined Battelle Northwest in 1990 as Senior Research Scientist. His professional experience includes employment as a marine biologist, university teaching, university research, and scientific consulting, and has served on a number of professional committees, in particular, as chair of the technical advisory committee of EPA's Puget Sound Estuary program. In 1990, Dr. Thom was invited to present a paper on habitat restoration to NOAA's conference on Restoring the Nation's Marine Environment. This conference initiated NOAA's program in marine restoration. Dr. Thom's research includes benthic primary production; the effects of pollution on nearshore marine systems in California, Washington and Alaska; habitat construction and restoration of marine and estuarine systems; effects of climate change on estuarine systems; and ecology of fisheries resources in nearshore systems.

Dr. Thom serves as Affiliate Associate Professor, School of Fisheries, University of Washington. Dr. Thom earned his BS in Biological Sciences from California State College, MS in Marine Algal Ecology from California State University, and PhD in Fisheries from University of Washington.

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RICHARD THOMSON earned his PhD (Physics and Oceanography) at the University of British Columbia (1972). He is a research scientist with the Institute of Ocean Sciences in Sidney, and has been involved with theoretical and field-oriented research into the physical oceanography of B.C. coastal waters since the mid-1970s. Early work on the circulation of Juan de Fuca Strait was conducted with scientists at the Pacific Marine Environmental Laboratory (NOAA) in Seattle, and on the BC/Washington continental shelf with scientists at University of Washington. Present research includes a long-term fisheries-oceanography project on the west coast of Vancouver Island, a study of deep-water intrusions into the Strait of Georgia, surface currents in the North Pacific using satellite-tracked drifters, and a multidisciplinary investigation of hydrothermal venting and deep-sea circulation over Juan de Fuca Ridge. Much of his present work involves the use of bio-acoustical techniques to determine possible links between hydrothermal venting and zooplankton biomass in the deep ocean. Dr. Thomson is the author of an introductory text on ocean sciences, *Oceanography of the British Columbia Coast.*

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PAUL WEST (PhD McMaster 1969) is a faculty member at the University of Victoria, Department of Environmental Studies. With Tom Fyles, he is involved in an organic indicators working group that explores environmental data management in collaboration with the Department of Fisheries and Oceans and Environment Canada; principally through Continental and Oceanographic Data Information System (CODIS). With graduate student Blair King they are working on chemical contaminant data for the Fraser River Basin and the Strait of Georgia. Dr. West was a member of the British Columbia Round Table on the Environment and Economy since its inception in 1990, and co-chair of the Round Table Monitoring Committee.

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Jack Word is a Staff Research Scientist and Marine Ecological Process group manager at Battelle Marine Research Laboratory. Over the past 25 years, he has pioneered research on toxicant and nutrient impacts to communities of benthic, microlayer, and shoreline organisms, by performing multidisciplinary programs off the coasts of Washington, California, Alaska and Mexico. He has performed acute toxicity experiments on over 20 species of invertebrates and vertebrates, and has developed testing protocols for numerous species. Dr. Word's research also includes evaluation of the effects of contaminants on long-term survival, acute and chronic toxicity tests (especially with sediments), bioaccumulation, fecundity, survival, and multi-generational effects on several species of marine organisms. Dr. Word earned his BS (Zoology) and MS (Biology) at California State University, and his PhD (Fisheries) at University of Washington.